The ESR spectra were recorded with an X-band spectrometer (modulation frequency of 1 Hz). Radical concentrations were measured with a single-crystal $CuCl_2 \cdot 2H_2O$ as a reference sample.[15]

The CO_2 yield were determined according to the published procedure.[16] The sealed tube with a sample under study (~0.5 g) was kept thermostated at a preset temperature, and then it was attached to a vacuum system and the seal was broken. Methanol vapor was condensed at −196 °C (~2.0 mL) and the sample was melted. The homogeneous solution produced was cooled to −80 °C and CO_2 and methanol were recondensed from the gas phase into an intermediate trap at −196 °C. The trap with condensate was warmed to −80 °C and CO_2 was again condensed in a V-shaped trap at −196 °C. The latter was warmed to −80 °C and the CO_2 pressure was measured with an oil manometer. These operations were repeated several times until a constant CO_2 pressure was attained. The accuracy of the measurement was ca. 10%.

Kinetic measurements of the PDSA decomposition rate in the PDSA–SA solid-phase system were made in a thermostatic reactor in an Ar atmosphere, where the crystalline samples prepared according to the above procedure were placed. At indicated time intervals the solid samples were removed and peroxide concentration was determined by the iodometric method.[17]

Propionic acid was identified in the PDSA–SA decomposition products by GLC. The initial sample (3.02 g) with 0.22-g PDSA content was placed into a round-bottom flask, which was preheated in a thermostat at 70 °C until the ESR signal entirely disappeared (~200 h). Reaction products were extracted with *n*-hexane and analyzed by GLC, using an internal standard (*n*-valeric acid). The propionic acid content in the reaction products was ~0.101 g. Analysis conditions: a 3 mm × 2 m column with SE-30 [5% on a Chromosorb W (60–80 mesh)]; temperature, 110 °C; gas carrier, nitrogen.

Registry No. I, 5905-59-9; IV, 16405-28-0; $HO_2CCH_2\dot{C}H_2$, 2887-43-6; $HO_2C(CH_2)_2CO\dot{O}$, 6233-24-5; $HO_2CCH((CH_2)_2CO_2H)\dot{C}HCO_2H$, 123290-22-2; $HO_2CCH(O_2C(CH_2)_2CO_2H)\dot{C}HCO_2H$, 123290-23-3; succinic acid, 110-15-6; fumaric acid, 110-17-8; glutaric acid, 110-94-1; peroxydisuccinic acid, 123-23-9; peroxydiglutaric acid, 10195-54-7.

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Crown Ether Alcohols. 1. Crystal and Molecular Structure of the Complex between *sym*-Hydroxydibenzo-14-crown-4 and Water Molecules ($[C_{18}H_{20}O_5] \cdot 1.25[H_2O] \cdot 0.125[CH_3OH]$) Including Interesting Water–Methanol Channels

Uriel Olsher,[*,†] **Felix Frolow,**[†] **Richard A. Bartsch,**[*,‡] **Michael J. Pugia,**[‡] **and Gil Shoham**[§]

Contribution from the Department of Chemical Services, Weizmann Institute of Science, Rehovot 76100, Israel, the Department of Chemistry and Biochemistry, Texas Tech University, Lubbock, Texas 79409, and the Department of Analytical and Inorganic Chemistry, The Hebrew University of Jerusalem, Jerusalem 91904, Israel. *Received December 21, 1988.*
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Abstract: The synthesis and crystal structure of the title compound are described. Single-crystal X-ray structure analysis indicates 8 formula units in the unit cell of parameters a = 16.024 (1) Å and c = 13.076 (1) Å. The space group is $I\bar{4}$. Direct methods yielded the structure, which was refined by least-squares techniques to a final R factor of 0.038 for 1533 independent observations. A water molecule forms a 1:1 neutral complex with the crown ether alcohol. In this complex, the water molecule is hydrogen bonded to the crown ether hydroxyl group. Four monohydrate complexes are hydrogen bonded to a central water molecule in a perfect tetrahedral geometry and to an apical methanol molecule. Unusual water–methanol channels are found in this structure. The crystal packing of the complex includes hydrophilic water–methanol channels which are surrounded by hydrophobic cylinders consisting mainly of benzo rings and methylene groups. The crystal structure provides a model for the encapsulation of water molecules by hydrophobic regions with potential application for the formation of hydrophilic pores in biological bilayers.

