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Structure of the 4-*tert*-Butylbenzyl Alcohol–β-Cyclodextrin Complex. Common Features in the Geometry of β-Cyclodextrin Dimeric Complexes

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Abstract

β-Cyclodextrin–4-*tert*-butylbenzyl alcohol decahydrate, $C_{42}H_{70}O_{35}.C_{11}H_{16}O.10H_2O$, $M_r = 1479{\cdot}40$, orthorhombic, $C222_1$, $a = 19{\cdot}196\,(7)$, $b = 24{\cdot}393\,(6)$, $c = 32{\cdot}808\,(9)$ Å, $V = 15363\,(8)$ Å^3, $Z = 8$, $D_x = 1{\cdot}279$ Mg m^{-3}, $\lambda(\text{Mo } K\alpha) = 0{\cdot}71069$ Å, $\mu = 0{\cdot}074$ mm^{-1}, $F(000) = 6336$, $T = 295\,(2)$ K, final $R = 0{\cdot}1127$ for 4287 observed reflections with $|F_o| \geq 3{\cdot}0\sigma(|F_o|)$. Two β-cyclodextrin (β-CD) molecules are held together by hydrogen bonds linking the secondary O(3)H hydroxyl groups to form dimers in the cavity of which two 4-*tert*-butylbenzyl alcohol molecules are accommodated. The interdimer space is filled with 10·2 water molecules distributed over 15 sites forming a dense hydrogen-bond network with themselves and the β-CD hydroxyl groups. A comparison of β-CD dimeric structures shows that the heptagonal symmetry of the β-CD molecules is slightly affected by the nature and shape of the guest molecule. An important factor for the positioning and stability of the guest in the β-CD cavity is the solvation of the guest polar group. The dimers form *C*-centered layers, the relative setting of which leads to four classes of molecular packing: channel, intermediate, screw channel and chessboard.

Introduction

The cyclodextrins, which are also named cyclomaltoses or cycloamyloses, are macrocycles obtained from the enzymatic degradation of starch. They are composed of six, seven or eight α-1,4-linked glucopyranose residues, called α-, β- or γ-cyclodextrin (α-CD, β-CD or γ-CD) respectively. They have the shape of a truncated cone with a cavity at its center and the narrow and wide rims are occupied by primary and secondary hydroxyl groups respectively. Thus, the CD molecules are hydrophilic at the periphery and hydrophobic in the central cavity and they are able to act as hosts in inclusion complexes with a wide variety of guest molecules having the appropriate dimensions. The guests are at least partly trapped within the cavity. It seems that several factors contribute to the stabilization of the complexes: hydrogen bonding between the guest and host molecules, hydrophobic binding, expulsion of water molecules, release of strain energy in the CD ring and polar interactions between the CD and guest molecules. Tabushi & Kuroda (1983) argue that the most important driving force for inclusion is the hydrophobic interaction, but others (Stoddart & Zarzycki, 1988) argue that the extent of each contribution depends on the nature of the host, guest and solvent molecules. Cylcodextrin inclusion complexes are of interest in fundamental research, as well as in industrial applications for microencapsulation of substances that are volatile, sensitive, active, toxic *etc.* (Saenger, 1980).

The crystal structure of the 4-*tert*-butylbenzyl alcohol β-CD complex (TERB) is part of a systematic crystallographic investigation of β-CD inclusion complexes, where only one parameter of the guest molecule is varied at a time (Mentzafos, Mavridis, Le Bas & de Rango, 1990). Furthermore, we attempt a comparison of the structural characteristics of the β-CD complexes in the crystalline state in order to see if there are similarities.

A search of the Cambridge Structural Database, Version 3.3 (Allen, Kennard & Taylor, 1983) and in the literature supplied us with data for 45 crystallographic structures of β-CD complexes. In 34 of them, crystallizing in space groups $C222_1$, $C2$, $P2_1$ or $P1$, a pair of β-CD molecules form dimers *via* O(3)···O′(3) hydrogen bonds. The molecules of a pair are related by a twofold axis, strictly crystallographic for space groups $C222_1$ and $C2$, and approximate for

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Table 1. *Crystal data and packing modes of the dimeric complexes*

Complex	a (Å)	b (Å)	c (Å)	α (°)	β (°)	γ (°)	V/Z (Å^3)	R	H:G*	References†
Space group $P1$ (packing type CH)										
NPII	15·461 (2)	15·575 (3)	15·316 (3)	103·98 (2)	100·92 (2)	104·23 (2)	1703	0·120	2:4	Jogun (1979)
p-Nitroacetanilide	15·13	15·54	15·69	88·65	98·16	103·14	1778	0·170	2:2	NATUAS 274 621
4-*tert*-Butyltoluene	15·562 (2)	15·564 (4)	15·835 (3)	102·11 (2)	102·15 (1)	103·64 (2)	1752	0·113	2:2	Mavridis *et al.* (1990)
Space group $P1$ (packing type IM)										
CARB	17·747 (5)	15·255 (5)	15·491 (5)	102·54 (1)	113·54 (1)	98·87 (1)	1807	0·110	2:2	ASBSDK 38 3063
CINN	18·186 (3)	15·486 (2)	15·392 (2)	102·78 (1)	113·61 (1)	99·74 (1)	1862	0·123	2:2	JCCCAT 881
NPI	17·980 (2)	15·424 (2)	15·299 (1)	103·0 (1)	113·5 (1)	99·4 (1)	1818	0·125	2:4	Jogun (1979)
(+)-Flurbiprofen	18·107 (2)	15·446 (2)	15·513 (2)	102·89 (1)	113·52 (1)	99·32 (1)	1866	0·095	2:2	CPBTAL 32 1662
Flurbiprofen	18·033 (2)	15·420 (2)	15·490 (2)	103·05 (1)	113·63 (1)	99·36 (1)	1843	0·084	2:2	CPBTAL 31 3363
p-Iodophenol	17·985 (3)	15·352 (3)	15·363 (3)	102·8 (1)	113·1 (1)	99·4 (1)	1827	0·122	2:3	NATUAS 274 617
m-Methylphenol	17·887 (2)	15·327 (2)	15·366 (1)	102·64 (1)	113·07 (1)	99·68 (1)	1864	0·130	2:3	Jogun (1979)
N-Ac-Ph-alanine	18·129 (2)	15·411 (2)	15·585 (2)	103·97 (1)	112·89 (1)	98·79 (1)	1871	0·118	2:2	TACAAH 73
Iloprost	18·08 (1)	15·47 (1)	15·45 (1)	103·10 (3)	99·40 (3)	112·99 (3)	1854	0·105	2:1	CRBRAT 192 43
Mean value	18·0 (1)	15·41 (7)	15·44 (9)	103·0 (4)	112 (5)	101 (5)	1850 (20)			
ASPI	19·777 (5)	15·247 (3)	15·475 (4)	102·63 (2)	116·96 (2)	104·12 (2)	1865	0·106	2:3	JOIPDF 2 701
(Barbital)$_2$	19·716 (3)	15·497 (1)	15·549 (2)	103·63 (1)	116·65 (1)	104·56 (1)	1881	0·254	2:2	ACACEQ 40 C78
MTSO	19·618 (3)	15·432 (1)	15·476 (3)	102·98 (2)	117·70 (1)	104·30 (1)	1846	0·18	2:3	MCLCA5 156 393
Mean value	19·70 (8)	15·4 (1)	15·50 (4)	103·1 (5)	117·1 (5)	104·3 (2)	1860 (20)			
Space group $P2_1$ (packing type SC)										
FENO	15·277 (3)	32·232 (7)	15·316 (3)		101·18 (1)		1850	0·108	2:2	JACSAT 110 5833
RFEN	15·26 (2)	32·76 (4)	15·35 (1)		101·53 (1)		1880	0·083	2:2	JACSAT 110 4379
SFENO	15·310 (3)	32·124 (7)	15·277 (3)		100·76 (1)		1845	0·113	2:2	JACSAT 110 4379
Phenobarbital	15·562 (1)	33·189 (3)	15·229 (1)		104·854 (7)		1901	0·160	2:2	ACACEQ 40 C78
p-Ethylaniline	15·300 (1)	32·311 (2)	15·584 (2)		102·40 (1)		1881	0·250	2:2	ASBSDK 37 1158
p-Iodoaniline	15·292 (3)	32·490 (5)	15·531 (4)		102·62 (2)		1882	?	?	ASBSDK 37 1158
Mean value	15·3 (1)	32·5 (4)	15·4 (1)		102·1 (4)		1870 (20)			
Space group $C2$ (packing type CH)										
PHEN	19·24	24·56	15·94		109·5		1775	0·150	2:2	Le Bas (1985)
KI$_7$	19·609 (5)	24·513 (7)	15·795 (6)		109·50 (2)		1789	0·170	2:2	JOIPDF 1 181
2,5-Diiodobenzoic acid	19·19 (1)	24·76 (2)	15·74 (1)		109·6 (3)		1761	0·190	2:2	CRBRAT 89 33
2-Br-5-*tert*-butylphenol	19·24 (1)	24·66 (2)	16·02 (1)		108·9 (2)		1797	0·180	2:2	CRBRAT 89 33
Benzocaine	18·746 (9)	24·528 (4)	15·658 (5)		110·21 (3)		1689	0·160	2:2	CRBRAT 102 31
Adamandan-1-ol	18·950 (3)	24·698 (5)	15·652 (3)		109·69 (3)		1724	0·160	?	ACA (1989) 108 PB17
Biphenyl	19·34	24·49	15·80		109·8		1768	0·160	?	Le Bas (1985)
Polyiodide	19·58	24·44	15·75		109·3		1778	?	?	JACSAT 102 2710
3,3-Dimethylbutylamine	19·187 (9)	24·56 (1)	15·893 (7)		108·77 (4)		1773	0·109		MCLCA5 186 185
Mean value	19·2 (3)	24·6 (1)	15·8 (1)		109·5 (4)		1760 (30)			
Space group $C222_1$ (packing type CB)										
BENZ	19·28	24·00	32·84				1899	0·130	2:2	Le Bas (1985)
MALO	19·09	24·27	32·58				1887	0·120	2:2	Le Bas (1985)
METH	19·16 (1)	24·97 (2)	32·60 (3)				1950	0·125	2:2	CRBRAT 142 21
TERB	19·196 (7)	24·393 (6)	32·808 (9)				1920	0·113	2:2	This work
Mean value	19·18 (8)	24·4 (4)	32·7 (1)				1910 (30)			

* H:G = host:guest.

† See *Notes for authors* (1983) for a description of journal codens. Full references have been deposited.

$P2_1$ and $P1$. Crystal data of the dimeric structures are given in Table 1. 12 structures besides the present one, each with an R factor less than 0·15 and easily accessible atomic coordinates, were chosen for detailed study: complexes of β-CD with benzophenone, benzil and phenylethylmalonic acid denoted PHEN, BENZ and MALO respectively (Le Bas, 1985), 1-adamantanecarboxylic acid (CARB; Hamilton & Sabesan, 1982*b*), 1-adamantanemethanol (METH; Hamilton, 1985), aspirin (ASPI; Nishioka, Nakanishi, Fujiwara & Tomita, 1984), *n*-propanol (NPI, phase I and NPII, phase II; Jogun, 1979), ethyl cinnamate (CINN; Hursthouse, Smith, Thornton-Pett & Utley, 1982), racemic fenoprofen (FENO; Hamilton & Chen, 1988*b*), and (*R*)- and (*S*)-fenoprofen (RFEN and SFEN respectively; Hamilton & Chen, 1988*a*). To describe the structures a normalized numbering scheme for the β-CD atoms has been adopted: O(mn) or C(mn) denote the mth atom of the nth glucosidic residue so that the O($3n$) atoms are hydrogen bonded to the O$'[3(8-n)]$ atoms of the twofold-axis-related β-CD molecule.

