

The Crystal Structure and Molecular Conformation of 2,6-Dimethylbenzoic Acid-18-crown-5 at -160°C

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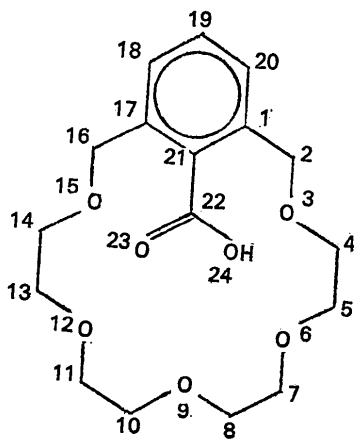
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2,6-Dimethylbenzoic acid-18-crown-5, $\text{C}_{17}\text{H}_{24}\text{O}_7$ (3,6,9,12,15-pentaoxa-21-carboxybicyclo[15,3,1]-heneicosa-1(21),17,19-triene), is monoclinic, space group $P2_1/c$, with $Z=4$ and $a=9.809(3)$, $b=12.848(4)$, $c=13.888(3)$ Å, $\beta=103.31(2)^{\circ}$ at -160°C . The structure was solved by weighted multi-solution tangent-formula phase refinement from diffractometer data collected with Mo radiation. Full-matrix least-squares refinement resulted in a final R of 0.055 for 2555 reflections. The molecular conformation appears to be determined by intramolecular $\text{O}-\text{H}\cdots\text{O}$ hydrogen bonding and $\text{O}\cdots\text{C}=\text{O}$ non-bonded interactions. Mean C-C and C-O bond lengths in the aliphatic region of the macro-ring are 1.505 and 1.423 Å respectively. The conformations of several related 18-membered macrocycles in different crystal structures are compared.

Introduction

The crystal structure of 2,6-dimethylbenzoic acid-18-crown-5‡ (systematic name: 3,6,9,12,15-pentaoxa-21-carboxybicyclo[15,3,1]heneicosa-1(21),17,19-triene) shown below was determined as part of a continuing study of inter- and intramolecular interactions in various derivatives of polyether macrocycles.



Data on the synthesis and binding properties toward cations of this compound are given by Newcomb & Cram (1975); host-guest structural relationships in its crystalline complex with *t*-butylamine are described in a previous paper (Goldberg, 1975*b*). The present investigation is motivated by the desire to find an accu-

rate geometry of the molecule and to rationalize the observed molecular conformation in terms of the stabilizing intramolecular interactions.

Experimental and structure determination

Single crystals of the title compound were supplied by Dr M. Newcomb. Preliminary precession and cone-axis photographs showed reciprocal-lattice symmetry $2/m$ and systematic extinctions ($0k0$ with k odd and $h0l$ with l odd) characteristic of space group $P2_1/c$. X-ray measurements were carried out on a Syntex $P\bar{1}$ automated diffractometer with graphite monochromatized Mo radiation ($K\alpha$ $\lambda=0.71069$ Å). The temperature was maintained at $-160 \pm 5^{\circ}\text{C}$ with the cooling apparatus designed by Professor C. E. Strouse (1975). The unit-cell constants (Table 1) were determined by a least-squares analysis of the 2θ values of fifteen chosen reflections.

Table 1. *Crystal data*

$\text{C}_{17}\text{H}_{24}\text{O}_7$, M.W. 340.4, m.p. $100-101^{\circ}\text{C}$
Monoclinic
$a=9.809(3)$, $b=12.848(4)$, $c=13.888(3)$ Å
$\beta=103.31(2)^{\circ}$, $V=1703.3$ Å ³
$F(000)=728$
$D_c(-160^{\circ}\text{C})=1.327$ g cm ⁻³ for $Z=4$
Space group $P2_1/c$
$\mu(\text{Mo } K\alpha)=1.1$ cm ⁻¹
Crystal dimensions: $0.35 \times 0.30 \times 0.20$ mm

The intensities of reflections within $0 < 2\theta \leq 60^{\circ}$ ($\sin\theta/\lambda \leq 0.704$ Å⁻¹) were collected by the $\theta-2\theta$ scan technique, with scans ranging from 1.1° below $K\alpha_1$ to 1.1° above $K\alpha_2$. All data were recorded at a constant 2° min⁻¹ scan rate. Reduction of the data to structure amplitudes was done in the usual manner; no corrections were made for absorption. Estimated standard deviations in the intensities were based on counting

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‡ The cyclic polyether compounds referred to in this paper are named by an extension of the scheme proposed by Pedersen (1967).

statistics allowing corrections for instrumental instability. From among the measured diffraction data, 2555 unique reflections with $F_o^2 \geq 3\sigma(F_o^2)$ (61 %) were selected for subsequent study.