Macrocylic polyethers (crown ethers) are known to form stable and often selective complexes with various cations.[1,2] Recently, these polyethers have been found to form complexes with neutral molecules as well.[3] Among the class of charged complexes the guests include protons and hydronium ions, and among the neutral guests are water molecules. Relatively little information is available concerning complexes of protons[4–7] and/or hydronium ions[8–14] with cyclic polyethers and other ionophores.[15–17] It is not surprising, therefore, that the interactions of water molecules with neutral ionophores, which are essential for the formation of the ionophore–hydronium ion complexes, have not yet received appropriate attention.[16–34]

The binding between crown ethers and protons in aprotic organic solvents is primarily due to interaction of the protons with

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[†] Weizmann Institute of Science.

[‡] Texas Tech University.

[§] The Hebrew University of Jerusalem.

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the macrocyclic ethereal oxygens.[4-7] Although 18-crown-6 remains unprotonated even in strongly acidic aqueous solutions, it readily complexes hydronium ions in acetonitrile.[8] In such aprotic media, the complexation appears to favor the inclusion of the hydronium ion within the central cavity of the crown ether, as has been demonstrated in 18-crown-6–hydronium ion adducts.[9] The structures of such 18-crown-6–hydronium ion complexes have been determined recently by X-ray crystallography.[11-13] The hydronium ion is anchored in the center of the macrocyclic ring cavity by three $OH^{+}\cdots O$ hydrogen bonds. Pyramidal geometry is found for the hydronium ion. Formation of 1:1 and 2:1 hydrates of acids in hydrophobic solvents in the absence of crown ethers has been demonstrated by IR spectroscopy.[35] Similar behavior might be anticipated in hydrophobic membranes.

Crown ethers are efficient agents for solubilizing water in chloroform.[34] Thus, when a macrocyclic polyether ionophore is incorporated into a hydrophobic membrane as a proton carrier, it should be solvated by water molecules. The crown ether probably interacts with hydronium ions (solvated protons), rather than with bare protons, at the acidic aqueous solution–hydrophobic membrane interface as well as within the membrane itself.[20,35] It seems likely, therefore, that the interaction between crown ethers and water molecules is important for the formation of the complexes of hydronium ions with cyclic polyethers and may play a central role in transport across synthetic and natural membranes.

Water molecule binding by cyclic polyethers might be enhanced through hydrogen-bonding interactions when the polyether molecule contains hydroxyl groups[16,22,31] or ionizable functions.[18,19] Macrocylic polyethers which possess hydroxyl groups have been reported by Gokel,[36] Okahara,[37,38] and Bartsch[39-43] and their co-workers. The alcohol functions in such compounds could potentially interact with an axially coordinated water molecule which is hydrogen bonded to the ethereal oxygens of the macrocylic polyether. In preliminary solvent polymeric membrane studies, liquid membranes containing *sym*-hydroxydibenzo-14-crown-4 (**1**) have been found to exhibit preference for complexation of protons over alkali and alkaline earth metal cations.[44] Hence, **1** and closely related crown ether alcohols are expected to function as selective proton ionophores and may also efficiently complex water molecules.

In this paper, we report the crystal structure of a monohydrate complex of crown ether alcohol **1**, a structure which also exhibits an interesting and unusual pattern of water–methanol channels.

Table I. Crystal Data for **1a**

tetragonal space group	$I\bar{4}$
a (Å)	16.024 (1)
c (Å)	13.076 (1)
V (Å^3)	3448.6 (7)
$C_{18}H_{24}O_5\cdot 1.25H_2O\cdot 0.125CH_3OH$	
M_r	444.62
Z	8
D_c (g cm^{-3})	1.478
method of measurement	$\omega - 2\theta$ scan
speed of measurement (deg min^{-1})	1
diffractometer	CAD4
radiation	Mo K$\bar{\alpha}$ (λ = 0.7714 Å)
θ_{max} (deg)	27
no. of reflections	
measured	3328
independent	1573
with $F_o > 3\sigma(F_c)$	1509
R_{sym}	0.02
final R, R_w	0.038, 0.042

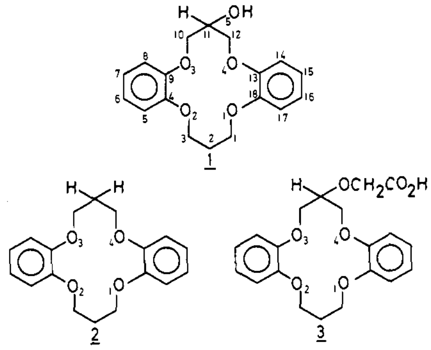

Figure 1. Molecular numbering schemes.

