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Crystal structure of β-cyclodextrin–benzoic acid inclusion complex

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Abstract

The inclusion complex of β-cyclodextrin (β-CD) with benzoic acid (BA) has been characterized crystallographically. Two β-CDs cocrystallize with two BAs, 0.7 ethanol and 20.65 water molecules $[2(C_6H_{10}O_5)_7{\cdot}2(C_7H_6O_2){\cdot}0.7(C_2H_6O){\cdot}20.65H_2O]$ in the triclinic space group $P1$ with unit cell constants: $a = 15.210(1)$, $b = 15.678(1)$, $c = 15.687(1)$ Å, $\alpha = 89.13(1)$, $\beta = 74.64(1)$, $\gamma = 76.40(1)°$. The anisotropic refinement of 1840 atomic parameters against 16,201 X-ray diffraction data converged at $R = 0.078$. In the crystal lattice, β-CD forms dimers stabilized by direct O-2(m)_1/O-3(m)_1···O-2(n)_2/O-3(n)_2 hydrogen bonds (intradimer) and by indirect O-6(m)_1···O-6(n)_2 hydrogen bonds with one or two bridging water molecules joined in between (interdimer). These dimers are stacked like coins in a roll constructing endless channels where the guest molecules are included. The BA molecules protrude with their COOH groups at the β-CD O-6-sides and are maintained in positions by hydrogen bonding to the surrounding O-6–H groups and water molecules. Water molecules (20.65) are distributed over 30 positions in the interstices between β-CD molecules, except the water sites W-1, W-2 that are located in the channel of the β-CD dimer. Water site W-2 is hydrogen bonded to the disordered ethanol molecule (occupancy 0.7).

Keywords: β-Cyclodextrin; Benzoic acid inclusion complexes; Crystal structures; X-ray analysis; Hydrogen bond

1. Introduction

β-Cyclodextrin (β-CD) is a macrocyclic oligosaccharide consisting of seven D-glucose units linked by α-(1→4) glycosidic bonds.[1] It has the shape of a truncated cone and is amphiphilic with apolar cavity coated by C–H groups and O-4, O-5 atoms, and hydrophilic rims with O-6–H groups on the narrower side, and O-2–H, O-3–H groups on the wider side (Fig. 1).

CDs are well known for their ability to form inclusion complexes[2] with various types of guest molecules fitting partially or completely into the host CD cavity as shown by crystallographic results.[3] Such beneficial property of CDs has been applied in many industries, e.g., foods, pharmaceutics, agriculture.[4] However, inclusion geometry and stoichiometry of the complexes are different from guest to guest. Therefore, a general direction for predicting the authentic CD inclusion complexes is not accessible.

Benzoic acid (BA) has been proven to form inclusion complexes with both α-CD and β-CD.[5–8] Various techniques have been employed to investigate the complexes, e.g., in solution by NMR,[5] by potentiometric titration;[6] in the gas phase by FAB mass spectroscopy,[7] by theoretical calculations.[8] The results predicted that the host–guest stoichiometry is 1:1, the BA aromatic

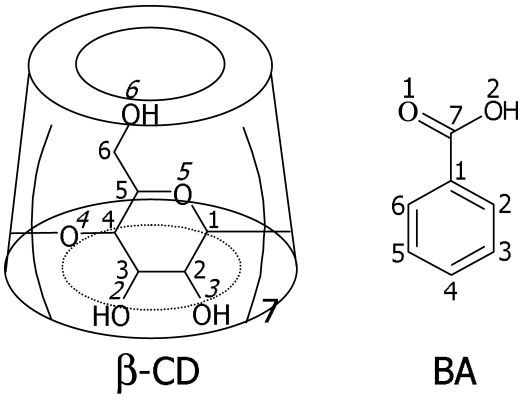

Fig. 1. Chemical structures and atomic numbering of β-CD and BA.