The structure was solved by direct methods with the *MULTAN* program (Germain, Main & Woolfson, 1971). After initial least-squares refinement of the trial heavy-atom model, the 24 hydrogen atoms were clearly located in a difference electron-density synthesis at $0.55\text{--}0.75 \text{ e } \text{\AA}^{-3}$. In subsequent full-matrix least-squares analysis with the $1/\sigma^2(F)$ weighting scheme, all positional parameters, anisotropic thermal parameters of the heavy atoms, isotropic thermal parameters of the hydrogen atoms and an overall scale factor were adjusted. This refinement converged to a conventional $R=0.046$, and with $w=1/\sigma^2(F_o)$ to a corresponding weighted index $r=[\sum w(\Delta F)^2/\sum wF_o^2]^{1/2}=0.045$. The goodness-of-fit, $[\sum w(\Delta F)^2/(n-m)]^{1/2}$, is 1.2 for $m=217$ parameters and $n=2555$ observations above threshold.* The analysis of $w(\Delta F)^2$ in ranges of F_o and of $\sin \theta$ was satisfactory, and a difference map calculated at this stage revealed no peaks whose absolute heights exceeded $0.3 \text{ e } \text{\AA}^{-3}$.

In order to improve the positional parameters of the atomic nuclei of carbon and oxygen, a weighting scheme modified by an exponential function of $\sin^2 \theta/\lambda^2$ was introduced into two final cycles of the refinement (based on F^2), following the procedure proposed in

* The structure factor tables have been deposited with the British Library Lending Division as Supplementary Publication No. SUP 31168 (10 pp.). Copies may be obtained through The Executive Secretary, International Union of Crystallography, 13 White Friars, Chester CH1 1NZ, England.

Dunitz & Seiler (1973). Hydrogen-atom parameters were not optimized in this process. The consequent discrepancy values were $R=0.055$, $r=0.049$ with $w(F_o) = \exp(14 \sin^2 \theta/\lambda^2)/\sigma^2(F_o)$ and $r' = \sum w'(F_o^2 - F_c^2)^2 / \sum w'F_o^4 = 0.0095$ with $w'(F_o^2) = w(F_o)/4F_o^2$. The standard deviations of the refined parameters were, however, very similar to those obtained from the calculations with unmodified $1/\sigma^2(F_o)$ weights.

The atomic scattering factors of Hanson, Herman, Lea & Skillman (1964) were used for the non-hydrogen atoms; those of Stewart, Davidson & Simpson (1965) were used for the hydrogen atoms. The final positional and thermal parameters, along with their standard deviations estimated from the inverse of the least-squares matrix, are presented in Tables 2 and 3. Bond distances resulting from calculations based on the different weighting systems are compared in Table 4.

All computations were performed on the IBM 360/91 computer at the UCLA Campus Computing Network with programs referred to elsewhere (e.g. Goldberg, 1975a, b).

Results and discussion

Bond distances and bond angles are shown in Tables 4 and 5. The molecular parameters compare well with the results of recently reported studies on related macrocyclic polyether compounds (e.g. Truter, 1973; Dunitz, Dobler, Seiler & Phizackerley, 1974; Goldberg, 1975a, b). Within the 18-membered ring, the C-C and the O-C bond lengths calculated from the results of the refinement with modified weights range from 1.493 to 1.512 Å and from 1.416 to 1.434 Å respectively.

Table 2. Fractional coordinates and thermal parameters U^{ij} (\AA^2) for the heavy atoms

The e.s.d.'s are given in parentheses in units of the last decimal place. The anisotropic temperature factor is in the form $\exp[-2\pi^2(h_i a^i)(h_j a^j) \cdot U^{ij} \times 10^{-4}]$, where h_i and a^i are reflection indices and reciprocal unit-cell edges respectively.