Experimental Section

Materials. 1,3-Bis(2-hydroxyphenoxy)propane was prepared by the reported method.[45,46] Other chemicals were reagent grade and were used

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Table II. Atom Coordinates ($\times 10^4$) and Temperature Factors ($Å^2 \times 10^3$)

	x/a	y/b	z/c	U_{eq}[a]
C1	3342 (2)	1251 (2)	254 (3)	72 (1)
C2	3390 (2)	955 (2)	−830 (4)	78 (2)
C3	3348 (2)	1588 (2)	−1649 (3)	73 (1)
C4	4210 (2)	2630 (2)	−2356 (2)	50 (1)
C5	3744 (2)	2730 (2)	−3227 (3)	63 (1)
C6	3948 (2)	3312 (3)	−3932 (2)	72 (1)
C7	4598 (2)	3797 (3)	−3788 (3)	61 (1)
C8	5072 (2)	3727 (2)	−2914 (2)	47 (1)
C9	4881 (2)	3136 (2)	−2197 (2)	54 (1)
C10	5957 (2)	3529 (2)	−1087 (2)	49 (1)
C11	6393 (2)	3219 (2)	−149 (2)	51 (1)
C12	5916 (2)	3224 (2)	826 (2)	45 (1)
C13	4827 (2)	2497 (2)	1608 (2)	56 (1)
C14	4971 (2)	2838 (2)	2559 (2)	74 (1)
C15	4462 (2)	2641 (3)	3368 (2)	85 (2)
C16	3827 (3)	2137 (3)	3232 (3)	74 (1)
C17	3671 (2)	1792 (2)	2285 (3)	51 (1)
C18	4171 (2)	1969 (2)	1467 (2)	56 (1)
O1	4080 (1)	1676 (1)	500 (2)	60 (1)
O2	4079 (1)	2066 (1)	−1609 (2)	59 (1)
O3	5291 (1)	3005 (1)	−1313 (2)	56 (1)
O4	5274 (1)	2652 (1)	751 (1)	51 (1)
O5	6735 (1)	2450 (1)	−332 (2)	58 (1)
O24	5565 (2)	1192 (2)	−780 (3)	89 (1)
O25[b]	5000	0	−2500	114 (2)
O26[b]	5000	0	594 (7)	90 (2)
C27[b]	5000	0	1657 (7)	94 (2)

[a] $U_{eq} = (1/3)$(trace of orthogonalized $\mathbf{U}_{ij}$ matrix). [b] Solvent atoms at special crystallographic positions.

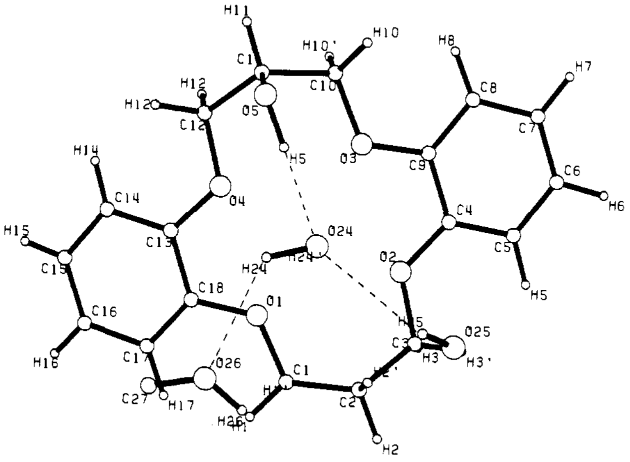

Figure 2. View of the molecular structure of **1a**.

Table III. Bond Lengths (Å)

C2–C1	1.500 (8)	O1–C1	1.420 (5)
C3–C2	1.486 (7)	O2–C3	1.419 (5)
C5–C4	1.378 (5)	C9–C4	1.381 (5)
O2–C4	1.355 (5)	C6–C5	1.361 (6)
C7–C6	1.330 (6)	C8–C7	1.383 (6)
C9–C8	1.377 (5)	O3–C9	1.350 (4)
C11–C10	1.503 (6)	O3–C10	1.408 (5)
C12–C11	1.493 (5)	O5–C11	1.387 (5)
O4–C12	1.399 (4)	C14–C13	1.381 (5)
C18–C13	1.380 (5)	O4–C13	1.359 (4)
C15–C14	1.380 (6)	C16–C15	1.330 (7)
C17–C16	1.382 (7)	C18–C17	1.374 (6)
O1–C18	1.359 (5)	C27–O26	1.39 (1)

Table IV. Bond Angles (deg)