Experimental

TERB was prepared by adding 4-*tert*-butylbenzyl alcohol to an aqueous solution of recrystallized β-CD, until the host:guest mole ratio was 1:10. The precipitate obtained was redissolved in water at 348 K and allowed to cool slowly over a five-day period. A crystal of dimensions 0·3 × 0·2 × 0·1 mm was sealed in a Lindemann glass capillary to prevent water loss, which makes the crystal opaque. The space group was determined by oscillation and Weissenberg photographs. The systematic extinctions hkl: $h+k=2n$; $00l$: $l=2n$ and the Laue class mmm uniquely determined the space group to be $C222_1$. Cell parameters were determined from 15 independent reflections with $20 < 2\theta < 26°$. Intensity data were collected on a Syntex $P2_1$ diffractometer with

Table 2. *Positional* (× 10^4) *and isotropic thermal parameters* $U = B/8\pi^2$ (× 10^3 Å^2) *of the non-*H *atoms and site-occupation factors* (*K*) *of the water molecules with e.s.d.'s in parentheses*

	x	y	z	U	K
C(11)	56 (6)	5714 (5)	1362 (4)	37 (3)	
C(21)	−505 (6)	5734 (5)	1689 (4)	40 (3)	
C(31)	−913 (6)	5230 (5)	1684 (4)	38 (3)	
C(41)	−1241 (6)	5162 (4)	1258 (4)	37 (3)	
C(51)	−690 (7)	5185 (5)	934 (4)	46 (3)	
O(51)	238 (4)	5656 (3)	980 (3)	42 (2)	
C(61)	−993 (8)	5224 (6)	515 (4)	57 (3)	
O(21)	−205 (4)	5844 (4)	2080 (3)	53 (2)	
O(31)	−1472 (4)	5253 (3)	1983 (3)	50 (2)	
O(61)	−1421 (5)	5703 (4)	471 (3)	66 (3)	
O(41)	1569 (4)	4634 (3)	1249 (2)	39 (2)	
C(12)	−2263 (6)	4616 (5)	1095 (4)	44 (3)	
C(22)	−2735 (7)	4361 (5)	1416 (4)	43 (3)	
C(32)	−2520 (6)	3780 (5)	1498 (4)	41 (3)	
C(42)	−2547 (7)	3449 (5)	1102 (4)	46 (3)	
C(52)	−2078 (7)	3736 (5)	788 (4)	45 (3)	
O(52)	−2272 (4)	4291 (3)	730 (3)	50 (2)	
C(62)	−2080 (8)	3472 (7)	375 (5)	40 (4)	
O(22)	−2717 (5)	4696 (3)	1776 (3)	51 (2)	
O(32)	−2998 (4)	3537 (3)	1788 (3)	50 (2)	
O(62)	2793 (6)	3512 (5)	203 (4)	83 (3)	
O(42)	−2279 (4)	2919 (3)	1186 (2)	42 (2)	
C(13)	−2696 (7)	2458 (5)	1068 (4)	48 (3)	
C(23)	−2732 (6)	2092 (5)	1453 (4)	41 (3)	
C(33)	−2014 (6)	1893 (5)	1569 (4)	44 (3)	
C(43)	−1720 (6)	1590 (5)	1206 (4)	42 (3)	
C(53)	−1728 (6)	1954 (5)	834 (4)	42 (3)	
O(53)	−2404 (5)	2161 (4)	757 (3)	54 (2)	
C(63)	−1526 (9)	1631 (7)	457 (5)	76 (4)	
O(23)	−3061 (5)	2385 (4)	1785 (3)	55 (2)	
O(33)	−2071 (5)	1525 (4)	1904 (3)	57 (2)	
O(63)	−1961 (7)	1179 (6)	392 (4)	103 (4)	
O(43)	−1009 (4)	1454 (3)	1312 (3)	44 (2)	
C(14)	−799 (7)	901 (5)	1250 (4)	49 (3)	
C(24)	−508 (6)	688 (5)	1654 (4)	40 (3)	
C(34)	130 (6)	1001 (5)	1774 (4)	43 (3)	
C(44)	649 (6)	967 (6)	1450 (4)	43 (3)	
C(54)	355 (8)	1161 (6)	1038 (5)	60 (4)	
O(54)	−277 (5)	872 (4)	947 (3)	53 (2)	
C(64)	823 (8)	1081 (6)	685 (5)	65 (4)	
O(24)	−1043 (4)	693 (4)	1954 (3)	53 (2)	
O(34)	411 (4)	759 (3)	2150 (3)	48 (2)	
O(64)	1087 (7)	557 (5)	664 (4)	90 (3)	
O(44)	1255 (4)	1295 (3)	1551 (2)	40 (2)	
C(15)	1912 (6)	1051 (5)	1547 (4)	42 (3)	
C(25)	2254 (6)	1156 (5)	1967 (4)	41 (3)	
C(35)	2349 (6)	1771 (5)	2013 (3)	40 (3)	
C(45)	2772 (6)	2006 (4)	1661 (3)	35 (3)	
C(55)	2466 (6)	1838 (5)	1243 (4)	42 (3)	
O(55)	2332 (4)	1246 (3)	1231 (3)	46 (2)	
C(65)	2929 (7)	1958 (6)	875 (4)	55 (3)	
O(25)	1838 (4)	947 (3)	2286 (3)	50 (2)	
O(35)	2702 (5)	1892 (4)	2381 (3)	55 (2)	
O(65)	3600 (6)	1709 (4)	926 (3)	74 (3)	
O(45)	2783 (4)	2582 (3)	1692 (2)	40 (2)	
C(16)	3418 (7)	2871 (5)	1691 (4)	47 (3)	
C(26)	3486 (7)	3206 (5)	2051 (4)	45 (3)	
C(36)	2934 (6)	3662 (5)	2055 (4)	38 (3)	
C(46)	2990 (6)	3992 (5)	1667 (4)	43 (3)	
C(56)	2951 (7)	3602 (5)	1296 (4)	56 (3)	
O(56)	3474 (5)	3179 (4)	1325 (3)	56 (2)	
C(66)	3055 (9)	3902 (7)	892 (5)	75 (4)	
O(26)	3455 (5)	2888 (4)	2407 (3)	58 (2)	
O(36)	3033 (5)	4004 (4)	2406 (3)	54 (2)	
O(66)	3660 (9)	4232 (7)	912 (5)	126 (5)	
O(46)	2448 (4)	4369 (3)	1653 (2)	35 (2)	
C(17)	2590 (6)	4928 (5)	1610 (4)	40 (3)	
C(27)	2268 (6)	5243 (5)	1943 (4)	39 (3)	
C(37)	1467 (6)	5192 (5)	1920 (4)	39 (2)	
C(47)	1243 (6)	5388 (4)	1489 (3)	34 (3)	
C(57)	1634 (7)	5088 (5)	1155 (4)	46 (3)	
O(57)	2377 (4)	5127 (3)	1228 (3)	45 (2)	
C(67)	1512 (8)	5366 (6)	755 (5)	64 (4)	
O(27)	2510 (4)	5067 (3)	2337 (2)	41 (2)	
O(37)	1157 (5)	5518 (4)	2220 (3)	51 (2)	
O(67*A*)	1690 (10)	5938 (8)	753 (6)	68 (5)	
O(67*B*)	1790 (20)	4930 (10)	435 (9)	111 (8)	
O(47)	519 (4)	5283 (3)	1445 (2)	40 (2)	
C(1)	240 (10)	3238 (8)	1642 (6)	90 (5)	
C(2)	280 (30)	2700 (20)	1870 (10)	250 (10)	
C(3)	480 (30)	3740 (20)	1850 (10)	270 (10)	
C(4)	−560 (20)	3280 (20)	1660 (20)	380 (10)	
C(5)	230 (10)	3260 (10)	1191 (6)	142 (8)	
C(6)	421	3765	1019	190 (10)	
C(7)	340	3852	602	240 (10)	
C(8)	68	3438	356	230 (10)	
C(9)	−124	2937	527	220 (10)	
C(10)	−44	2850	945	220 (10)	
C(O)	−60 (30)	3530 (20)	−170 (10)	260 (10)	
O	650 (20)	3270 (10)	−420 (10)	260 (10)	
W(21)	4164 (9)	1712 (7)	2410 (6)	132 (5)	1·00
W(22)	4100 (20)	4660 (10)	3060 (10)	172 (9)	0·75
W(23)	4330 (20)	2050 (20)	3250 (10)	290 (10)	1·00
W(24)	4280 (20)	4650 (10)	2285 (8)	108 (6)	0·60
W(26*A*)	4640 (30)	3290 (20)	2840 (20)	170 (10)	0·40
W(26*B*)	5000	2830 (30)	2500	270 (10)	0·30
W(32)	4430 (30)	3590 (20)	3210 (20)	180 (10)	0·40
W(34)	4010 (20)	4720 (20)	2680 (20)	140 (10)	0·40
W(61)	2266 (5)	486 (4)	213 (3)	57 (2)	1·00
W(62I)	4100 (30)	3960 (20)	4450 (10)	220 (10)	0·60
W(62II)	3500 (20)	2640 (20)	4970 (10)	310 (10)	1·00
W(63*A*)	1240 (10)	130 (10)	4607 (8)	82 (6)	0·50
W(63*B*)	1690 (20)	140 (10)	4617 (8)	90 (7)	0·50
W(64)	4840 (30)	4830 (2)	4650 (10)	270 (10)	0·75
W(65)	4890 (10)	2210 (8)	1052 (7)	162 (6)	1·00

* *W*(62I) and *W*(62II) refer to two discrete molecules being 3·81 (6) Å apart.

Nb-filtered Mo $K\alpha$ radiation with an θ–2θ scan mode up to 45° in 2θ. A scan speed of 2·0–16·0° min^{-1} (2θ) was used with a scan width of 1·8° (2θ) plus the $\alpha_1 - \alpha_2$ divergence. Data collected, unique reflections and R_{int}: 5875, 5473 and 0·016. Range of h, k and l: $-26\rightarrow0$, $0\rightarrow20$ and $-35\rightarrow0$ respectively. The stability of the crystal was monitored by three standard reflections measured every 67 reflections. No crystal decay was observed (fluctuation smaller than 3%). 4287 reflections with $|F_o| \geq 3\sigma(|F_o|)$ were considered observed. The intensities were corrected for Lorentz and polarization effects. No absorption correction was applied (μ = 0·074 mm^{-1}).