	<i>x</i>	<i>y</i>	<i>z</i>	U^{11}	U^{22}	U^{33}	U^{12}	U^{23}	U^{13}
C(1)	0.4112 (2)	0.4582 (2)	0.2220 (2)	125 (8)	97 (8)	129 (8)	8 (6)	6 (7)	25 (7)
C(2)	0.5649 (3)	0.4473 (2)	0.2701 (2)	143 (9)	114 (9)	218 (9)	29 (7)	-13 (8)	5 (7)
O(3)	0.6280 (2)	0.5466 (2)	0.2655 (1)	128 (7)	161 (7)	193 (7)	-1 (5)	22 (6)	24 (6)
C(4)	0.7740 (3)	0.5477 (2)	0.3082 (2)	125 (9)	225 (10)	308 (12)	12 (8)	-6 (9)	44 (8)
C(5)	0.8125 (3)	0.5402 (2)	0.4194 (2)	168 (10)	196 (11)	311 (13)	-4 (8)	33 (9)	-65 (9)
O(6)	0.7744 (2)	0.6339 (2)	0.4614 (1)	228 (8)	202 (8)	177 (8)	-30 (6)	50 (6)	13 (6)
C(7)	0.7792 (3)	0.6225 (3)	0.5641 (2)	167 (10)	358 (15)	190 (11)	-48 (10)	138 (10)	-39 (8)
C(8)	0.7121 (3)	0.7150 (3)	0.5990 (2)	211 (11)	372 (15)	122 (9)	-140 (11)	21 (10)	2 (8)
O(9)	0.5685 (2)	0.7201 (2)	0.5485 (2)	198 (8)	320 (11)	175 (8)	-88 (7)	-94 (7)	21 (6)
C(10)	0.4950 (3)	0.8023 (3)	0.5847 (2)	274 (14)	298 (14)	216 (11)	-143 (10)	-152 (10)	83 (10)
C(11)	0.3528 (3)	0.8167 (2)	0.5172 (2)	279 (13)	220 (13)	215 (11)	-35 (9)	-80 (8)	118 (10)
O(12)	0.2677 (2)	0.7286 (2)	0.5241 (2)	214 (9)	207 (8)	214 (8)	-44 (7)	-35 (7)	43 (7)
C(13)	0.1249 (3)	0.7437 (2)	0.4770 (2)	215 (11)	263 (13)	213 (11)	49 (9)	-52 (9)	74 (8)
C(14)	0.0939 (3)	0.7428 (2)	0.3652 (2)	225 (11)	189 (10)	200 (11)	75 (8)	-30 (8)	57 (8)
O(15)	0.1189 (2)	0.6417 (2)	0.3319 (1)	202 (8)	160 (7)	165 (7)	21 (6)	-15 (6)	73 (6)
C(16)	0.1053 (2)	0.6394 (2)	0.2278 (2)	153 (9)	180 (9)	143 (9)	18 (7)	-5 (7)	32 (7)
C(17)	0.1893 (2)	0.5494 (2)	0.2023 (2)	134 (8)	149 (9)	94 (8)	-16 (7)	-11 (7)	31 (6)
C(18)	0.1263 (2)	0.4773 (2)	0.1309 (2)	123 (8)	168 (10)	155 (8)	-25 (7)	-14 (7)	14 (7)
C(19)	0.2054 (3)	0.3966 (2)	0.1045 (2)	200 (10)	177 (10)	170 (9)	-63 (8)	-46 (8)	52 (8)
C(20)	0.3474 (3)	0.3879 (2)	0.1493 (2)	192 (10)	129 (9)	163 (9)	-29 (8)	-27 (7)	49 (8)
C(21)	0.3311 (2)	0.5392 (2)	0.2486 (1)	128 (8)	82 (8)	100 (7)	-17 (6)	-5 (6)	25 (6)
C(22)	0.3970 (2)	0.6182 (2)	0.3254 (2)	114 (8)	132 (9)	118 (8)	-18 (7)	-23 (7)	32 (6)
O(23)	0.3964 (2)	0.7108 (1)	0.3076 (1)	202 (8)	108 (7)	165 (7)	-18 (5)	0 (6)	60 (6)
O(24)	0.4517 (2)	0.5757 (1)	0.4123 (1)	204 (8)	152 (7)	96 (7)	-35 (6)	8 (5)	-10 (5)

Bond distances in the benzene moiety average 1.395 Å; however, the bonds C(21)–C(1) and C(21)–C(17) are longer, probably due to the substitution of an electron-withdrawing –COOH group on C(21). The corresponding dimensions of the aromatic and aliphatic C–C bonds and the length of the carbonyl bond resulting

from the least-squares refinement with $1/\sigma^2(F_o)$ weights (Table 4) are less acceptable. The O–H bond length for H coordinates derived from the least-squares calculations is much shorter (0.88 Å) than that for H

Table 3. Atomic parameters for the hydrogen atoms

The numbering of each hydrogen atom corresponds to that of the carbon or oxygen atom to which the hydrogen is bonded. $\langle\sigma(p)\rangle = 0.025$ Å, $p = x, y, z$; $\langle\sigma(U)\rangle = 0.007$ Å².

	<i>x</i>	<i>y</i>	<i>z</i>	<i>U</i> (Å ²)
H(2a)	0.582	0.423	0.341	0.023
H(2b)	0.608	0.392	0.235	0.020
H(4a)	0.810	0.612	0.287	0.019
H(4b)	0.823	0.487	0.282	0.023
H(5a)	0.918	0.529	0.440	0.023
H(5b)	0.769	0.481	0.445	0.023
H(7a)	0.877	0.619	0.600	0.021
H(7b)	0.727	0.559	0.571	0.028
H(8a)	0.756	0.781	0.586	0.018
H(8b)	0.722	0.710	0.674	0.023
H(10a)	0.548	0.865	0.585	0.033
H(10b)	0.486	0.784	0.655	0.027
H(11a)	0.363	0.828	0.448	0.022
H(11b)	0.310	0.878	0.539	0.026
H(13a)	0.092	0.811	0.497	0.024
H(13b)	0.070	0.685	0.500	0.028
H(14a)	0.155	0.794	0.341	0.022
H(14b)	–0.001	0.763	0.342	0.027
H(16a)	0.139	0.705	0.206	0.020
H(16b)	0.005	0.631	0.193	0.021
H(18)	0.030	0.485	0.102	0.017
H(19)	0.162	0.347	0.056	0.020
H(20)	0.401	0.329	0.132	0.022
H(24)	0.486	0.626	0.453	0.026

Table 4. Bond distances (Å)

Columns (a) and (b) refer to refinements based on modified and unmodified experimental weights respectively (see text). Bond distances in columns (a) and (c) were derived from coordinates listed in Tables 2 and 3.