O1–C1–C2	109.0 (4)	C3–C2–C1	117.3 (4)
O2–C3–C2	108.3 (4)	C9–C4–C5	119.2 (4)
O2–C4–C5	126.1 (4)	O2–C4–C9	114.7 (3)
C6–C5–C4	120.5 (4)	C7–C6–C5	120.6 (4)
C8–C7–C6	120.7 (4)	C9–C8–C7	119.6 (4)
C8–C9–C4	119.3 (4)	O3–C9–C4	115.1 (3)
O3–C9–C8	125.5 (4)	O3–C10–C11	109.4 (3)
C12–C11–C10	116.8 (3)	O5–C11–C10	110.5 (3)
O5–C11–C12	111.2 (3)	O4–C12–C11	108.8 (3)
C18–C13–C14	120.0 (4)	O4–C13–C14	125.3 (3)
O4–C13–C18	114.7 (3)	C15–C14–C13	119.7 (4)
C16–C15–C14	120.4 (4)	C17–C16–C15	120.7 (5)
C18–C17–C16	120.3 (4)	C17–C18–C13	118.9 (4)
O1–C18–C13	115.2 (3)	O1–C18–C17	126.0 (4)
C18–O1–C1	118.2 (4)	C4–O2–C3	118.3 (3)
C10–O3–C9	117.6 (3)	C13–O4–C12	117.5 (3)

as received from commercial suppliers.

Synthesis of *sym*-Hydroxydibenzo-14-crown-4 (1). Under nitrogen, 1,3-bis(hydroxyphenoxy)propane (4.00 g, 16 mmol) and LiOH (0.71 g, 30 mmol) in water (380 mL) were heated at 90 °C to achieve solution, and then the solution was cooled to 55 °C. During 3 h, epichlorohydrin (1.2 mL, 15 mmol) was added, and heating and stirring were continued from 10 h at 55 °C. After a second addition of LiOH (0.71 g, 30 mmol) in one portion, epichlorohydrin (1.2 mL, 15 mmol) was introduced over 3 h, and heating and stirring were continued for another 10 h. After cooling, the solid material was separated by filtration and dissolved in CH_2Cl_2. The CH_2Cl_2 solution was dried with $MgSO_4$, reduced to a small volume in vacuo, and loaded onto a short column of silica gel. Elution with Et_2O separated the product from contaminating polymeric materials. Evaporation of the eluent in vacuo gave *sym*-hydroxydibenzo-14-crown-4 (3.4 g, 70%): mp 153–154 °C (lit. mp[43] 153–154 °C); IR (KBr) 3560–3200 cm^{-1} (OH); ^1H NMR ($CDCl_3$ + CD_3COCD_3) δ 2.26 (m, 2 H), 2.92 (br s, 1 H), 4.0–4.6 (m, 9 H), 6.95 (m, 8 H).

Crystal Data. Single crystals of *sym*-hydroxydibenzo-14-crown-4 were grown from a 1:1 (volume) solution of CH_2Cl_2 and methanol–water (90:10 by volume). Preliminary Weissenberg and precession photographs indicated that the crystal had tetragonal symmetry and belonged to space group $I\bar{4}$ (No. 82). Diffraction data were collected on an automated four-circle diffractometer (Enraf-Nonius CAD 4) with graphite monochromatized Mo K$\bar{\alpha}$ radiation (λ = 0.7114 Å). Crystal data and relevant details of experimental conditions are summarized in Table I. Intensity data were corrected for diffraction decay and for Lorentz and polarization effects. Due to the small absorption coefficient, no absorption correction was applied. After data reduction, only those reflections with $F_o > 3\sigma(F_o)$ were retained for subsequent calculations.

Structure Determination. The structure was solved, with some difficulty, by a combination of methods methods and Fourier techniques. The first attempt to solve the structure with the usual direct methods (MULTAN80[47a]) was unsuccessful in terms of obtaining any structural starting point. A similar approach based on an automatic choice of starting phase set using related direct methods (SHELXS-84[47b]) was also unsuccessful. A reasonable phasing for the data was achieved only when a limited number of the strongest negative quartets was specifically selected for the determination of the starting phases. One of these attempts resulted in an electron density map sufficiently clear to solve the structure. All non-hydrogen atoms, except the water oxygen atoms, were located in the *E* map resulting from the best set of starting phases (CFOM = 0.01). The positions of the two remaining water oxygen atoms as well as the atoms of the methanol molecule were determined from difference Fourier synthesis. Full-matrix least-squares techniques (SHELX-76[47c]) were used for the refinement of the structure, utilizing anisotropic temperature parameters for all non-hydrogen atoms. All hydrogen atoms were located directly from the difference electron density maps, and their positions were refined with a riding model (C–H, 1.08 Å; O–H, 0.98 Å) and individual isotropic temperature parameters. The refinement converged to *R* and R_w values of 0.038 and 0.042, respectively. In the final cycle of refinement, the largest ratio of shift/ESD was less than 0.01, and in the final difference electron density map, there were no peaks greater than 0.2 e/Å^3.