The coordinates of the isomorphous structure of the benzil β-CD complex (Le Bas, 1985) were used as the initial coordinates for the β-CD molecule. Subsequent difference electron density maps, $\Delta\rho$, revealed the non-H atoms of the guest and water molecules. Then all the coordinates were refined. After the completion of the refinement, the water and guest atomic positions were again tested by two difference electron density syntheses in order to cross-check the parameters of host, guest and solvent: one involving only the host and water non-H atoms, the other involving the host and guest non-H atoms. In both cases all the missing atoms appeared at almost the same positions as those obtained from the previous complete refinement. Isotropic thermal parameters have been used throughout the refinement. The occupancy factors of water molecules were refined and at the latest stages of refinement the values truncated to the first [or the second for *W*(22) and *W*(64)] decimal place and then kept constant. All the calculations were performed with a modified version of *SHELX76* (Sheldrick, 1976). Scattering factors were taken from *International Tables for X-ray Crystallography* (1974, Vol. IV). The refinement based on F proceeded by full-matrix least squares, in which $\sum w\Delta F^2$ was minimized. The phenyl group of the guest molecule was considered as a regular hexagon with bond lengths of 1·395 Å. For H atoms linked to C atoms calculated coordinates were used (C—H distance 0·96 Å). The hydroxyl H atoms have not been found. The structure was refined to R = 0·1127 and wR = 0·1530 with $1/w = \sigma^2(F_o) + 0{\cdot}0071F_o^2$ for observed reflections (R = 0·1480 and wR = 0·1990 for all reflections). Sixteen reflections showing poor agreement were given zero weight during final refinement cycles. S = 2·39 and the maximum shift/e.s.d. = 0·193 (U of H atom). The maximum and minimum peaks observed in the final $\Delta\rho$ map were 0·600 and −0·411 e Å^{-3}. The number of refined parameters was 429. Variability and disorder of the water content and disorder of the guest molecule, associated with disorder of the primary hydroxyl groups of the β-CD molecule, result in the poor diffracting power of the crystals of β-CD complexes in a fashion similar to protein crystals. The small number of observations did not allow us to use anisotropic refinement since the ratio of observed reflections to parameters was too small. Most of the related structures determined so far, see Table 1, are refined isotropically to R factors of 11–18%.*

The atomic coordinates of the title compound are given in Table 2.

Discussion

The structure of TERB

A numbering scheme for the β-CD and the guest molecules is given in Fig. 1. Two β-CD molecules related by the twofold crystal axis parallel to b form a head-to-head dimer by means of O(3)···O′(3) hydrogen bonds producing a cavity in the interior of which a pair of guest molecules is accommodated (Fig. 2). The sevenfold axis of the dimer, defined here as normal to the average O(4) plane, forms an angle of 10 (1)° with the crystallographic c axis. The dimers form a C-centered layer. In the interdimer space 10·2 (2) water molecules, distributed over 15 sites, form a network of hydrogen bonds among themselves and with the β-CD hydroxyl groups (Table 4).

All glucose residues have the $^4C_1$ conformation. With the exception of O(67), disordered over two positions A and B (occupancy factor 0·5 each), no other disordered atoms have been observed in the host molecule. The primary hydroxyl groups having a *gauche–gauche* orientation point outward from the cavity, except atom O(67B) which has a *gauche–trans* orientation pointing inward and forming a hydrogen bond with the O(67B) atom of an adjacent dimer (Fig. 3) linked by a twofold axis parallel to a [O···O distance 2·87 (5) Å]. The observed dispersion of the values of the corresponding bond lengths or angles of glucose residues is not significant (Table 3) if those associated with the O(67B) atom are not taken into account. The sevenfold symmetry of the β-CD appears to be well maintained. This is reflected in the O(4n)···O[4(n + 1)] distances [average 4·38 (3) Å] and O[4(n − 1)]···O(4n)···O[4(n + 1)] angles [average 128·6 (9)°]. The latter is equal to the angle of the regular heptagon (128·5714...°). Moreover, the deviations of the glycosidic O(4) atoms from their optimum plane are very small, less than 0·02 Å [O(43)]. The dihedral angles between the above-

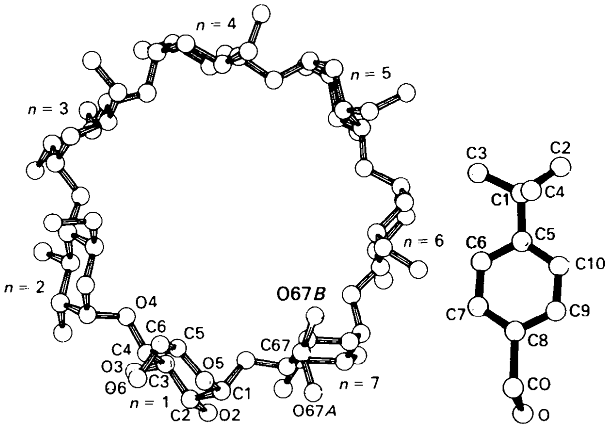

Fig. 1. An *ORTEP*II (Johnson, 1976) diagram showing the β-CD and *tert*-butylbenzyl alcohol molecules and the numbering scheme.

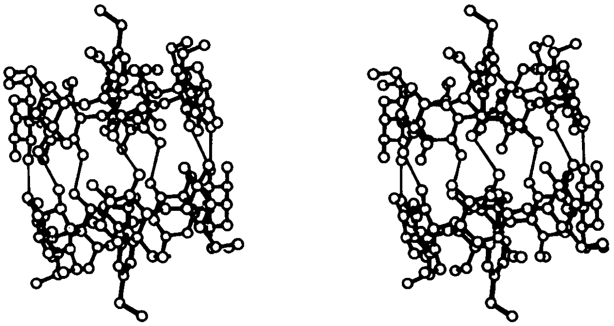

Fig. 2. Stereoscopic view of the β-CD dimer with the guest molecules inside the cavity.

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* Lists of H-atom parameters, bond lengths and angles of the guest molecules, full references to Tables 1 and 7, geometrical features of the O(4) planes and structure factors have been deposited with the British Library Document Supply Centre as Supplementary Publication No. SUP 54136 (43 pp.). Copies may be obtained through The Technical Editor, International Union of Crystallography, 5 Abbey Square, Chester CH1 2HU, England.

Table 3. *Bond lengths* (Å) *and angles* (°) *of the host molecule of TERB*

*n** =	1	2	3	4	5	6	7
C(1*n*)—C(2*n*)	1·52 (2)	1·52 (2)	1·55 (2)	1·53 (2)	1·55 (2)	1·44 (2)	1·47 (2)
C(2*n*)—C(3*n*)	1·46 (2)	1·50 (2)	1·51 (2)	1·50 (2)	1·52 (2)	1·53 (2)	1·54 (2)
C(3*n*)—C(4*n*)	1·54 (4)	1·53 (2)	1·51 (2)	1·46 (2)	1·52 (2)	1·51 (2)	1·55 (2)
C(4*n*)—C(5*n*)	1·50 (2)	1·54 (2)	1·51 (2)	1·54 (2)	1·54 (2)	1·55 (2)	1·51 (2)
C(5*n*)—O(5*n*)	1·45 (1)	1·42 (1)	1·42 (2)	1·43 (2)	1·47 (1)	1·44 (2)	1·45 (2)
O(5*n*)—C(1*n*)	1·38 (1)	1·44 (2)	1·37 (2)	1·42 (2)	1·40 (2)	1·42 (2)	1·41 (1)
C(2*n*)—O(2*n*)	1·43 (2)	1·44 (1)	1·45 (1)	1·42 (2)	1·41 (2)	1·40 (2)	1·44 (1)
C(3*n*)—O(3*n*)	1·46 (1)	1·45 (1)	1·42 (1)	1·47 (2)	1·42 (1)	1·43 (1)	1·40 (2)
C(5*n*)—C(6*n*)	1·50 (2)	1·50 (2)	1·52 (2)	1·48 (2)	1·53 (2)	1·53 (2)	1·49 (2)
C(6*n*)—O(6*n*)	1·44 (2)	1·48 (2)	1·40 (2)	1·38 (2)	1·43 (2)	1·41 (2)	1·44 (2)*A*
C(6*n*)—O(6*n*)							1·58 (3)*B*
C(4*n*)—O(4*n*)	1·43 (1)	1·42 (1)	1·45 (2)	1·45 (2)	1·41 (1)	1·39 (1)	1·42 (1)
C[1(*n* − 1)]—O(4*n*)	1·42 (2)	1·44 (1)	1·42 (2)	1·39 (1)	1·41 (2)	1·40 (1)	1·40 (1)
C(1*n*)—C(2*n*)—C(3*n*)	110·2 (9)	110 (1)	111 (1)	111 (1)	108 (1)	111 (1)	110 (1)
C(2*n*)—C(3*n*)—C(4*n*)	108·8 (9)	110 (1)	107 (1)	110 (1)	111 (1)	109 (1)	107·1 (9)
C(3*n*)—C(4*n*)—C(5*n*)	110·4 (9)	108 (1)	110·2 (9)	112 (1)	111·7 (9)	109 (1)	111·9 (9)
C(4*n*)—C(5*n*)—O(5*n*)	112·4 (9)	112 (1)	111·3 (1)	110 (1)	110·7 (9)	111 (1)	110 (1)
C(5*n*)—O(5*n*)—C(1*n*)	114·8 (9)	114·3 (9)	115 (1)	115 (1)	114·6 (1)	112 (1)	114·2 (9)
O(5*n*)—C(1*n*)—C(2*n*)	110·9 (9)	110·1 (9)	109 (1)	109 (1)	111·1 (9)	113 (1)	111·1 (9)
C(1*n*)—C(2*n*)—O(2*n*)	110·7 (9)	109 (1)	110 (1)	109·5 (9)	111·1 (9)	111 (1)	112·1 (9)
C(3*n*)—C(2*n*)—O(2*n*)	113 (1)	112 (1)	111 (1)	114 (1)	110 (1)	111 (1)	109·9 (9)
C(2*n*)—C(3*n*)—O(3*n*)	110·9 (9)	109 (1)	109·2 (9)	108·4 (9)	110 (1)	109·6 (9)	110 (1)
C(4*n*)—C(3*n*)—O(3*n*)	108·3 (9)	108·7 (9)	109·2 (9)	110 (1)	108·3 (9)	110·9 (9)	110·4 (9)
C(4*n*)—C(5*n*)—C(6*n*)	112 (1)	114 (1)	110 (1)	115 (1)	115 (1)	112 (1)	110 (1)
O(5*n*)—C(5*n*)—C(6*n*)	106 (1)	107 (1)	106 (1)	107 (1)	105·7 (9)	108 (1)	106 (1)
C(5*n*)—C(6*n*)—O(6*n*)	111 (1)	108 (1)	112 (1)	113 (1)	110 (1)	110 (1)	114 (1)*A*
C(5*n*)—C(6*n*)—O(6*n*)							104 (2)*B*
C(3*n*)—C(4*n*)—O(4*n*)	107·2 (9)	108 (1)	105·9 (9)	110·4 (9)	109·2 (9)	109·1 (9)	107·9 (9)
C(5*n*)—C(4*n*)—O(4*n*)	109·3 (9)	109 (1)	109·8 (1)	109 (1)	109·5 (9)	110 (1)	108·9 (9)
C(2*n*)—C(1*n*)—O[4(*n* − 1)]	109·4 (9)	109 (1)	105 (1)	107 (1)	107·6 (9)	111 (1)	110·6 (9)
O(5*n*)—C(1*n*)—O[4(*n* − 1)]	111·0 (9)	108·9 (9)	113 (1)	110 (1)	112·6 (9)	109 (1)	111·9 (9)
C(4*n*)—O(4*n*)—C[1(*n* + 1)]	116·5 (9)	117·5 (9)	116·7 (9)	119·1 (9)	120·8 (9)	120·2 (9)	120·3 (8)

* If $n = 7$, $n + 1 = 1$.

mentioned O(4) plane and the optimum planes of the C(2), C(3), C(5) and O(5) atoms of each glucose residue range from 80 to 87° with an average of 83 (2)°. Therefore, the difference between the narrower and wider rim diameters is not as large as shown in the usual schematic representations.