	(a)	(b)	(c)
C(1)–C(2)	1.508 (3)	1.506 (3)	C(2)–H(2a) 1.01 (2)
C(2)–O(3)	1.426 (3)	1.429 (3)	C(2)–H(2b) 1.01 (3)
O(3)–C(4)	1.418 (3)	1.421 (3)	C(4)–H(4a) 0.97 (3)
C(4)–C(5)	1.506 (5)	1.504 (4)	C(4)–H(4b) 1.03 (3)
C(5)–O(6)	1.425 (4)	1.426 (3)	C(5)–H(5a) 1.02 (3)
O(6)–C(7)	1.424 (4)	1.423 (3)	C(5)–H(5b) 0.98 (3)
C(7)–C(8)	1.493 (5)	1.487 (4)	C(7)–H(7a) 0.97 (2)
C(8)–O(9)	1.424 (3)	1.422 (3)	C(7)–H(7b) 0.98 (3)
O(9)–C(10)	1.434 (4)	1.430 (3)	C(8)–H(8a) 0.98 (2)
C(10)–C(11)	1.503 (4)	1.493 (3)	C(8)–H(8b) 1.03 (3)
C(11)–O(12)	1.424 (4)	1.423 (3)	C(10)–H(10a) 0.96 (3)
O(12)–C(13)	1.416 (3)	1.419 (3)	C(10)–H(10b) 1.03 (3)
C(13)–C(14)	1.512 (4)	1.506 (3)	C(11)–H(11a) 0.99 (3)
C(14)–O(15)	1.419 (4)	1.421 (3)	C(11)–H(11b) 0.97 (3)
O(15)–C(16)	1.422 (3)	1.426 (3)	C(13)–H(13a) 0.99 (3)
C(16)–C(17)	1.509 (4)	1.504 (3)	C(13)–H(13b) 1.02 (3)
C(17)–C(18)	1.392 (3)	1.389 (3)	C(14)–H(14a) 1.00 (3)
C(17)–C(21)	1.398 (3)	1.403 (3)	C(14)–H(14b) 0.95 (3)
C(18)–C(19)	1.394 (4)	1.386 (3)	C(16)–H(16a) 0.98 (3)
C(19)–C(20)	1.393 (4)	1.384 (3)	C(16)–H(16b) 1.00 (2)
C(20)–C(1)	1.392 (4)	1.394 (3)	C(18)–H(18) 0.94 (2)
C(21)–C(1)	1.403 (3)	1.400 (3)	C(19)–H(19) 0.95 (2)
C(21)–C(22)	1.506 (3)	1.507 (3)	C(20)–H(20) 0.99 (3)
C(22)–O(23)	1.216 (3)	1.208 (3)	O(24)–H(24) 0.88 (2)
C(22)–O(24)	1.321 (3)	1.324 (2)	

Table 5. Bond angles (°)

C(1)–C(2)–O(3)	107.3 (2)	C(16)–C(17)–C(21)	120.2 (2)
C(2)–O(3)–C(4)	113.5 (2)	C(21)–C(17)–C(18)	119.8 (2)
O(3)–C(4)–C(5)	114.7 (3)	C(17)–C(18)–C(19)	120.0 (2)
C(4)–C(5)–O(6)	109.8 (2)	C(18)–C(19)–C(20)	120.1 (2)
C(5)–O(6)–C(7)	111.8 (2)	C(19)–C(20)–C(1)	120.6 (2)
O(6)–C(7)–C(8)	109.1 (2)	C(20)–C(1)–C(2)	119.9 (2)
C(7)–C(8)–O(9)	109.6 (2)	C(20)–C(1)–C(21)	119.1 (2)
C(8)–O(9)–C(10)	112.3 (2)	C(21)–C(1)–C(2)	121.0 (2)
O(9)–C(10)–C(11)	109.9 (2)	C(1)–C(21)–C(17)	120.4 (2)
C(10)–C(11)–O(12)	109.6 (2)	C(1)–C(21)–C(22)	120.7 (2)
C(11)–O(12)–C(13)	113.1 (2)	C(17)–C(21)–C(22)	118.9 (2)
O(12)–C(13)–C(14)	114.6 (3)	C(21)–C(22)–O(23)	122.3 (2)
C(13)–C(14)–O(15)	109.4 (2)	C(21)–C(22)–O(24)	112.8 (2)
C(14)–O(15)–C(16)	111.6 (2)	O(23)–C(22)–O(24)	124.9 (2)
O(15)–C(16)–C(17)	109.0 (2)	C(22)–O(24)–H(24)	108 (1)
C(16)–C(17)–C(18)	120.0 (2)	[H–C–H] _{average}	109 ± 2

Table 6. Analysis of thermal motion

(a) Rigid-body motion

The eigenvectors of **L** and **T** and of the molecular tensor of inertia **I** are referred to the orthogonal axes **a**, **b*** and **a** × **b*** in terms of the corresponding direction cosines. Components of the origin shifts $q(q_1, q_2, q_3)$ referred to the molecular centroid are given in Å.