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Table 1
Summary of crystallographic data for 2β-CD·2BA·0.7C_2H_5OH·20.65H_2O

Chemical formula	$2(C_6H_{10}O_5)_7{\cdot}2(C_7H_6O_2){\cdot}0.7(C_2H_6O){\cdot}20.65H_2O$
Chemical formula weight	2917.6
Crystal habit, color	rod, colorless
Crystal size (mm^3)	$0.5\times0.6\times0.7$
Crystal system	triclinic
Space group	$P1$
a (Å)	15.210(1)
b (Å)	15.678(1)
c (Å)	15.687(1)
α (°)	89.13(1)
β (°)	74.64(1)
γ (°)	76.40(1)
V ($Å^3$)	3501.4(1)
Z	1
D_{calcd} (g cm^{-3})	1.364
μ (mm^{-1})	0.12
$F(000)$	1515
Diffractometer	SMART CCD (Bruker)
Radiation type, wavelength (Å)	Mo K_α, 0.71073
Temperature (°C)	20
Data collection method	ω scans with 0.3° steps
θ Range (°)	1.35–30.50
Index ranges	$-21\le h\le0$, $-22\le k\le19$, $-21\le l\le22$
Resolution (Å)	0.7
Reflections measured	25,704
Independent reflections	16,201 [$R_{int}=0.037$]
Reflections observed [$I>2\sigma(I)$]	10,022
Structure solution	Molecular replacement (PATSEE)
Refinement method	blocked-matrix least-squares on F^2
Weighting scheme	$w=[S^2(F_o^2)+(0.0963P)^2+2.2578P]^{-1}$, where $P=(F_o^2+2F_c^2)/3$
Data/parameters	16,201/1840
R [$F^2>2\sigma(F^2)$]	R [a] $=0.078$, wR [b] $=0.177$
R (all data)	R [a] $=0.134$, wR [b] $=0.216$
Goodness-of-fit	1.031
Highest peak/deepest hole (e $Å^{-3}$)	0.52/−0.30

[a] $R=\Sigma\,\|\|F_o|-|F_c\|/\Sigma\,|F_o|$.
[b] $wR=\Sigma\,\{w(F_o^2-F_c^2)^2/\Sigma\,w(F_o^2)^2\}^{1/2}$.

ring is parallel to the CD molecular axis and the COOH group points toward the narrower rim of the cone. A detailed structure of the inclusion complex is not yet reported so far. In this paper, we present insight into the three-dimensional structure of β-CD–BA inclusion complex by means of X-ray crystallography.

2. Experimental

2.1. Crystallization and X-ray diffraction

β-CD purchased from Cyclolab (Budapest/Hungary), BA and EtOH from Merck were used as received. β-CD (0.05 mol) and BA (0.10 mol) were dissolved in 2 mL of 50:50 (% v/v) water–EtOH at room temperature (rt). The solution was warmed to 60 °C for 1 h and cooled down slowly. Rodlike, colorless crystals formed in 1 week by slow solvent evaporation.

A single crystal of β-CD–BA complex with dimensions $0.4\times0.5\times0.7$ mm^3 was mounted in a glass capillary sealed at both ends with a trace of mother liquor. X-ray data collection was performed at rt using a SMART CCD diffractometer (Bruker) with Mo K_α radiation ($\lambda=0.71073$ Å) operating at 50 kV, 30 mA. A total of 25,704 reflections were measured in θ range of 1.35–30.50° (0.7 Å resolution). Data were corrected for Lorentz, polarization, and absorption effects and merged by SADABS[9] and SHELXTL[10] to yield 16,201 unique reflections. The crystal belongs to triclinic space group $P1$ (for more details, see Table 1).

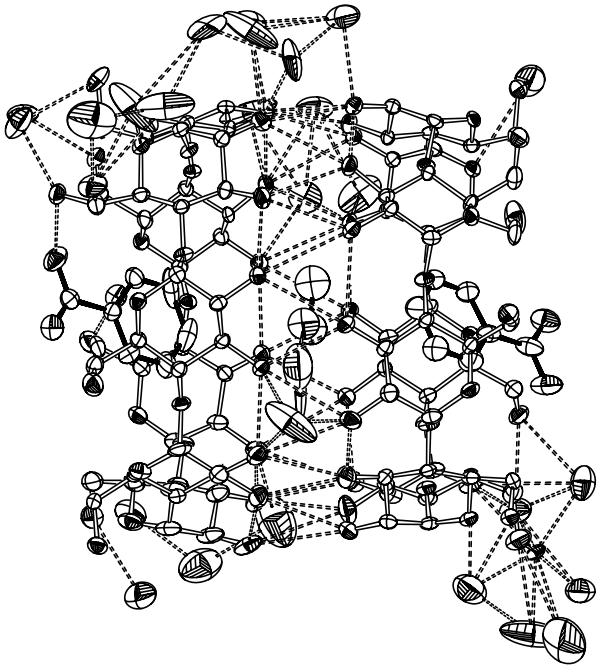
2.2. Structure determination and refinement