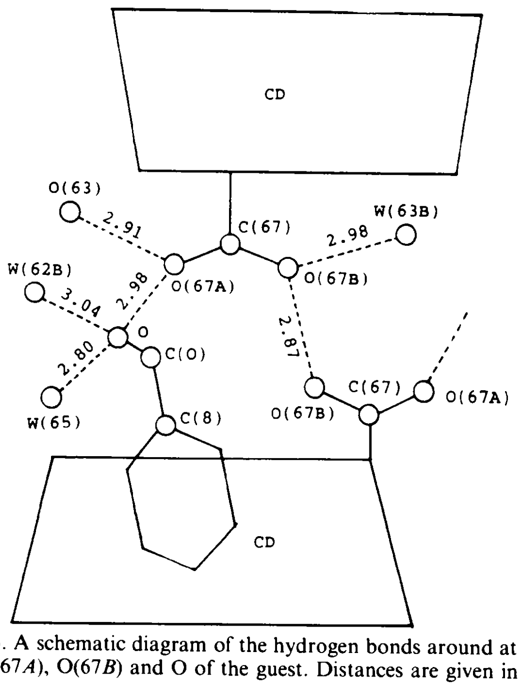


Fig. 3. A schematic diagram of the hydrogen bonds around atoms O(67*A*), O(67*B*) and O of the guest. Distances are given in Å.

The conformation of the β-CD macrocycle is stabilized through strong intramolecular O(3*n*)···O[2(*n* + 1)] hydrogen bonds corresponding to the flip-flop system described by Saenger and his collaborators (Betzel, Saenger, Hingerty & Brown, 1984; Zabel, Saenger & Mason, 1986). The O(3*n*)···O[2(*n* + 1)] distances [average 2·81 (2) Å] and bond angles C(3*n*)—O(3*n*)···O[2(*n* + 1)] [average 116·0 (6)°] and O(3*n*)···O[2(*n* + 1)]—C[2(*n* + 1)] [average 118·6 (7)°] lie within the usual values for hydrogen bonds (Table 4).

The thermal parameters of the guest atoms have high values. Attempts to find more than one molecular site failed. The molecule was located in the cavity, with the phenyl plane forming an angle of 18° with the sevenfold β-CD axis. The *tert*-butyl group is buried inside the hydrophobic cavity. The phenyl group is located at the primary hydroxyl region, while the guest hydroxyl group protrudes from the cavity (Fig. 2). The latter forms two hydrogen bonds (Fig. 3), one with the 100% occupied *W*(65) [O···*W*(65) distance 2·80 (4) Å] and a weaker one, with the disordered 50% occupied O(67*A*) of an adjacent β-CD dimer having a *gauche–gauche* configuration [O···O(67*A*) distance 2·98 (4) Å]. Thus, the twofold disorder of the above-mentioned O(67) is now understood in terms of host–guest–water interactions. It is interesting to recall that a similar phenomenon has been reported in the complex of α-CD cyclopentanone (Tsoucaris, Le Bas, Rysanek & Villain, 1987). There, as a consequence of the chan-

Table 4. *Hydrogen bonds* (Å) *and angles* (°) *for TERB*

Intramolecular
(*a*) O(3*n*)···O[2(*n* + 1)]*
(*b*) C(3*n*)—O(3*n*)···O[2(*n* + 1)]
(*c*) O(3*n*)···O[2(*n* + 1)]—C[2(*n* + 1)]

Intradimer
(*a*) O(3*n*)···O′[3(8 − *n*)]
(*b*) C(3*n*)—O(3*n*)···O′[3(8 − *n*)]

	Intramolecular (*a*)	Intramolecular (*b*)	Intramolecular (*c*)	Intradimer (*a*)	Intradimer (*b*)
n = 1	2·83 (1)	116·2 (6)	119·4 (7)	2·76 (1)	119·1 (6)
n = 2	2·81 (1)	115·7 (6)	118·5 (7)	2·88 (1)	117·2 (6)
n = 3	2·84 (1)	116·3 (7)	117·9 (7)	2·79 (1)	118·7 (7)
n = 4	2·81 (1)	115·1 (6)	119·5 (7)	2·79 (1)	118·9 (6)
n = 5	2·83 (1)	116·7 (6)	118·7 (7)		118·9 (6)
n = 6	2·79 (1)	115·3 (6)	118·7 (7)		120·3 (7)
n = 7	2·77 (1)	116·6 (7)	118·7 (7)		116·1 (7)

With water molecules

O(61)···*W*(61)	2·71 (1)	C(61)—O(61)···*W*(61)	113·9 (8)
O(62)···*W*(62I)	2·80 (1)	C(62)—O(62)···*W*(62I)	101·9 (8)
O(62)···*W*(62II)	2·96 (5)	C(62)—O(62)···*W*(62II)	131 (1)
O(62)···*W*(61)	2·80 (1)	C(62)—O(62)···*W*(61)	101·9 (8)
O(63)···*W*(63*A*)	2·92 (3)	C(63)—O(63)···*W*(63*A*)	114 (1)
O(63)···*W*(63*B*)	2·58 (3)	C(63)—O(63)···*W*(63*B*)	131 (1)
O(64)···*W*(61)	2·71 (2)	C(64)—O(64)···*W*(61)	113·1 (9)
O(64)···*W*(64)	2·71 (5)	C(64)—O(64)···*W*(64)	113 (1)
O(65)···*W*(65)	2·79 (2)	C(65)—O(65)···*W*(65)	128·8 (9)
O(66)···*W*(63*A*)	2·78 (3)	C(66)—O(66)···*W*(63*A*)	118 (1)
O(66)···*W*(63*B*)	2·90 (3)	C(66)—O(66)···*W*(63*B*)	103 (1)
O(21)···*W*(21)	2·67 (2)	C(21)—O(21)···*W*(21)	109·2 (7)
O(22)···*W*(22)	2·72 (3)	C(22)—O(22)···*W*(22)	97·0 (9)
O(23)···*W*(23)	2·57 (4)	C(23)—O(23)···*W*(23)	103 (1)
O(24)···*W*(24)	2·83 (3)	C(24)—O(24)···*W*(24)	95·6 (8)
O(26)···*W*(26*A*)	2·86 (6)	C(26)—O(26)···*W*(26*A*)	101 (1)
O(26)···*W*(26*B*)	2·98 (1)	C(26)—O(26)···*W*(26*B*)	94 (1)
O(32)···*W*(32)	2·75 (6)	C(32)—O(32)···*W*(32)	128 (2)
O(34)···*W*(22)	2·92 (3)	C(34)—O(34)···*W*(22)	106·8 (9)
O(34)···*W*(34)	2·81 (5)	C(34)—O(34)···*W*(34)	132 (2)
O(35)···*W*(21)	2·84 (3)	C(35)—O(35)···*W*(21)	117·9 (7)
O(36)···*W*(24)	2·91 (3)	C(36)—O(36)···*W*(24)	108·4 (8)
O(36)···*W*(34)	2·72 (5)	C(36)—O(36)···*W*(34)	137 (2)

* If *n* = 7 then *n* + 1 = 1.

nel packing, it is the *gauche–trans* (inward) conformation which brings the primary hydroxyl group above the guest of the adjacent layer and forms a hydrogen bond between this hydroxyl group and the carbonyl group of the cyclopentanone. In conclusion, the ability of the host to have the primary hydroxyl groups in two conformations, the hydrogen-bond ability of the guest and the presence of water induces the packing mode. It appears that the guest molecule participating in the hydrogen-bond network contributes to the stability of the crystal. It is worth noting that the benzyl alcohol β-CD complex (Harata, Uekama, Otagiri, Hirayama & Ohtani, 1985), crystallizing in the herringbone mode, exhibits the opposite orientation while the angle of the phenyl group with the sevenfold axis is similar to the one found in the present structure (20°). However, in this case there is no dimerization of the host. The whole molecule is enclosed within the cavity and the guest hydroxyl group forms a strong hydrogen bond [O···O(3) distance 2·74 Å] with the hydroxyl group of an adjacent β-CD molecule. This comparison may provide a clue for the mechanism of the dimer formation in β-CD complexes: the additional hydrophobic element (*tert*-butyl group) requires a larger hydrophobic environment than that provided by a monomeric host molecule. Such an environment is precisely created by the dimer formation. The minimum distance between the C atoms of the methyl groups of the two guest molecules included in the dimer is 4·25 (14) Å which may be considered as a loose van der Waals contact.

Comparison of the β-CD complexes

The β-CD conformation. The average values of the bond lengths and angles of the structures considered in detail are the same as those of TERB within two standard deviations (Table 5). No disordered atoms have been observed in the host molecules with the exception of some primary hydroxyl groups having at least one site with a *gauche–trans* orientation pointing inward. However, the latter's occupancy is always smaller or equal to that of the *gauche–gauche* orientation.

In all structures strong O(3*n*)···O[2(*n* + 1)] intramolecular hydrogen bonds of the flip-flop type are formed [average value 2·78 (2), range 2·74–2·82 Å], which are generally accepted as stabilizing the round shape of β-CD. Thermodynamic calculations have shown that they lower the energy of β-CD by 163 kJ mol^{-1} *i.e.* 79 kJ mol^{-1} more than in α-CD (Bergeron, 1984). They may also play an important role in the stabilization of the structure in solution (Onda, Yamamoto, Inoue & Chujo, 1988). It is observed that the C(3*n*)—O(3*n*)···O[2(*n* + 1)] angles [average 116·7 (7), range 116–118°] are slightly smaller than the O(3*n*)···O[2(*n* + 1)]—C[2(*n* + 1)] angles [average 119·1 (8), range 118–121°]. This slight difference of 2° is systematic and in agreement with the NMR results that the α- and β-CD's prefer to form intramolecular hydrogen bonds in which O(3)H is the proton donor. Crystallographic studies on methylated β-CD also support this hypothesis (Harata, 1990).

The β-CD conformation may be compared by studying the geometry of the heptagons formed by the glycosidic O(4) atoms. For all the structures considered here the deviations of the O(4) atoms from their optimum planes are small {average 0·024, maximum value 0·106 Å [O(46) for NPII]}. Thus, the heptagons of the dimeric structures form less distorted planes than those of the monomeric structures whose deviations range from 0·077 for the hexamethylenetetramine β-CD complex (Harata, 1984) to 0·280 Å for the 'empty' β-CD (Lindner & Saenger, 1982). The relative differences in the distances and angles of the heptagons and in those of the apices from its center, CE [defined from O(4) alone], are small and comparable to the e.s.d.'s. In general, we think that the deviation of the β-CD molecule from sevenfold symmetry depends not only on the size of the guest molecule but on its nature, shape, and/or its orientation and depth of penetra-

Table 5. *Mean values of the bond lengths* (Å) *and angles* (°) *for dimeric β-CD complexes* (*names as in Table* 1)

A and *B* denote two crystallographically independent molecules.