	Eigenvalues	Eigenvectors		
I	1577 (at. wt. Å ²)	0.3818	0.4668	0.7977
	1892	0.8865	–0.4291	–0.1732
	3278	0.2614	0.7733	–0.5776
L	4.51 deg. ²	–0.8723	–0.4872	0.0421
	2.40	–0.0599	0.1919	0.9796
	0.27	–0.4853	0.8520	–0.1965
T	168×10^{-4} Å ²	0.8893	–0.1438	–0.4342
	125	0.3890	0.7371	0.5526
	109	0.2406	–0.6603	0.7114

$$q(-0.65, -0.53, -1.33)$$

$$\langle(\Delta U)^2\rangle^{1/2} = 0.0028 \text{ Å}^2$$

(b) Vibration parameters of atoms in the aliphatic ring

The eigenvalues of the tensors of atomic thermal motion are *l*, *m* and *n*, while *p* represents the vibration component of atom *i* perpendicular to a plane defined by this atom and its two bonded neighbours.

<i>i</i>	<i>l</i>	<i>m</i>	<i>n</i>	<i>p</i>
C(2)	0.025 Å ²	0.015 Å ²	0.010 Å ²	0.022 Å ²
O(3)	0.025	0.015	0.013	0.021
C(4)	0.031	0.023	0.012	0.022
C(5)	0.042	0.019	0.012	0.021
O(6)	0.029	0.019	0.014	0.021
C(7)	0.048	0.017	0.010	0.017
C(8)	0.047	0.014	0.011	0.015
O(9)	0.038	0.022	0.010	0.028
C(10)	0.047	0.022	0.009	0.027
C(11)	0.034	0.022	0.012	0.013
O(12)	0.026	0.022	0.016	0.020
C(13)	0.031	0.023	0.013	0.027
C(14)	0.029	0.021	0.011	0.026
O(15)	0.022	0.018	0.012	0.020
C(16)	0.019	0.015	0.014	0.018

parameters obtained from the peak maximum in a difference synthesis (1.01 \AA). Further discussion is based on the modified weighting scheme data.

The structure was subjected to a rigid-body analysis in terms of translation, libration and screw motion tensors (Schomaker & Trueblood, 1968). Some of the results are shown in Table 6. The discrepancy between the observed and the calculated parameters is $\langle(\Delta U^{ij})^2\rangle^{1/2} = 0.0028 \text{ \AA}^2$, about 3.5 times higher than the average value of $\sigma(U_{ij}^0)$, indicating that the assumption of rigid-body motion is marginally valid. The indicated corrections in bond lengths did not exceed 0.002 \AA ; no corrections were applied.

A qualitative examination of the tensors of atomic thermal motion suggests that torsional vibrations in the crown-ether ring have only a relatively small effect on the molecular dimensions. For any ring atom (i) the vibration tensor component along the normal (\mathbf{q}_i) to a plane defined by this atom and its two bonded neighbours is smaller than 0.028 \AA^2 of which a significant part is due to translational vibrations; the average squared amplitude of translational motion of the molecule is 0.013 \AA^2 (Table 6). It is interesting, however, to correlate the discrepancies between the lengths of the aliphatic C–C bonds with the thermal vibrations of the corresponding carbon atoms. Thus, Table 6 and Fig. 1 show that C(5), C(7), C(8), C(10) and to a lesser extent C(4), O(9), C(11) exhibit a strongly anisotropic in-plane motion perpendicular to the normals \mathbf{q}_i , most probably reflecting other kinds of internal vibrations. Correspondingly, the C(7)–C(8), C(10)–C(11) and C(4)–C(5) interatomic bonds appear to be shorter than the C(13)–C(14) bond by 0.019 , 0.010 and 0.006 \AA respectively; the relative shortening may be due to a displacement of the peak centroids from the 'real' atomic positions as a result of such vibrations.

The overall conformation of the molecule is different from that found in the crystal structure of the complex with *t*-butylamine (Goldberg, 1975*b*). The molecular skeleton shows approximate C_2 symmetry, with the carboxyl group pointing toward the center of the ether ring. The interplanar angles defined by the normals to the mean plane of the 18-membered ring (\mathbf{r}), and to the planes of the carboxyl (\mathbf{s}) and the benzyl (\mathbf{t}) groups are: 72° between \mathbf{r} and \mathbf{s} , 18° between \mathbf{r} and \mathbf{t} , and 59° between \mathbf{s} and \mathbf{t} .

The torsion angles in the macro-ring (Fig. 1) indicate that the conformation about the peripheral C–C bonds is close to synclinal and about most of the C–O bonds is nearly antiplanar. However, the small torsion angles about the O(3)–C(4) (71.8°) and O(12)–C(13) (72.9°) bonds introduce short 1–4 contacts between the $>\text{CH}_2(2)$ and $>\text{CH}_2(5)$, and the $>\text{CH}_2(11)$ and $>\text{CH}_2(14)$ methylene units. This is reflected in a significant widening of bond angles at C(4) and C(13) by about 5° , and at O(3) and O(12) by about 1° , as compared with the typical geometry in less strained regions of the polyether molecule (Table 5; Goldberg, 1975*a*). The presence of the trigonal atoms C(1), C(17) and C(21)

in the 18-membered ring causes a decrease in the absolute values of torsion angles about the bonds C(1)–C(2) and C(16)–C(17) by 13 – 17° with respect to the observed average of 67° for the aliphatic C–C bonds. The distances between atoms on the border of the macro-ring cavity include: O(9) \cdots C(21), 4.87 ; O(6) \cdots O(12), 5.37 ; O(3) \cdots O(15), 5.42 ; O(3) \cdots O(12), 6.05 ; O(6) \cdots O(15), 6.27 \AA .