Results

The molecular numbering scheme for uncomplexed coronand **1** is presented in Figure 1. The final coordinates for all non-hydrogen atoms of the monohydrate complex of **1** (designated **1a**) are listed in Table II. A view of the final structure of the monohydrate complex is depicted in Figure 2. As may be seen, a water molecule forms an inclusion complex with **1**. The water

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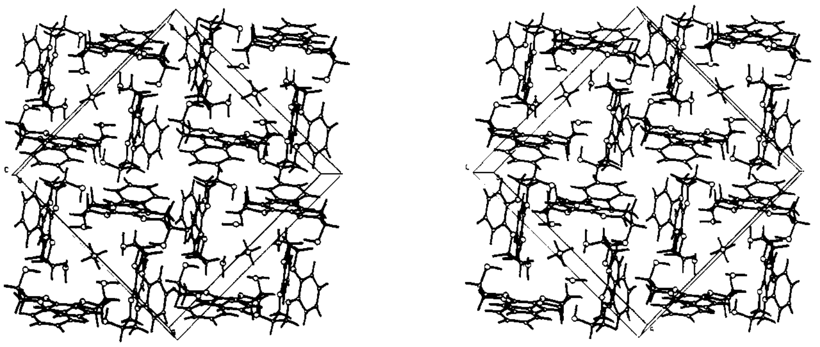

Figure 3. Contents of the unit cell viewed down the *c* axis. Hydrogen atoms of the central water molecule are disordered following $\bar{4}$ symmetry.

molecule O24 is hydrogen bonded by the pendant hydroxyl group. All bond distances (Table III) and angles (Table IV) of **1a** are within the expected ranges,[48] with the exceptions of relatively short aliphatic C–C distances (mean value 1.49 Å). Such short C–C distances have been reported previously in similar macrocyclic polyethers[48-50] and may be due to the interaction with the adjacent C–O etheral linkages.[49,50] The average C–C–O–C torsion angle is 174° [close to the usual antiperiplanar (trans) conformation which is 180°], and the average C–C–C–O torsion angle is 69° [close to the usual synclinal (gauche) conformation which is 60°] (Table SIII). These values are similar to those of larger crown ethers, both complexed and uncomplexed,[48-51] and indicate that no significant ring strain is encountered by the coronand upon complexation.

The aromatic rings of **1a** are planar within 0.01 Å. The ethereal oxygens of the macrocyclic ring of **1a** are nearly coplanar, with an average deviation from planarity of 0.01 Å. The oxygen of the guest water molecule (O24) is 2.41 Å above the center of this plane. One of its protons (H24′) is pointed directly toward the center of the macrocyclic cavity and is located 1.44 Å above it. In general, the two "halves" of the skeleton of **1a** are very nearly planar and form a V-shape at an angle of 138° with each other. The complex **2a**[52] of dibenzo-14-crown-4 (**2**) with Li$^+$ and the complex **3a**[29] of ionized *sym*-dibenzo-14-crown-4-oxyacetic acid (**3**) with Li$^+$ display a similar planarity of the macrocyclic ethereal oxygens and have angles between the two V-shaped halves of 121° and 118.6° for **2a** and **3a**, respectively. The average diagonal distance between the opposite oxygen atoms across the macrocyclic ring in **1a** is 3.76 Å (O1–O3 = 3.76 Å, O2–O4 = 3.76 Å). The corresponding distances for **2a** and **3a** are 3.77 and 3.76 Å, respectively.

The relatively short hydroxyl–water intermolecular distance (O5–O24 of 2.85 Å) indicates fairly strong hydrogen bonding.[23,53] The rather long O1,2,3,4–O24 intermolecular average distance of 3.06 Å suggests weak hydrogen bonds between the four ethereal oxygens and the water molecule.[23,33]

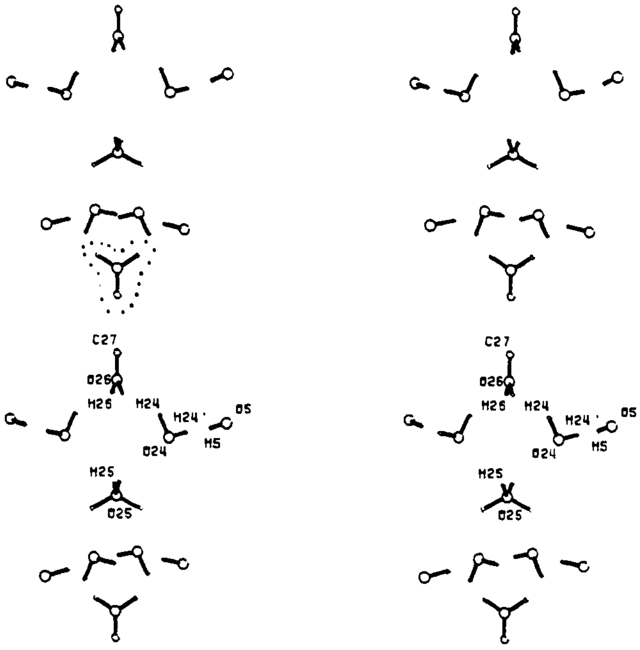

Figure 4. View of the contents of the channel. The methanol molecule occupies a special position, and its hydroxyl hydrogen is disordered over two sites related by 2-fold symmetry. Both possible positions are shown.