Distances between atoms (*a*) and (*b*)

(*a*)	C(1)	C(2)	C(3)	C(4)	C(5)	O(5)	C(2)	C(3)	C(5)	C(6)	C(4)	C(1†)
(*b*)	C(2)	C(3)	C(4)	C(5)	O(5)	C(1)	O(2)	O(3)	C(6)	O(6)	O(4)	O(4)
NPII*A*	1·524 (7)	1·523 (8)	1·522 (9)	1·54 (2)	1·44 (1)	1·41 (1)	1·427 (9)	1·429 (7)	1·519 (9)	*	1·43 (1)	1·415 (9)
NPII*B*	1·53 (1)	1·52 (1)	1·53 (2)	1·53 (1)	1·451 (9)	1·413 (9)	1·422 (8)	1·431 (9)	1·52 (2)	1·42 (3)	1·430 (7)	1·42 (1)
ASPI*A*	1·52 (4)	1·52 (2)	1·53 (2)	1·54 (2)	1·45 (2)	1·42 (3)	1·43 (2)	1·43 (2)	1·56 (2)	1·40 (3)	1·43 (2)	1·44 (2)
ASPI*B*	1·52 (4)	1·51 (2)	1·53 (2)	1·55 (2)	1·45 (3)	1·42 (3)	1·43 (2)	1·45 (2)	1·54 (4)	1·42 (4)	1·43 (2)	1·43 (1)
CARB*A*	1·53 (3)	1·51 (2)	1·53 (2)	1·52 (2)	1·46 (3)	1·41 (3)	1·44 (2)	1·45 (2)	1·53 (4)	1·43 (3)	1·44 (2)	1·43 (2)
CARB*B*	1·53 (3)	1·52 (3)	1·54 (3)	1·54 (2)	1·46 (6)	1·43 (6)	1·44 (2)	1·44 (2)	1·52 (2)	1·45 (3)	1·44 (2)	1·43 (2)
CINN*A*	1·51 (2)	1·52 (4)	1·51 (3)	1·52 (4)	1·45 (2)	1·41 (3)	1·43 (2)	1·45 (1)	1·54 (2)	1·44 (5)	1·45 (5)	1·43 (3)
CINN*B*	1·50 (3)	1·51 (3)	1·53 (4)	1·54 (2)	1·44 (2)	1·43 (3)	1·43 (3)	1·43 (1)	1·56 (1)	1·43 (4)	1·45 (2)	1·42 (3)
NPI*A*	1·52 (1)	1·517 (9)	1·524 (9)	1·534 (8)	1·437 (5)	1·412 (9)	1·427 (6)	1·429 (7)	1·522 (8)	1·42 (2)	1·434 (7)	1·422 (5)
NPI*B*	1·53 (1)	1·516 (8)	1·52 (2)	1·534 (8)	1·446 (9)	1·417 (8)	1·429 (9)	1·433 (6)	1·517 (4)	1·44 (4)	1·431 (8)	1·417 (9)
FENO*A*	1·52 (3)	1·51 (3)	1·53 (3)	1·51 (3)	1·44 (3)	1·41 (2)	1·45 (4)	1·42 (3)	1·53 (3)	1·41 (3)	1·43 (2)	1·43 (1)
FENO*B*	1·51 (4)	1·53 (3)	1·52 (3)	1·51 (2)	1·46 (2)	1·42 (2)	1·42 (3)	1·43 (3)	1·51 (6)	1·43 (5)	1·43 (2)	1·42 (3)
RFEN*A*	1·51 (4)	1·53 (4)	1·51 (2)	1·52 (2)	1·45 (3)	1·42 (3)	1·42 (2)	1·43 (2)	1·52 (4)	1·43 (2)	1·45 (2)	1·42 (3)
RFEN*B*	1·53 (4)	1·52 (4)	1·51 (2)	1·51 (4)	1·44 (3)	1·41 (2)	1·42 (4)	1·46 (3)	1·51 (3)	*	1·46 (4)	1·42 (3)
SFEN*A*	1·54 (5)	1·49 (3)	1·51 (2)	1·54 (5)	1·45 (4)	1·40 (2)	1·41 (5)	1·44 (3)	1·52 (6)	1·41 (2)	1·43 (4)	1·41 (3)
SFEN*B*	1·48 (5)	*	1·53 (5)	1·51 (7)	1·42 (3)	1·44 (4)	1·44 (3)	1·41 (7)	1·52 (5)	1·41 (6)	1·32 (3)	1·41 (3)
PHEN	1·53 (3)	1·50 (2)	1·54 (4)	1·55 (4)	1·45 (5)	1·43 (5)	1·45 (3)	1·45 (3)	1·57 (1)	1·44 (3)	1.44 (3)	1·42 (3)
BENZ	1·52 (2)	1·55 (2)	1·50 (2)	1·53 (3)	1·46 (1)	1·39 (2)	1·44 (2)	1·45 (1)	1·53 (4)	1·44 (2)	1·47 (1)	1·44 (2)
MALO	1·53 (5)	1·52 (8)	1·55 (5)	1·54 (4)	1·42 (3)	1·43 (5)	1·45 (4)	1·46 (4)	1·52 (4)	1·41 (4)	1·42 (6)	1·44 (4)
METH	1·51 (2)	1·52 (5)	1·52 (3)	1·51 (3)	1·42 (2)	1·42 (2)	1·43 (3)	1·43 (3)	1·48 (2)	1·43 (2)	1·43 (1)	1·42 (3)
TERB	1·51 (4)	1·51 (3)	1·52 (3)	1·53 (2)	1·44 (2)	1·41 (2)	1·43 (2)	1·44 (3)	1·51 (2)	1·43 (3)	1·42 (2)	1·41 (2)

Angles (*a*)—(*b*)—(*c*)

(*a*)	C(1)	C(2)	C(3)	C(4)	C(5)	O(5)	C(1)	C(3)	C(2)
(*b*)	C(2)	C(3)	C(4)	C(5)	O(5)	C(1)	C(2)	C(2)	C(3)
(*c*)	C(3)	C(4)	C(5)	O(5)	C(1)	C(2)	O(2)	O(2)	O(3)
NPII*A*	110 (1)	108 (1)	110 (1)	113 (2)	114·0 (6)	110·3 (7)	110 (1)	112 (1)	111 (1)
NPII*B*	110 (1)	108·8 (6)	110 (1)	112·1 (4)	114 (1)	110·1 (7)	110 (1)	111 (1)	110 (2)
ASPI*A*	110 (2)	108 (1)	109 (1)	109 (1)	116 (1)	109 (1)	110 (1)	110 (2)	109 (1)
ASPI*B*	110 (1)	107 (1)	109 (2)	110 (1)	114 (1)	110 (2)	109 (2)	111 (1)	109 (1)
CARB*A*	110 (2)	107 (2)	110 (2)	109 (2)	114 (2)	108·7 (8)	109 (3)	111 (1)	107 (1)
CARB*B*	109·3 (8)	107 (2)	110 (2)	109 (3)	113 (5)	109 (3)	109 (1)	110 (2)	109 (3)
CINN*A*	109 (1)	108 (2)	108·9 (5)	109 (1)	115 (2)	109 (1)	110 (2)	111 (3)	109 (2)
CINN*B*	111 (2)	108 (1)	108 (1)	109 (1)	115 (1)	109·2 (6)	110 (1)	110 (1)	110 (1)
NPI*A*	109·7 (6)	108·3 (5)	111 (1)	110 (1)	114·6 (6)	110·3 (7)	111 (1)	111 (1)	110 (1)
NPI*A*	109·7 (8)	108·3 (6)	110·8 (8)	109·7 (8)	113·9 (7)	110·4 (7)	110·0 (7)	111 (1)	110 (1)
FENO*A*	111 (2)	108 (2)	111 (2)	112 (2)	115 (2)	110 (1)	110 (1)	110 (2)	110 (2)
FENO*B*	110 (2)	109 (2)	111 (2)	111 (2)	114 (3)	111 (3)	112 (2)	111 (2)	110 (2)
RFEN*A*	110 (1)	108 (2)	111 (2)	110 (1)	114 (2)	111 (2)	111 (1)	111 (2)	109 (1)
RFEN*B*	108·5 (9)	109 (3)	111 (2)	111 (2)	114·9 (9)	110 (1)	111 (1)	113 (2)	109 (2)
SFEN*A*	110 (2)	110 (4)	111 (3)	109 (4)	115 (1)	110 (3)	110 (3)	113 (2)	111 (1)
SFEN*B*	111 (5)	107 (5)	111 (6)	113 (3)	112 (3)	111 (3)	111 (4)	110 (3)	111 (5)
PHEN	111 (2)	108 (1)	107·5 (9)	108 (3)	115 (2)	109 (2)	108 (1)	111 (1)	110 (1)
BENZ	109 (2)	107 (1)	110·6 (4)	108 (1)	115·2 (8)	111 (1)	111 (1)	110·7 (6)	108 (1)
MALO	109 (4)	108 (2)	108 (1)	110 (3)	116 (1)	109 (2)	109 (3)	111 (2)	108 (3)
METH	110 (2)	108 (1)	113 (2)	111 (1)	115 (2)	111 (2)	111 (2)	112 (1)	111 (2)
TERB	110 (1)	109 (2)	110 (2)	111 (1)	114 (1)	110 (1)	110 (1)	112 (2)	110 (1)

(*a*)	C(4)	C(4)	O(5)	C(5)	C(3)	C(5)	C(2)	O(5)	C(4)
(*b*)	C(3)	C(5)	C(5)	C(6)	C(4)	C(4)	C(1)	C(1)	O(4)
(*c*)	O(3)	C(6)	C(6)	O(6)	O(4)	O(4)	O(4)†	O(4)†	C(1)‡
NPII*A*	109 (1)	113 (2)	107·1 (9)	*	108 (1)	109·0 (7)	107·8 (8)	110·9 (9)	118 (1)
NPII*B*	110 (2)	112·1 (4)	106 (2)	111 (1)	108 (1)	108·7 (7)	108·0 (8)	111·0 (8)	117·5 (9)
ASPI*A*	108 (2)	112 (1)	106 (1)	110 (2)	108 (1)	107 (1)	108 (1)	109 (3)	116 (2)
ASPI*B*	109 (1)	111 (1)	105 (1)	111 (3)	107 (1)	107 (2)	108 (1)	110 (1)	117 (1)
CARB*A*	107 (1)	113 (2)	105 (2)	111 (3)	106 (1)	107·7 (6)	108 (1)	111 (2)	117 (2)
CARB*B*	109 (2)	112 (2)	106 (3)	110 (3)	107 (1)	108 (1)	109 (2)	112 (5)	117·5 (9)
CINN*A*	108 (2)	112 (2)	106 (1)	109 (3)	106 (2)	108 (1)	109 (2)	109·8 (9)	117·2 (6)
CINN*B*	108 (1)	112 (2)	106 (2)	109 (2)	107 (2)	107 (1)	109 (1)	109 (1)	117 (2)
NPI*A*	108·8 (8)	112·1 (5)	106·1 (7)	111 (1)	107·6 (8)	109·0 (6)	108 (1)	110·8 (6)	117·9 (8)
NPI*B*	110 (2)	113 (1)	106·1 (7)	111 (1)	107·3 (9)	108·9 (7)	107·7 (6)	110·6 (5)	117·6 (6)
FENO*A*	111 (2)	112 (2)	106 (2)	111 (3)	108 (3)	109 (3)	108 (2)	110 (3)	117 (2)
FENO*B*	110 (1)	113 (2)	106 (3)	112 (3)	108 (1)	109 (2)	108 (3)	110 (2)	118 (1)
RFEN*A*	111 (2)	114 (2)	105 (1)	111 (2)	108 (2)	108 (1)	108 (2)	111 (2)	118·4 (9)
RFEN*B*	110 (2)	114 (2)	107 (2)	110 (3)	107 (2)	109 (2)	108 (2)	111 (2)	118 (1)
SFEN*A*	110 (1)	111 (4)	105 (2)	113 (2)	109 (3)	108 (2)	107 (1)	113 (2)	119 (3)
SFEN*B*	110 (4)	114 (5)	106 (3)	112 (3)	107 (3)	110 (3)	109 (3)	110 (2)	118 (2)
PHEN	107 (1)	112 (4)	107 (2)	108 (3)	106 (2)	107 (3)	108 (8)	110 (2)	116 (2)
BENZ	110·1 (9)	112 (1)	105·7 (8)	111 (1)	105 (2)	106·4 (9)	107·8 (7)	110 (1)	117 (1)
MALO	107 (1)	112 (2)	106 (3)	111 (3)	106 (3)	110 (4)	109 (3)	109 (2)	117 (3)
METH	111 (2)	114 (3)	107 (3)	112 (2)	108 (1)	109 (2)	109 (2)	111 (2)	119 (2)
TERB	109 (1)	113 (2)	107 (1)	111 (2)	108 (2)	109 (1)	109 (2)	111 (1)	119 (2)