Two principal factors seem to stabilize the above-described conformation of the flexible pentaether molecule. As shown in Fig. 1, the centered carboxylic substituent takes part in intramolecular hydrogen bonding with the transannular ether-oxygen O(9). The geometry of this hydrogen bond, which may enhance the polarization of the two C(22)–O bonds, is described by the following distances: O(24)–H(24), 0.88 ; O(24) \cdots O(9), 2.71 ; H(24) \cdots O(9), 1.84 \AA ; and angles: O(24)–

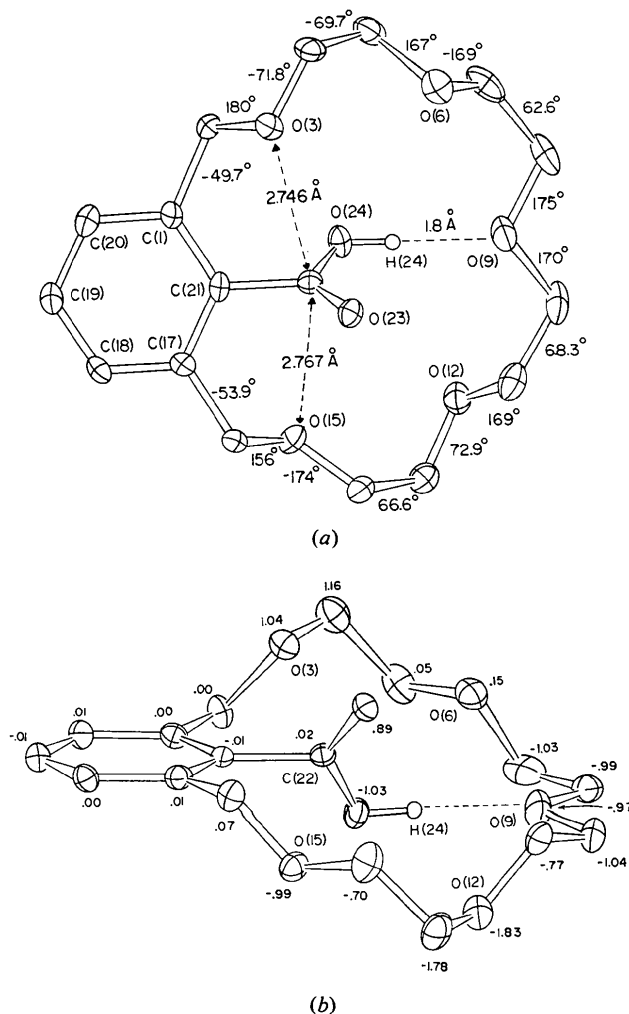


Fig. 1. Two views of the molecular unit showing 55% probability thermal ellipsoids. (a) Dihedral angles about the peripheral bonds; the structure is projected on the plane of the benzene moiety. (b) Deviations (\AA) of all atoms from this plane.

H(24)···O(9), 174°; C(22)–O(24)···O(9), 112°. In addition, the C···O nonbonded distances involving the two nucleophilic atoms O(3) and O(15) and the electrophilic atom C(22) are significantly shorter than usual van der Waals contacts [O(3)···C(22), 2.75 Å; O(15)···C(22), 2.77 Å], suggesting the presence of attractive dipole–dipole O···C=O interactions (Bürgi, Dunitz & Shefter, 1974). Further geometrical details

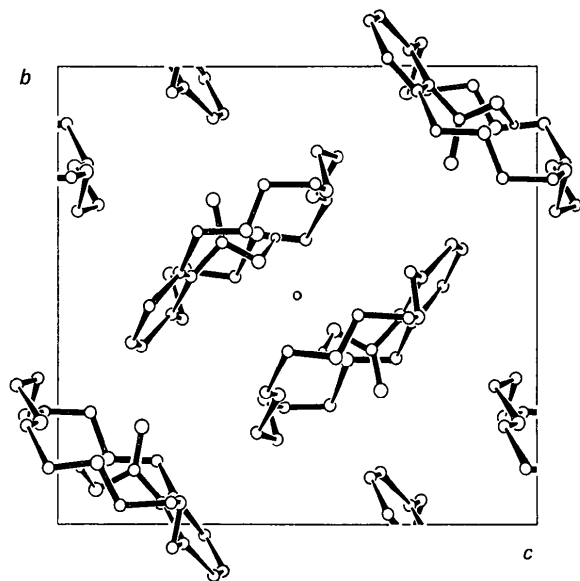
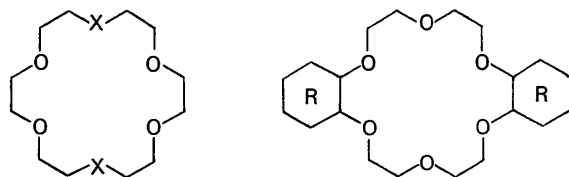
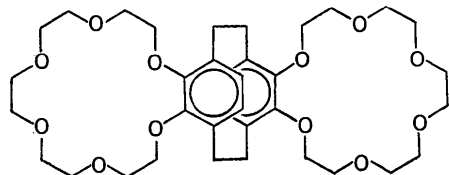


Fig. 2. View of the crystal structure down the *a* axis. Direction cosines of the molecular principal axes of inertia with respect to the orthogonal frame *a*, *b*^{*}, *a* × *b*^{*} are given in Table 6.