Table V. Hydrogen-Bond Parameters

A–H···B	A···B (Å)	A–H···B (deg)
O24–H24···O26	2.861 (7)	168 (3)
O5–H5′···O24	2.850 (4)	152 (2)
O25–H25···O24	3.101 (7)	100 (3)

In addition to the water–crown ether interaction described above, each guest molecule is further hydrogen bonded to additional "packing" water molecules (O25) such that the packing water molecule (which displays a $\bar{4}$ crystallographic symmetry) is hydrogen bonded by four neighboring guest water molecules in a perfect (symmetrically required) tetrahedral arrangement (Figure 3). The observed O24–O25 intermolecular distance of 3.10 Å indicates rather weak hydrogen bonds between these water molecules.[23] In addition to the surrounding guest water molecules, there are two sites for a methanol molecule (the oxygen of which is O26) on each side (above and below) of the central packing water molecule (O25) (Figure 4). The distance between the two symmetrically related packing water molecules (O25) is 7.5 Å. Since this distance does not allow for the simultaneous occupancy of two methanol sites, we assume a disordered arrangement where only one of the two symmetry-related sites between each two O25 atoms is occupied by a methanol molecule. The methanol molecule of each of these two disordered sites interacts with the guest water molecules of **1a**. The short distance between these two molecules with an O26–O24 distance of 2.86 Å indicates a relatively strong hydrogen bond (Table V). Unit cell translation of this cluster of guest water, packing water, and methanol (Figure 4) forms a solvent channel propagating along the $\bar{4}$ symmetry axis of the crystal. Furthermore, the water molecules, the ethereal groups, and the hydroxyl groups form extended hydrophilic regions, whereas the benzo units of **1** and the methyl groups of the methanol molecules form extended hydrophobic regions. The extended hydrophobic regions form closely packed elongated "cylinders", at the center of which the "channels" of the extended hydrophilic regions are sited. The hydrophilic channels are completely surrounded by the hydrophobic cylinders, so that there

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is no contact between adjacent channels. This kind of crystal structure of alternating hydrophilic/hydrophobic regions in general and of hydrophilic channels within hydrophobic media in particular has been observed before[29] and appears to be more common among structures which exhibit extensive intermolecular hydrogen bonds.

Discussion

The overall conformation of the dibenzo-14-crown-4 skeleton in complex **1a** is similar to the unmodified coronand in **2a** and the modified coronand in **3a**. However, there is a significant difference in the central V-shape dihedral angle, a parameter that determines how "open" the wings of the coronand will be and the accessibility of a cation and counteranion into and around the central cavity. The difference of about 20° in the V-angle between the Li^+ complexes **2a** and **3a** (121° and 118.6°, respectively) and the monohydrate complex **1a** (138°) can be attributed to the difference between the energies of ion–dipole interaction in **2a** and **3a** and the hydrogen-bonding interaction in **1a**. That is, the energy gain from the square-pyramidal structure formed by the four etheral oxygens and the complexed fifth group is significantly greater when this group is a cation rather than H_2O. This energy gain allows a sharper bend in V-structure at the cost of conformational strain energy of the macrocyclic skeleton itself.

The conformation of the coronand skeleton in **3a**[29] closely resembles that for the coronand in **2a**.[52] The Li^+ is coordinated by four oxygens of the crown ether in both structures and by the anion in **2a** and by a water molecule in **3a**, in an observed 1:1 stoichiometry. This five-coordinate structure adopts a nearly perfect square-pyramidal geometry. The most effective ion–dipole interactions in five-coordination geometry can be achieved in an arrangement of a perfect square-pyramid or a trigonal-bipyramid configuration of the dipoles around the Li^+.[54] The coronand molecules **2a** and **3a** achieve this favorable square pyramid by forming a V-shape angle of about 120°.

The average diagonal distances between the opposite oxygen atoms O1–O3, O2–O4 across the macrocylic rings in **2a**, **3a**, and **1a** are 3.77, 3.77, and 3.76 Å, respectively. Thus, the effective cavity size is practically identical in the three complexes, even though **2a** and **3a** contain Li^+ and **1a** contains a water molecule. This observation indicates that the differences in the V-shape angle in **2a**, **3a**, and **1a** do not involve a variation in the effective cavity size of the macrocyclic ring; yet, they do affect binding by changing the orientation of the ethereal oxygen dipole moments.