* Some of the seven values deviate by more than 10% from the calculated mean value.
† Atoms belong to the *n* − 1 residue.
‡ Atoms belong to the *n* + 1 residue.

tion inside the cavity. This is apparent in the case of CARB crystallizing in $P1$. The two guest molecules have a different degree of penetration in each β-CD monomer. The β-CD molecule with the better-fitting guest is less distorted. A general trend observed up to now is that the heptagons seem to be a little more distorted in the structures where the molecules of the dimer are related by an approximate twofold axis. In conclusion, the heptagonal symmetry of the β-CD molecule is better maintained in the dimeric structures than in the monomeric ones. The β-CD molecule is conformationally more regular than that of the α-CD, where the torus is distorted by rotation of one glycosidic residue (Koehler, Saenger & Van Gunsteren, 1987).

The guest molecule. The usual host:guest ratio of the dimer β-CD inclusion complexes is 2:2 (Table 1). In some structures where the guest is small one or two more guests may be accommodated in the interface of the β-CD's as in ASPI and *p*-iodophenol complexes (Stezowski, Jogun, Eckle & Bartels, 1978). Only in the β-CD complex with the bulky iloprost molecule (Steiner, Hinrichs, Saenger & Hoyer, 1989) is the host:guest ratio 2:1.

The majority of the guest molecules of the β-CD complexes consist of a hydrophobic moiety and a polar group, found as a rule in the region of the primary hydroxyl groups or protruding from it. Exceptions are (*a*) the 3,3-dimethylbutylamine (Mavridis, Hadjoudis & Tsoucaris, 1990*a*) and the *p*-ethylaniline (Tokuoka, Fujiwara & Tomita, 1981) β-CD complexes where the amine group forming a hydrogen bond to a water molecule is found at the dimeric interface and (*b*) the SFEN and the racemic FENO where the guests are oriented head-to-tail and the hydrophilic group of only one guest molecule protrudes from the region of the primary hydroxyl groups, while the other is found in the dimeric interface.

The exact position of the hydrophobic moiety depends on its size and nature. It may be found near the dimeric interface, as in TERB, in the middle of the β-CD cavity as in ASPI or even in the primary hydroxyl group region as in the *p*-iodophenol complex. If the guest is bulky, one of the two guest molecules [phenobarbital (Nakanishi, Fujiwara & Tomita, 1984); CARB] or both (METH) are found mostly out of the cavity in the primary hydroxyl group region and the polar groups form hydrogen bonds with water molecules or primary hydroxyl groups of adjacent hosts. In *p*-nitroacetanilide (Harding, MacLennan & Paton, 1978) and benzocaine (Hamilton & Sabesan, 1982*a*), where two hydrophilic groups are present in the guest, the most polar group is found in the primary hydroxyl group region, while the other is in the secondary region. The guest is tilted to occupy most of the available space in the cavity. In the absence of polar groups the guest molecule is not stabilized by hydrogen bonds and as a rule it shows high thermal motion (4-*tert*-butyltoluene; Mavridis, Hadjoudis & Tsoucaris, 1990*b*) or is not located at all (biphenyl; Le Bas, 1985). These observations are in accordance with Bergeron's conclusion (Bergeron, Channing, McGovern & Roberts, 1979) that the solvation of the polar group is the most important factor in the positioning and stability of the guest in the β-CD cavity.

The β-CD dimer. The distances $O(3n)\cdots O'[3(8-n)]$ [average 2·80 (6), range 2·71–2·90 Å] and the angles $C(3n)—O(3n)\cdots O[3(8-n)]$ [average 118 (1), range 114–122°] indicate that hydrogen bonds link the O(3) hydroxyl groups of two adjacent β-CD molecules to form a dimer.

There are two indications that the sandwiched area between the two β-CD molecules is rather hydrophobic: in ASPI the salicylic acid molecule trapped in the interface does not form hydrogen bonds with the β-CD secondary hydroxyl groups. In several complexes such as those of benzocaine (Hamilton & Sabesan, 1982*a*), METH, *p*-ethylaniline (Tokuoka, Fujiwara & Tomita, 1981) and 3,3-dimethylbutylamine (Mavridis, Hadjoudis & Tsoucaris, 1990*a*), the polar groups found in that area are not hydrogen bonded to the secondary hydroxyl groups but to a water molecule trapped inside the cavity.

Adjacent dimers of the same layer form hydrogen bonds by means of the primary hydroxyl groups. In the majority of the *C*-centered crystals these dimers are related by the *C* operation. An $O(63)\cdots O(67)$ bond [average 2·84 (9), range 2·72–3·03 Å] is observed in all the structures considered in detail except that of MALO. Direct hydrogen bonding between the primary hydroxyls of the dimers of adjacent layers has been observed only in a very few cases (ASPI, CARB and TERB).

The water network. The number of water molecules per β-CD molecule varies from 7·5 (biphenyl; Le Bas, 1985) to 13·35 (CARB) occupying from 12 (benzocain; Hamilton & Sabesan, 1982*a*) to 16 (METH) sites. The majority exhibit high thermal motion and low occupancy. In a comparative study of the same β-CD complex at different temperatures (Stezowski, 1985) it has been observed that the $U_{\rm iso}$ values of the O atoms of the water molecules range from 0·024 to 0·113 Å^2 at 110 K and from 0·070 to 0·436 Å^2 at room temperature. Despite the seemingly intrinsic disorder of the water molecules, a quasi-invariant water network organized in layers has been shown to exist (Le Bas & Tsoucaris, 1986; Le Bas, Rysanek & Tsoucaris, 1990).

We have assumed that the water molecules are hydrogen bonded to the hydroxyl groups if the

Table 6. *Hydrogen bonds* (Å) *for the* O *atoms of the hydroxyl groups* (*a*) *with water molecules* (*b*)

Bonds of primary hydroxyl groups

(*a*)	O(61)	O(62)	O(63)	O(64)	O(65)	O(66)	O(66)	O(67)
(*b*)	*W*(61)	*W*(62)	*W*(63)	*W*(64)	*W*(65)	*W*(63)	*W*(66)	*W*(67)
NPII*A*	2·65	2·86	2·99	2·74	2·80		2·79	2·75
NPII*B*	3·01	2·81	3·06	2·67	2·78			2·80
ASPI*A*	2·68	2·76	2·71	2·69	2·77		2·98	2·74
ASPI*B*	2·74	2·78	2·67	2·63	2·71	2·96		2·76
CARB*A*	2·73	2·95	2·78	2·83	2·73	2·81	2·98	2·75
CARB*B*	2·69	2·76	2·66	2·70	2·84		2·75	2·83
CINN*A*	2·70		2·84	2·85	2·75		2·93	2·67
CINN*B*	2·74	2·64	2·80	2·71	2·76		2·98	2·70
NPI*A*	2·68	2·71	2·65	2·83	2·74		2·87	2·73
NPI*B*	2·75	2·73	2·75	2·77	2·70		2·63	2·72
FENO*A*	2·71	2·72	2·79	2·78	2·78	2·83	2·78	2·77
FENO*B*	2·69		2·74	2·68	2·73	2·75	3·02	2·71
RFEN*A*	2·74	2·77	2·82	2·68	2·76	2·74	2·74	2·73
RFEN*B*	2·62		2·75	2·67		2·76	2·99	
SFEN*A*	2·75	2·70	2·89	2·75	2·75	2·78	2·85	2·82
SFEN*B*	2·72		2·67	2·73	2·74	2·78	3·06	2·67
PHEN	2·77	2·70	2·82	2·99	2·72	2·80	2·83	
BENZ	2·77	2·78	2·78	2·95	2·80	2·74		2·71
MALO		2·76	2·75	2·66		2·81		
METH	2·71	2·69	2·75	2·69	2·61	2·71	2·87	2·91
TERB	2·71	2·80	2·92	2·71	2·79	2·78		
Mean	2·73	2·76	2·79	2·76	2·75	2·79	2·87	2·75
E.s.d.	0·08	0·07	0·11	0·10	0·05	0·06	0·12	0·06

Bonds of secondary hydroxyl groups

(*a*)	O(21)	O(22)	O(23)	O(24)	O(26)	O(32)	O(34)	O(35)	O(36)
(*b*)	*W*(21)	*W*(22)	*W*(23)	*W*(24)	*W*(26)	*W*(32)	*W*(22)	*W*(21)	*W*(24)
NPII*A*	2·65	2·83			2·65		2·79	2·88	
NPII*B*	2·64	2·84	2·68		2·80		2·79	2·81	
ASPI*A*	2·70		2·73	2·83	2·91			2·87	
ASPI*B*	2·70	2·73		2·73		2·91	2·94	2·83	2·92
CARB*A*	2·68		2·81	2·68	2·82	2·90	2·99	2·85	2·78
CARB*B*		2·70	2·76	2·63					2·95
CINN*A*		2·93		2·70	2·91	2·89			
CINN*B*				2·73	2·79				
NPI*A*	2·66		2·99	2·73	2·77	3·14		2·91	2·78
NPI*B*	2·68		2·83	2·70	2·83			2·87	2·83
FENO*A*	2·76	2·68	2·67	2·62		2·88	2·84	2·97	2·89
FENO*B*	2·74	2·77	2·75	2·75	2·90	2·93	2·82	2·85	2·95
RFEN*A*	2·67	2·69	2·62	2·80		2·88		2·85	2·85
RFEN*B*	2·76	2·71	2·78	2·72	2·94	2·89	2·94	2·86	2·91
SFEN*A*	2·66	2·66	2·67	2·72	2·87		2·87	2·83	2·79
SFEN*B*	2·71		2·66	2·74		2·99		2·86	2·92
PHEN	2·62	3·00	2·85	2·83	2·91	3·03	2·69	2·88	3·03
BENZ	2·66	2·77	2·71	2·71	2·79	3·00	2·84	2·94	2·90
MALO	2·75	2·74	2·77	2·78	2·70	2·82	2·88	2·76	2·84
METH	2·68	2·67	2·73	2·76	2·99	2·86	2·79	2·84	2·74
TERB	2·67	2·72	2·57	2·86	2·85	2·75	2·92	2·84	2·91
Mean	2·69	2·76	2·74	2·74	2·84	2·92	2·85	2·86	2·87
E.s.d.	0·04	0·10	0·10	0·06	0·09	0·10	0·08	0·05	0·08

O···*W* distances and the corresponding C—O···*W* angles are in the ranges 2·57–3·14 Å and 93–128°, a rather extended region but generally accepted on account of their usual disorder and the inability to locate the H atoms. In Table 6 we have listed the probable hydrogen bonds if they are common to at least 13 of the 21 β-CD molecules compared. The water molecules have been characterized by the label of the O atom of the β-CD hydroxyl group at which they are bonded. There are several water oxygen sites common to many structures but only the *W*(63) and *W*(64) O atoms are common to all 13 structures considered in detail.