The crystal structure was determined by molecular replacement with program PATSEE[11] using the structure of β-CD–7-hydroxy-4-methylcoumarin complex[12] as a phasing model (only the β-CD backbone was used for the calculations, O-6 atoms were omitted). β-CD O-6 atoms, water oxygen atoms, BA, and EtOH molecules could be located by difference Fourier electron density maps aided by the graphic program XTALVIEW.[13] All O-6 atoms of the two β-CD molecules are fully occupied, except for O-66 of β-CD #1 that is doubly disordered. Two BA molecules are found fully occupied within the β-CD cavities. Ethanol (occupancy 0.7) was located in the channel of the β-CD dimer. Water molecules (20.65) were distributed over 30 sites, located preferentially in the interstices between β-CD molecules. All hydrogen atoms were placed at theoretical positions according to the 'riding model'.[14] The structure was refined by blocked-matrix least-squares on F^2 with program SHELXL-97.[14] Anisotropic refinement of 1840 atomic parameters against 16,201 data with $F^2>2\sigma(F^2)$ converged at $R=0.078$ (except for EtOH that was refined isotropically). All atoms show normal thermal motion with U_{eq} in the range 0.03–0.14 $Å^2$, except for EtOH and most water molecules that have higher U_{eq}, 0.10–0.31 $Å^2$ (see the thermal ellipsoid plots in Fig. 2).

A summary of crystallographic data and the geometrical parameters for the β-CD–BA inclusion complex are given in Tables 1 and 2, respectively. The final fractional atomic coordinates and equivalent isotropic

thermal displacement factors are given as supplementary material.

The atomic numbering scheme is that used conventionally for carbohydrates, i.e., the first number denotes the position in the glucose and the second number the glucose number in the CD macrocycle. Additionally, extra numbers 1 and 2 are used to indicate the β-CD molecules # 1 and 2, respectively. For example C-32_1 denotes C-3 of glucose unit # 2 of β-CD molecule # 1 (see Fig. 1). The letters A, B indicate disordered atoms. For the guest molecules, similar atomic numbering is adopted and the letter Z indicates the two BA molecules, e.g., C-4Z_2 stands for C-4 of BA molecule # 2 (see Fig. 1).



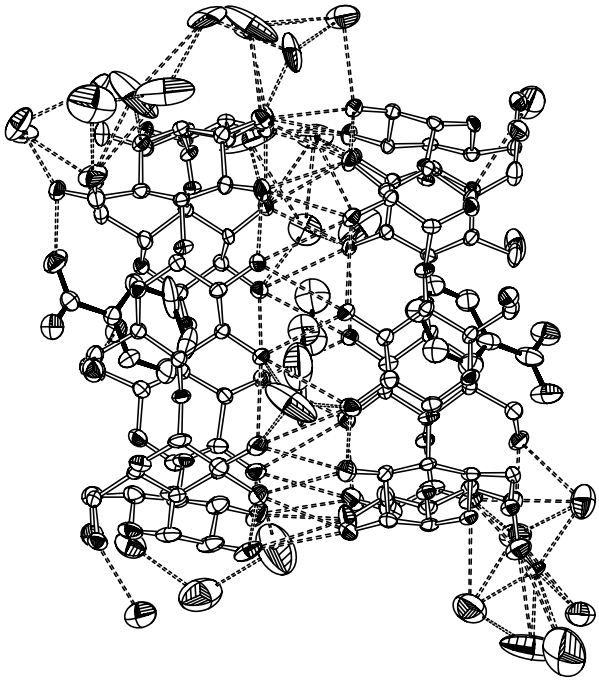


Fig. 2. ORTEP-III[22] stereo plot of the 2β-CD·2BA·$0.7C_2H_5OH$·$20.65H_2O$ inclusion complex drawn with thermal ellipsoid (30%) representation. Ellipsoids with and without octant shading are O_{CD}, O_W and C_{CD}, respectively; β-CD bonds are represented by white sticks and BA bonds black sticks. Dashed lines indicate possible O–H···O hydrogen bonds with O···O separation within 3.5 Å.