Novel aspects of the present structure are (i) the hydrogen-bonding interaction of the central water molecule with ethereal oxygens and (ii) the unique crystal structure of **1a** with water and methanol-filled channels.

The relative rigidity of the macrocyclic ring portion of complex **1a** and the rather short pendant hydroxyl arm do not allow for a perfect covering of the apical area in the monohydrate complex and therefore leave a large part of it exposed. The inclusion of this water molecule (O24) is therefore accompanied by another linkage to an additional water molecule (O25) and a methanol oxygen (O26).

The arrangement of the crown ether and water molecules within the crystallographic unit cell (Figure 3) is also of interest. The coronands are assembled in a hydrophobic sphere, interacting with each other through the aromatic rings and aliphatic portions of the crown ethers and methyl groups of the methanol molecules, while the ethereal oxygens, the hydroxy groups, and the water molecules form a hydrogen-bonded network which fills the interior. This observation correlates with results which show that the formation of host–guest complexes depends on the number and position of the benzo groups present in the macrocyclic rings of the host molecules.[55,56] The two benzo units of **1** and the methyl group of the methanol molecules form a hydrophobic sphere which encapsulates the hydrophilic region containing the hydroxyl groups, ethereal units, and water molecules.

The methanol molecule has a double function in the formation of this special three-dimensional network. It provides a hydroxyl group which participates in the hydrogen-bonding network, and its methyl group participates in intermolecular hydrophobic interactions in the hydrophobic region, which is necessary for the formation of the elongated crystal packing.

Molecules that contain hydrophilic and hydrophobic regions are known as surfacants, amphiphiles, or detergents.[57-59] They are the building blocks for a variety of micellar structures that provide media for many biological[59,60] and industrial[61] chemical reactions. In the crystal structure of **1a**, the central water molecule (O25) is hydrogen bonded to four monohydrate units in a micellelike assembly. The present structure may be beneficial in the design and synthesis of micellar and channel structures.

Closer examination of the extensive water network (Figure 4) shows a unique ordered water channel structure which also includes methanol molecules. The hydrogen-bonding interaction in the hydrophilic region may be one of the primary forces which holds the crystallographic assembly together and could be a significant factor in the thermodynamic stability of the complex in the solid state. Quantum chemical calculations show that chain-like hydrogen bonding in a crystal structure is energetically favored over individual interactions.[62] This is due to a cooperative effect which leads to increased hydrogen-bonding activity of a hydroxyl group if it is already accepting or donating a hydrogen bond.[63,64] In the present structure, the conjugated hydrogen-bonding network in the crystal structure of **1a** is consistent with this criteria, which explains, at least partially, the existence of the complex hydrogen-bonding interactions, the energetical preference of the solvent network, and the overall stability of the resulting structure in the crystal (see Table V).

With regard to the relationship between the monohydrate crystal structure and the structure of the complex in solution and in polymeric membranes, it seems reasonable that the crystal structure should resemble, at least to some extent, the arrangement of the solvated free crown ether in hydrophobic solvents as well as in natural and synthetic membranes. The first step in the water–methanol channel formation is likely to be the interaction between **1** and a water molecule to form a monohydrate complex similar to **1a** (Figure 2).[13] The monohydrate complexes could then interact with additional water and methanol molecules to form the channel structure. The monohydrate complex may represent a mechanistic model for proton transport through a membrane by the formation of hydronium ion–cyclic polyether complexes.

The solvation of acids by water molecules has been extensively studied through various experiments in solution and also by a number of detailed crystallographic analyses.[53] It was found that only two oxygens are directly involved in the solvation of a proton, although additional water molecules may be hydrogen bonded to the hydrated acid. The distances between the two oxygens interacting with a proton were found to be 2.4–2.5 Å. The bonding arrangement about the two oxygens is pyramidal with angles close to those in a perfect tetrahedral geometry, and the proton has been found to be collinear with the two oxygens. The crystal structures of hydronium ion–macrocyclic polyether complexes[11-13] reveal that the hydronium ion is anchored in the center of the macrocyclic

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ring cavity by three OH$^+$···O hydrogen bonds. The pyramidal geometry found for the hydronium ion in these complexes indicates that this conformation is probably the most stable in an ion-solvating environment.[11] The molecular structure of monohydrate complex **1a** offers a possible ligand for proton solvation.