Two separate sub-networks are formed, one involving hydrogen bonds with the primary and another with the secondary hydroxyl groups (Table 6). None of the primary hydroxyl groups links to a water site of the secondary sub-network and *vice versa*. The access of the secondary hydroxyl groups is limited by the dimerization of the β-CD molecule. There is a tendency for the O(3)···*W* distances to be longer [average 2·87 (5), range 2·75–3·14 Å] compared to those of O(2)···*W* [average 2·75 (5), range 2·57–3·00 Å] and O(6)···*W* [average 2·77 (4), range 2·62–3·01 Å]. The water sub-layer constituting the interface between two adjacent dimeric layers contributes to the cohesiveness of the crystal since direct hydrogen bonds between their dimers are rare. One to three water molecules per β-CD molecule belonging to the so-called secondary hydration sphere are only hydrogen bonded to other water molecules. Owing to the dense hydrogen-bond network the water molecules are held more tightly than the guest molecules. Thus, the mean temperature factors of the water O atoms are less affected by the temperature than those of the atoms of the guest molecule (Stezowski, 1985).

The C-centered layers. Dimeric structures of the same space group have similar cell dimensions except those of space group $P1$, where two categories exist (Table 1) with the b and c axes around 15·5 Å. In the first category the a axis is nearly 15·5 Å, while in the second category it is 18·0 or 19·7 Å. The two distinct values in the second category are due to the arbitrary assignment of the unit-cell axis as a or $a + b$. An appropriate cell reduction leads to the same value for a (Table 7).

The optimal O(4) planes of the β-CD molecules of a dimer are almost parallel [average angle 1·0 (3), range 0·5–1·3°]. If we perform the transformations (Table 7) (i) $a' = a + b$, $b' = b - a$ for $P1$, the first category (Harding, MacLennan & Paton, 1978), (ii) $a' = b + c$, $b' = b - a$, $c' = a$ (or $c' = a + b$ when $|a|$ is about 19·7 Å) for $P1$, the second category, and (iii) $a' = a + c$, $b' = c - a$ and $c' = b$ for the $P2_1$ dimeric structures, a common pseudo-C-dimeric layer is created for all of them. Its a' and b' axes are nearly equal to the a and b values for the $C222_1$ and $C2$ structures with an average value of $\gamma = 90{\cdot}2\ (7)^\circ$ and the approximate twofold axis of the dimer is nearly parallel to b'. Therefore, all the dimeric structures can be considered to consist of centered or pseudo-centered dimeric layers of unit area about 460 Å^2. Each layer has a deformed hexagonal packing appearance where each β-CD dimer is surrounded by two others at a distance of about 19·3 Å and four more at a distance of about $(19^2 + 24^2)^{1/2}/2 \simeq 15{\cdot}4$ Å.

Packing modes of the β-CD molecules. The relative setting of the dimeric layers leads to four classes of molecular packing. Three of them have been identified as channel (CH), chessboard (CB) and intermediate (IM) (Le Bas, Rysanek & Tsoucaris, 1990), formerly characterized as *A*, *B* and

Table 7. *Reduction of the cell dimensions* (Å, °) *of the* $P1$ *and* $P2_1$ *space groups*

	a'	b'	c'	α'	β'	γ'	References†
$P1$ (CH)							
Transformation: $a' = a + b$, $b' = b - a$, $c' = c$							
NPII	19·593	23·735	15·575	89·76	112·51	90·55	Jogun (1979)
p-Nitroacetaniline	19·066	24·027	15·690	96·00	95·36	91·57	NATUAS 274 621
4-*tert*-Butyltoluene	19·240	24·467	15·835	90·02	109·87	90·01	Mavridis *et al.* (1990*a*)
Mean value	19·3 (3)	24·1 (4)	15·7 (1)			90·7 (8)	
$P1$ (IM)							
Transformation: $a' = b + c$, $b' = b - c$, $c' = a$ [$c' = a + b$ for ASPI, (barbital)$_2$ and MTSO]							
CARB	19·237	23·985	17·747	99·20	116·35	89·10	ASBSDK 38 3063
CINN	19·269	24·128	18·184	98·45	117·12	90·36	JCCCAT 881
NPI	19·126	24·044	17·980	98·57	116·79	90·48	Jogun (1979)
(+)-Flurbiprofen	19·296	24·210	18·107	98·77	116·77	89·75	CPBTAL 32 1662
Flurbiprofen	19·231	24·199	18·033	98·80	116·95	89·73	CPBTAL 31 3363
p-Iodophenol	19·162	24·004	17·985	98·43	116·45	89·96	NATUAS 274 617
m-Methylphenol	19·182	23·960	17·887	98·26	116·63	89·85	Jogun (1979)
N-Ac-Ph-alanine	19·090	24·420	18·129	98·73	116·16	89·34	TACAAH 73
Iloprost	19·227	24·215	18·081	98·36	116·46	89·89	CPBTAL 192 43
ASPI	19·203	23·982	18·310	82·39	116·42	89·13	JOIPDF 2 701
(Barbital)$_2$	19·193	24·403	18·123	82·32	116·29	89·90	ACACEQ 49 C78
MTSO	19·245	24·186	17·984	81·41	116·51	89·83	MCLCA5 156 393
Mean value	19·21 (6)	24·2 (2)	18·1 (1)	98·7 (3)*	116·6 (3)	89·8 (4)	
$P2_1$ (SC)							
Transformation: $a' = a + c$, $b' = c - a$, $c' = b$							
FENO	19·422	23·637	32·232	90·00	90·00	90·15	JACSAT 110 5833
RFEN	19·361	23·709	32·760	90·00	90·00	90·34	JACSAT 110 4379
SFEN	19·505	23·561	32·124	90·00	90·00	90·13	JACSAT 110 4379
Phenobarbital	18·777	24·405	33·189	90·00	90·00	91·28	ACASEQ 40 C78
p-Ethylaniline	19·353	24·070	32·311	90·00	90·00	91·08	ASBSDK 37 1158
p-Iodoaniline	19·269	24·059	32·490	90·00	90·00	90·91	ASBSDK 37 1158
Mean value	19·3 (3)	23·9 (3)	32·5 (5)			90·6 (5)	

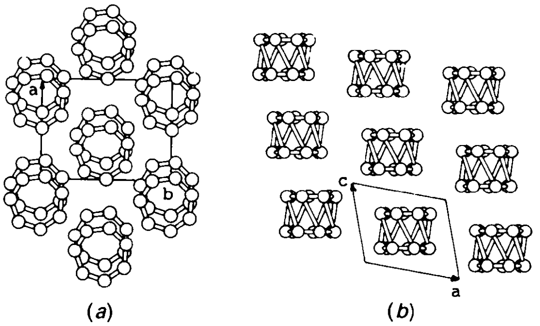
* Mean value of the nine first structures with $a < 19·0$ Å and that of the three last structures is 82·0 (5)°.

† See footnote to Table 1.

C respectively (Le Bas, 1985; Le Bas & Tsoucaris, 1986). We propose the name screw channel (SC) for the fourth. The CH structures crystallize in space groups $C2$ or $P1$ and the CB, IM and SC in $C222_1$, $P1$ and $P2_1$ respectively (Figs. 4–7).

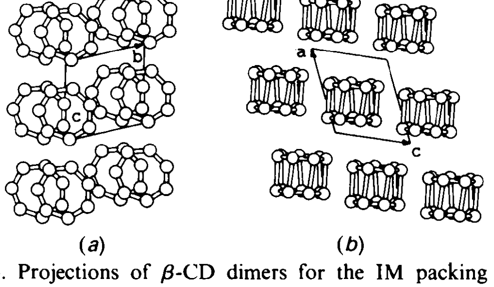
In both CH and IM structures the dimers are all parallel stacked on top of each other in a direction parallel to the *c* or *a* axes. The relative average shifting of two consecutive dimers is 2·7 (2) (3·1 for $P1$ structures) and 6·0 (2) Å respectively. In the CH mode the channel is only slightly deformed at the interdimeric interface. In the IM mode the shift is almost equal to the inner diameter of the β-CD cavity at the primary edge (Bergeron, 1984); it also compares with the average radius of the heptagon (5·03 Å). Thus, the sevenfold axis of a dimer is located near the rim of a dimer below (Fig. 5*a*). Such a large shift results in the discontinuity of the channel and justifies the term intermediate, *i.e.* between the CH and the CB modes described below. IM has been termed as 'cage type' by Saenger (Saenger, 1984, 1985).

In CB and SC packing modes the adjacent dimeric layers are related by the twofold screw axis. Although the average planes of the O(4) heptagons of the same dimeric layer are still parallel among themselves, they form an angle of about 20° with the O(4) planes of consecutive layers. In SC, each dimer packs above another dimer as in the CH mode but the channel has a 'screw' appearance because the



(*a*) (*b*)

Fig. 4. Projections of β-CD dimers for the CH packing mode (PHEN). Each β-CD molecule is represented by its O(4) heptagon. (*a*) Projection onto the average plane of the O(4) heptagons. The dimer is represented by one heptagon only. (*b*) Projection along the *b* axis.



(*a*) (*b*)

Fig. 5. Projections of β-CD dimers for the IM packing mode (CARB). Representation of β-CD molecules as in Fig. 4. (*a*) Projection onto the average plane of the O(4) heptagons. (*b*) Projection along the normal to the *ac* plane.

consecutive dimers are not parallel (Fig. 6). The mean distance of the projections of the centers of two such dimers on the *ac* plane is 2·6 (2) Å, a value somewhat smaller than that observed for the CH packing mode. In the CB packing mode each dimer is located above the interdimer space of the dimeric layer underneath filled with solvent molecules. This gives the structure a 'three-dimensional chessboard' appearance. The mean distance of the projections of the centers of two successive dimers related by the twofold screw axis on the *ab* plane is 8·7 (2) Å. There is almost no superposition of the heptagon projections of two adjacent layers (Fig. 7*a*).

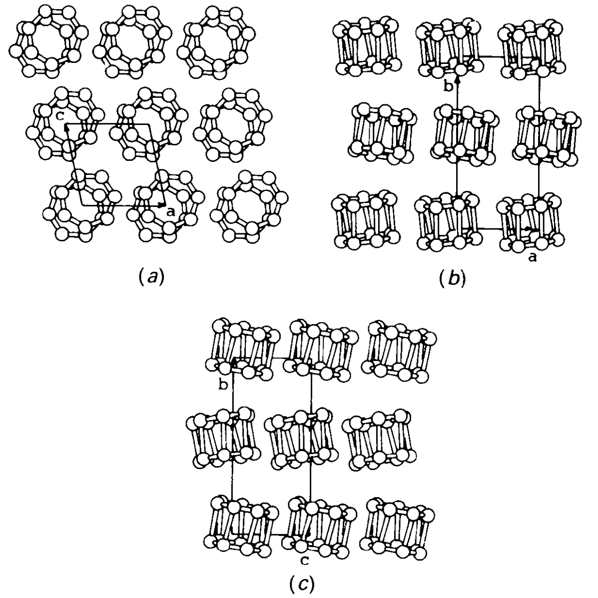


Fig. 6. Projections of the β-CD dimers for the SC packing mode (FENO). Representation of β-CD molecules as in Fig. 4. (*a*) Onto *ac*, (*b*) onto *ab* and (*c*) onto the *bc* planes.