(I). X=O (II). X=S
(III). X=NH

(IV). R – aromatic ring
(V). R – saturated ring



(VI).

Fig. 3. Formulae: (I) 18-crown-6; (II) 1,10-dithio-18-crown-6; (III) 1,10-diaza-18-crown-6; (IV) dibenzo-18-crown-6; (V) dicyclohexyl-18-crown-6; (VI) [2,2]paracyclophane-bis-18-crown-6.

of the present structure are also characteristic of such interactions (Bürgi *et al.*, 1974); they include the angles O(3)···C(22)=O (103°) and O(15)···C(22)=O (87°), and the indication that one of the lone pairs of each benzyl O points toward the carbonyl C. The carbon atom C(22), being engaged in two non-bonding contacts with oxygen atoms on opposite sides of the ring is not displaced from the plane defined by C(21), O(23) and O(24).

The overall pattern of thermal motion is consistent with the molecular conformation and the intramolecular interactions just described; the largest vibrations are associated with atoms C(7), C(8) and C(10). Data for the least-squares planes through different parts of the molecule are given in Table 7. Examination of planes (3) and (5) indicates that the five ether-oxygen atoms are approximately coplanar, and that the hydrogen-bonded O(9) lies approximately in the plane of the carboxyl group. The crystal packing is shown in Fig. 2. All intermolecular distances are longer than or equal to the sums of the van der Waals radii.

Table 7. Least-squares planes

(a) Equations (as $Ax + By + Cz = D$) and definition of planes *x*, *y*, *z* are fractional coordinates of a point in a plane and *D* is the distance of the plane from unit-cell origin.

	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i> (Å)	Definition
(1)	3.970	7.454	-10.846	2.643	benzene ring
(2)	2.547	10.348	-8.031	4.537	18-membered ring
(3)	1.303	11.369	-6.458	5.299	five ether-oxygen atoms
(4)	1.223	11.181	-6.839	4.944	as in (3) + C(21)
(5)	9.442	-1.190	-6.521	0.891	carboxyl group

(b) Deviations (Å × 10²) from the planes.

- (1) see Fig. 1.
- (2) O(3) 59; O(6) 29; O(9) -4; O(12) -53; O(15) -26; C(19) -75; C(21) -11; C(22) 26.
- (3) O(3) 2; O(6) -6; O(9) 9; O(12) -5; O(15) 1; C(21) -34; C(22) 15; O(24) -83.
- (4) O(3) 12; O(6) -6; O(9) 5; O(12) -5; O(15) 11; C(21) -21; C(22) 23; O(23) 139.
- (5) O(3) 266; O(6) 266; O(9) 4; O(12) -265; O(15) -269; C(21) -3; H(24) 0.

The angle between normals to planes (1) and (2) is 18°, (1) and (4) is 27°, (1) and (5) is 59°, (2) and (5) is 72°, (3) and (5) is 81°.

It is interesting to extend the present discussion on molecular conformation to related uncomplexed systems of 18-membered hexaheterocycles (Fig. 3). The reported structural studies (Truter, 1973; Dunitz *et al.*, 1974; Goldberg, 1975*a*) show that such polydentate ligands tend to adopt a highly symmetric conformation when complexed with metal cations or small organic species of effective radius ≥ 1.4 Å. The ligating hetero atoms, occupying the relative positions 1, 4, 7, 10, 13 and 16 of the aliphatic ring, form a hexagonal cavity and are almost equally displaced (2.7–2.9 Å) from its center. The average torsion angles about the ring C–C and C–O bonds are close to 180° and 65° respectively.

As in the present investigation of the 18-crown-5

derivative, the conformation of the free flexible ligands may be different from that in any of the corresponding host-guest complexes. The differences are particularly evident in the relative arrangement of the hetero atoms, and thus in the shape of the cavity. Such variations have been observed in the crystal structures of 18-crown-6 (I) (Dunitz & Seiler, 1974), two isomers of dicyclohexyl-18-crown-6 (V) (Dalley, Smith, Larson, Christensen & Izatt, 1975), and dibenzo-18-crown-6 (IV) (Bright & Truter, 1970). In each of these uncomplexed molecules, the hexagon defined by the ether O atoms is expanded along two diagonals and contracted along the third; the corresponding O...O distances across the elliptical cavity are greater than 6.6 Å for the long dimensions, and range from 4.0 [in (V)] to 4.7 Å [in (IV)] for the short diagonal. In fact, shorter interatomic distances across the ring give rise to some stabilizing nonbonding interactions. Nevertheless, the deformation of the cavities, with respect to their nearly circular shapes in the complexed compounds, is obviously limited by the torsional strain introduced into the cyclic systems. An elliptical arrangement of the hetero atoms has also been observed in uncomplexed molecules of 1,10-dithio-18-crown-6 (II) (Dalley, Smith, Larson, Matheson, Christensen & Izatt, 1975).