The results of preliminary solvent polymeric membrane transport studies conducted with **1** indicate that crown ether alcohol **1** is selective for protons.[44] Among the alkali metal and alkaline earth cations, there is a slight preference for K$^+$. The observed selectivity sequence of the liquid anion-exchanger membrane electrodes based on ionophore **1** follows the Hofmeister lyotopic series.[65] Formation of monohydrate complex **1a** provides an explanation of the solvent polymeric membrane selectivity measurements for crown ether alcohol **1**, since the monohydrate complex should strongly bind protons. Furthermore, the encapsulated water molecule would hinder coordination of metal cations. Such spatial hindrance explains the relatively poor binding and poor selectivity among alkali and alkaline earth cations. The poor selectivity toward anions can also be attributed to the formation of monohydrate complex **1a**, which prevents possible specific interaction between the crown ether alcohol and anions.

Synthetic attempts are now underway to prepare coronands with longer pendant hydroxyl-containing arms and crown ether diols. Potential applications for a polymerized network of units of **1** are the drying of organic solvents by water complexation, the selective transport of water in reverse osmosis membrane devices, and the formation of hydrophilic pores in biological bilayers.

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Registry No. 1, 78328-81-1; **1a**, 123567-47-5; 1,3-bis(2-hydroxyphenoxy)propane, 42397-72-8; epichlorohydrin, 106-89-8.

Supplementary Material Available: Table SI listing anisotropic temperature factors, Table SII listing hydrogen atom coordinates, and Table SIII listing torsion angles (3 pages); Table SIV listing observed and calculated structure factors (9 pages). Ordering information is given on any current masthead page.

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X-ray Crystallographic Support of a Chiral Recognition Model

William H. Pirkle,* John A. Burke, III, and Scott R. Wilson[†]

Contribution from the School of Chemical Sciences, Roger Adams Laboratory, University of Illinois at Urbana—Champaign, Urbana, Illinois 61801.

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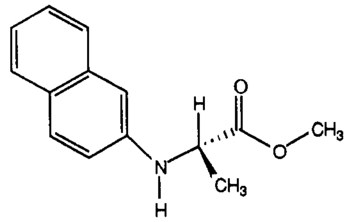
Abstract: Both *N*-(3,5-dinitrobenzoyl)leucine n-propylamide, **1**, and methyl (2-naphthyl)alaninate, **2**, are close models of the chiral selectors incorporated into commercial chiral stationary-phase HPLC columns. Each selector is capable of "recognizing" the stereochemistry of the other. A structure for the homochiral solution complex formed from (*S*)-**1** and (*S*)-**2** has been postulated from experimental data. Structures for both the homochiral and heterochiral complexes have been suggested on the basis of a computational approach. The structure of a crystalline 1:1 complex of (*S*)-**1** and (*S*)-**2** has been determined by X-ray crystallography and found to be in basic agreement with that originally postulated for the analogous complex in solution and with that from the computational study.

The development of chiral stationary phases (CSPs) for the chromatographic separation of enantiomers has altered modern-day approaches to stereochemical analysis and enantiomer separation.[1] In some instances, the development of these phases has been aided by hypotheses concerning the mechanisms of chiral recognition.[2] This is particularly true for those chiral phases derived from *N*-(3,5-dinitrobenzoyl)-α-amino acids and from *N*-aryl-α-amino acids.[3] High-performance liquid chromatography columns with CSPs derived either from *N*-(3,5-dinitrobenzoyl)-leucine or from *N*-(2-naphthyl)alanine show the ability to separate the enantiomers of a wide variety of compounds. Owing to their commercial availability,[4] such columns are finding ready acceptance by the chemical community. Consequently, rationales purporting to account for the ability of these chiral phases to differentiate between the enantiomers of client substances are of interest to the users of such columns.



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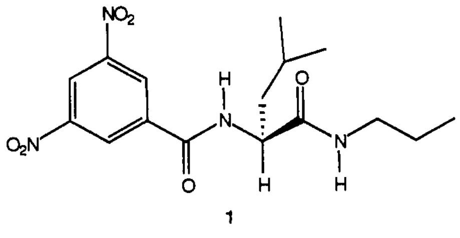

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Chiral recognition models pertaining to the mode of operation of these CSPs have been advanced and are founded upon a body of experimental data.[3] Several such models have attracted the attention of workers who have attempted to define the origin of chiral recognition in these systems by computational methods.[5] Of present relevance is the recent report[5b] by Topiol et al. of a study of the interaction of *N*-(3,5-dinitrobenzoyl)leucine *n*-propyl amide, **1**, with methyl *N*-(2-naphthyl)alaninate, **2**. To quantitate the energy difference between two computer-generated structures, one must know the energy of each. The computed structure for

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[†] Correspondence concerning the X-ray structure should be directed to this author.

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