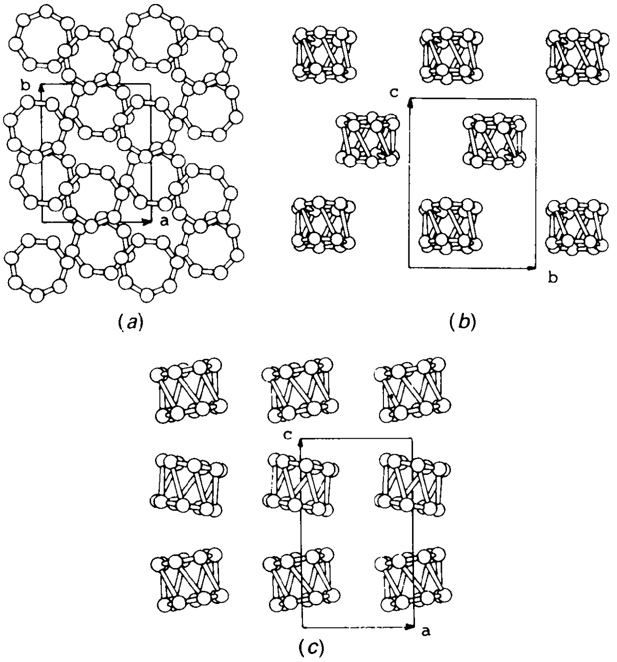


Fig. 7. Projections of the β-CD dimers for the CB packing mode (TERB). Representation of β-CD molecules as in Fig. 4. (*a*) Onto *ab*, (*b*) onto *bc* and (*c*) onto the *ac* planes.

Three cases of layer structures are worth noting. The 1,4-diazabicyclo[2.2.2]octane complex (Harata, 1982), which in contrast to the other monomeric structures forms layers stacking in CB mode. It crystallizes in $P2_1$ and the sevenfold molecular axis forms an angle of 10·3° with *b*, the latter having half of the expected size of the $P2_1$ dimeric structures [16·598 (1) Å]. In the $(\text{barbital})_4$ complex (Nakanishi, Arai, Fujiwara & Tomita, 1984) two dimers are linked to form a tetrameric channel but the tetramers are arranged according to the IM packing mode. The *a* axis is 34·341 (5) Å which is almost equal to the sum of the *a* axes of CH and IM modes. Therefore, this case may be considered as a combination of a CH and an IM mode. Similarly in (*S*)-(−)-methyl-*p*-tolylsulfoxide (Fujiwara, Tomita, Marseigne & Vicens, 1988) two dimers per asymmetric unit forming tetrameric channels are stacked in CB mode crystallizing in $P2_1$ with a *b* axis of about 2 × 32·5 = 65 Å. Summarizing, we note that all known dimeric β-CD complexes crystallize in layers. The monomeric β-CD complexes crystallize in herringbone structures except one that also forms layers.

In Table 1 the volume per inclusion unit is also given. The smallest is associated with CH and the highest with CB. IM and SC have similar intermediate volumes. These values probably reflect the extent of the hydration shell over the primary faces of the dimer. It should be mentioned here that the herringbone monomeric structures have a notably smaller volume [average value 1530 (10) Å^3] in accordance with the face that this packing type has the most compact arrangement. The same observation has been made for α-CD complexes (Saenger, 1985).

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References

Allen, F. H., Kennard, O. & Taylor, R. (1983). *Acc. Chem. Res* **16**, 146–153.
Bergeron, R. (1984). *Incl. Compd.* **3**, 391–443.
Bergeron, R., Channing, M., McGovern, K. & Roberts, W. (1979). *Bioorg. Chem.* **8**, 263–281.

Betzel, C., Saenger, W., Hingerty, B. & Brown, G. (1984). *J. Am. Chem. Soc.* **106**, 7545–7557.
Fujiwara, T., Tomita, K., Marseigne, I. & Vicens, J. (1988). *Mol. Cryst. Liq. Cryst. Incl. Nonlinear Opt.* **156**, 393–404.
Hamilton, J. (1985). *Carbohydr. Res.* **142**, 21–37.
Hamilton, J. & Chen, L. (1988*a*). *J. Am. Chem. Soc.* **110**, 4379–4391.
Hamilton, J. & Chen, L. (1988*b*). *J. Am. Chem. Soc.* **110**, 5833–5841.
Hamilton, J. & Sabesan, M. (1982*a*). *Carbohydr. Res.* **102**, 31–46.
Hamilton, J. & Sabesan, M. (1982*b*). *Acta Cryst.* **B38**, 3063–3069.
Harata, K. (1982). *Bull. Chem. Soc. Jpn*, **55**, 2315–2320.
Harata, K. (1984). *Bull. Chem. Soc. Jpn*, **57** (9), 2596–2599.
Harata, K. (1990). *Minutes International Symposium on Cyclodextrins, Paris*, p. 77. Paris: Editions de Santé.
Harata, K., Uekama, K., Otagiri, M., Hirayama, F. & Ohtani, Y. (1985). *Bull. Chem. Soc. Jpn*, **58**(4), 1234–1238.
Harding, M., MacLennan, J. & Paton, M. (1978). *Nature (London)*, **274**, 621–623.
Hursthouse, M., Smith, C., Thornton-Pett, M. & Utley, J. (1982). *J. Chem. Soc. Chem. Commun*, pp. 881–882.
Jogun, K. (1979). PhD Thesis, Univ. Stuttgart, Germany.
Johnson, C. K. (1976). *ORTEP*II. Report ORNL-5138. Oak Ridge National Laboratory, Tennessee, USA.
Koehler, J., Saenger, W. & Van Gunsteren, W. (1987). *Eur. Biophys. J.* **15**, 211–224.
Le Bas, G. (1985). PhD Thesis, Univ. de Pierre et Marie Curie, Paris, France.
Le Bas, G., Rysanek, N. & Tsoucaris, G. (1990). *Minutes International Symposium on Cyclodextrins, Paris*, p. 114. Paris: Editions de Santé.
Le Bas, G. & Tsoucaris, G. (1986). *Mol. Cryst. Liq. Cryst.* **137**, 287-301.
Lindner, K. & Saenger, W. (1982). *Carbohydr. Res.* **99**, 103–115.
Mavridis, I., Hadjoudis, E. & Tsoucaris, G. (1990*a*). *Mol. Cryst. Liq. Cryst.* **186**, 185–188.
Mavridis, I., Hadjoudis, E. & Tsoucaris, G. (1990*b*). *Minutes International Symposium on Cyclodextrins, Paris*, p. 154. Paris: Editions de Santé.
Mentzafos, D., Mavridis, I., Le Bas, G. & de Rango, C. (1990). *Minutes International Symposium on Cyclodextrins, Paris*, p. 158. Paris: Editions de Santé.
Nakanishi, I., Arai, M., Fujiwara, T. & Tomita, K. (1984). *J. Incl. Phenom.* **2**, 689–699.
Nakanishi, I., Fujiwara, T. & Tomita, K. (1984). *Acta Cryst.* **A40**, C-78.
Nishioka, F., Nakanishi, I., Fujiwara, T. & Tomita, K. (1984). *J. Incl. Phenom.* **2**, 701–714.
Notes for authors (1983). *Acta Cryst.* **A39**, 174–196.
Onda, M., Yamamoto, Y., Inoue, Y. & Chujo, R. (1988). *Bull. Chem. Soc. Jpn*, **61**, 4015–4021.
Saenger, W. (1980). *Angew Chem. Int. Ed. Engl.* **19**, 344–362.
Saenger, W. (1984). *J. Incl. Phenom.* **2**, 445–454.
Saenger, W. (1985). *Isr. J. Chem.* **25**, 43–50.
Sheldrick, G. M. (1976). *SHELX76*. Program for crystal structure determination. Univ. of Cambridge, England.
Steiner, T., Hinrichs, W., Saenger, W. & Hoyer, G.-A. (1989). *Carbohydr. Res.* **192**, 43–49.
Stezowski, J. (1985). *Trans. Am. Crystallogr. Assoc.* pp. 73–82.
Stezowski, J., Jogun, K., Eckle, E. & Bartels, K. (1978). *Nature (London)*, **274**, 617–619.
Stoddart, J. F. & Zarzycki, R. (1988). *Recl Trav. Chim. Pays-Bas*, **107–109**, 515–528.
Tabushi, I. & Kuroda, Y. (1983). *Adv. Catal.* **32**, 417–466.
Tokuoka, R., Fujiwara, T. & Tomita, K. (1981). *Acta Cryst.* **B37**, 1158–1160.
Tsoucaris, G., Le Bas, G., Rysanek, N. & Villain, F. (1987). *J. Incl. Phenom.* **5**, 77–84.
Zabel, V., Saenger, W. & Mason, S. (1986). *J. Am. Chem. Soc.* **108**, 3664–3673.

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Phase Transitions in $N(CH_3)_4HSO_4$: a Novel Compound with an Incommensurate Phase

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Abstract

Two phase transitions have been detected by calorimetric and optical studies in crystals of $N(CH_3)_4HSO_4$. At $T_i = 232\ (2)$ K, the crystal undergoes a second-order orthorhombic to incommensurate transition and at $T_c = 202\ (2)$ K, a first-order incommensurate to monoclinic transition. The structures of the three phases have been studied by single-crystal X-ray diffraction. The orthorhombic normal phase, measured at room temperature, exhibits two orientations of the sulfate ions. In the incommensurate phase, the modulation vector is parallel to $\mathbf{c}^*$ with $\mathbf{q} \simeq 0{\cdot}39\mathbf{c}^*$; the two orientations of the sulfate are retained in this phase. The structure of the low-temperature phase was determined at 175 K; the orientational phenomenon disappears while twin domains are observed. Crystal data: tetramethylammonium hydrogen sulfate, $C_4H_{12}N^+.HO_4S^-$, $M_r = 171{\cdot}2$. At room temperature: $Pn2_1a$, $a = 16{\cdot}467\ (9)$, $b = 7{\cdot}543\ (6)$, $c = 6{\cdot}939\ (5)$ Å, $Z = 4$, $\lambda(\text{Mo } K\alpha) = 0{\cdot}71069$ Å, $R = 0{\cdot}055$ for 931 reflections. At $T = 215$ K: $P^{Pn2_1a}_{1\bar{1}1}$, $a = 16{\cdot}230\ (4)$, $b = 7{\cdot}581\ (2)$, $c = 6{\cdot}825\ (1)$ Å, $Z = 4$, $\lambda(\text{Cu } K\alpha) = 1{\cdot}5418$ Å, $R = 0{\cdot}047$ for 647 main reflections. At $T = 175$ K: $P2_1$, $a = 17{\cdot}451\ (1)$, $b = 7{\cdot}595\ (1)$, $c = 13{\cdot}563\ (1)$ Å, $\beta = 112{\cdot}140\ (2)°$, $Z = 8$, $\lambda(\text{Cu } K\alpha) = 1{\cdot}5418$ Å, $R = 0{\cdot}064$ for 1680 reflections.

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