Furthermore, we note that in (I) the free space inside the deformed ring of the crown-ether is apparently 'filled' by two H atoms that form transannular H...O contacts, with distances approximately equal to the sum of the corresponding van der Waals radii. Such an arrangement, with those H atoms pointing toward the center of the molecule, arises because the conformations about two of the ethylenic bonds are antiplanar rather than *gauche* (Dunitz & Seiler, 1974); they are *gauche* in most of the related structures of macrocyclic polyethers. On the other hand, the conformations of the hexa-ether rings in (IV) (Bright & Truter, 1970) and in [2,2]paracyclophane-bis-18-crown-6 (VI) (Parker, Helgeson, Maverick & Trueblood, 1973) are partially affected by strong geometric constraints due to the presence of the aromatic substituents. The distribution of torsion angles in the macrocyclic skeleton is somewhat irregular in both compounds. In fact, compound (VI) is characterized by a significant structural disorder. Moreover, the published results of an isotropic refinement of (IV) include several exceptionally large temperature factors of carbon and oxygen atoms ($B > 10 \text{ \AA}^2$), which suggests that the ring moiety of the uncomplexed ligand may be similarly disordered.

Finally, the crystal structures of 1,10-diaza-18-crown-6 (III) (Herceg & Weiss, 1972) and of the corresponding 1:1 complex with KCNS (Moras, Metz, Herceg & Weiss, 1972) show that the geometries of the uncomplexed and complexed ligands are virtually the same, resembling the D_{3d} conformation of an ideal 18-crown-6 model. In the uncomplexed molecule the H atoms bonded to the two N atoms point toward the center of the macro-ring and form relatively short non-

bonding contacts (2.5 Å) with the surrounding oxygen atoms, thus stabilizing the favourable unstrained 'crown' conformation. The overall geometry of the molecule is preserved in the metal complex since its formation is associated mainly with an inversion at the nitrogen atoms; in the complex, the nitrogen lone pairs are involved in bonding interactions with the centered cation, and the two hydrogen atoms adopt axial positions with respect to the molecular ring.

We plan to correlate those observations on the effects of transannular nonbonding interactions and molecular disorder on the overall conformation of the flexible uncomplexed polyether species with quantitative results of molecular-deformation and strain-energy calculations, as well as with further structural studies.

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References

- BRIGHT, D. & TRUTER, M. R. (1970). *J. Chem. Soc. (B)*, pp. 1544-1550.
- BÜRGI, H. B., DUNITZ, J. D. & SHEFTER, E. (1974). *Acta Cryst.* B30, 1517-1527.
- DALLEY, N. K., SMITH, J. S., LARSON, S. B., CHRISTENSEN, J. J. & IZATT, R. M. (1975). *J. C. S. Chem. Commun.* pp. 43-44.
- DALLEY, N. K., SMITH, J. S., LARSON, S. B., MATHESON, K. L., CHRISTENSEN, J. J. & IZATT, R. M. (1975). *J. C. S. Chem. Commun.* pp. 84-85.
- DUNITZ, J. D., DOBLER, M., SEILER, P. & PHIZACKERLEY, R. P. (1974). *Acta Cryst.* B30, 2733-2738.
- DUNITZ, J. D. & SEILER, P. (1973). *Acta Cryst.* B29, 589-595.
- DUNITZ, J. D. & SEILER, P. (1974). *Acta Cryst.* B30, 2739-2741.
- GERMAIN, G., MAIN, P. & WOLFSON, M. M. (1971). *Acta Cryst.* A27, 368-376.
- GOLDBERG, I. (1975a). *Acta Cryst.* B31, 754-762.
- GOLDBERG, I. (1975b). *Acta Cryst.* B31, 2592-2600.
- HANSON, H. P., HERMAN, F., LEA, J. D. & SKILLMAN, S. (1964). *Acta Cryst.* 17, 1040-1044.
- HERCEG, M. & WEISS, R. (1972). *Bull. Soc. Chim. Fr.* pp. 549-551.
- MORAS, D., METZ, B., HERCEG, M. & WEISS, R. (1972). *Bull. Soc. Chim. Fr.* pp. 551-555.
- NEWCOMB, M. & CRAM, D. J. (1975). *J. Amer. Chem. Soc.* 97, 1257-1259.
- PARKER, K., HELGESON, R. C., MAVERICK, E. & TRUEBLOOD, K. N. (1973). Amer. Cryst. Assoc. Abstracts, Winter Meeting, Florida.
- PEDERSEN, C. J. (1967). *J. Amer. Chem. Soc.* 89, 7017-7036.
- SCHOMAKER, V. & TRUEBLOOD, K. N. (1968). *Acta Cryst.* B24, 63-76.
- STEWART, R. F., DAVIDSON, E. R. & SIMPSON, W. T. (1965). *J. Chem. Phys.* 42, 3175-3187.
- STROUSE, C. E. (1975). To be published.
- TRUTER, M. R. (1973). *Struct. Bond.* 16, 71-111.