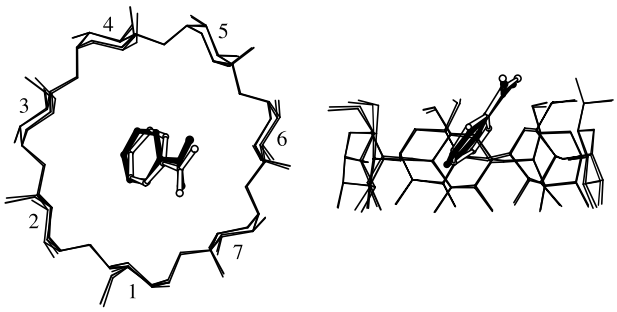


Fig. 3. Superposition of β-CD # 1 (thin line) on β-CD # 2 (thick line). BA # 1 and # 2 shown with white and black ball-and-stick, respectively (small balls are C and bigger O). Top view on the left and side view on the right.

3. Results and discussion

3.1. Structural description of β-CD macrocycles

The asymmetric unit consists of two β-CDs, two BAs, 0.7 ethanol, and 20.65 water molecules. The two β-CD molecules are almost identical as indicated by small rms deviation of superposition 0.13 Å (O-6 and H-atoms were excluded from the calculations), see Fig. 3. All glucose residues adopt a slightly distorted $^4C_1$ chair conformation as shown by the Cremer–Pople puckering parameters, Q and θ[15] in the range 0.54–0.58 Å, 3–10°, respectively, Table 2. The orientation of the glucose about the O-4 glycosidic bond is described by the torsion angles ψ, ϕ in the ranges 108.7–128.1°, 119.1–132.1°, showing that all glucoses are oriented *syn* (i.e., all O-2–H, O-3–H groups are on the same side of the cone), Table 2. This can be seen also by the narrow span of tilt angle 1.9–12.6°. The annular shape of β-CD is stabilized by intramolecular, interglucose O-3(n)···O-2($n+1$) hydrogen bonds with O···O distances 2.69–2.85 Å. In addition, the O-4($n+1$)–O-4(n)–O-4($n-1$) angles 124.8–132.2° and the small deviations of O-4 atoms from their common least-squares plane (< 0.11 Å) are evidences for the well defined heptagon formed by the lines connecting the O-4 atoms in the β-CD macrocycles.

The orientation of the C-6–O-6 bond is described by torsion angles C-4–C-5–C-6–O-6 and O-5–C-5–C-6–O-6

Table 2
Geometrical parameters of 2β-CD·2BA·0.7C_2H_5OH·20.65H_2O (distances in Å and angles in °)

Residue	1	2	3	4	5	6	7
Q [a], θ [b]	0.58, 10	0.56, 6	0.57, 4	0.57, 4	0.55, 3	0.57, 4	0.57, 5
	0.55, **4** [i]	**0.58**, **7**	**0.57**, **8**	**0.58**, **3**	**0.54**, **4**	**0.55**, **8**	**0.57**, **9**
ϕ [c], ψ [c]	112.4(7), 119.5(7)	128.1(7), 126.1(8)	112.2(7), 132.1(7)	113.2(6), 128.3(6)	108.7(6), 127.8(6)	112.8(6), 127.6(6)	115.6(6), 123.8(6)
	115.8(6), **131.2(6)**	**116.0(6)**, **129.3(6)**	**113.4(6)**, **129.4(6)**	**113.2(6)**, **125.4(6)**	**115.2(7)**, **126.2(7)**	**116.7(6)**, **119.1(7)**	**122.6(6)**, **123.4(6)**
Tilt angle [d]	3.7(2)	5.8(5)	10.9(5)	12.6(3)	10.0(1)	9.9(2)	6.4(2)
	7.2(4)	**10.1(3)**	**8.9(1)**	**6.7(2)**	**6.9(2)**	**1.9(1)**	**3.6(3)**
O-4 angle [e]	124.8(2)	128.5(2)	132.2(1)	126.3(1)	126.6(1)	130.9(1)	130.2(1)
	130.5(1)	**126.3(1)**	**127.0(1)**	**132.4(1)**	**127.8(1)**	**125.6(1)**	**130.3(1)**
Distances							
O-4 deviation [f]	−0.11	0.06	−0.01	0.01	−0.03	−0.01	0.09
	0.01	**0.03**	**−0.01**	**−0.01**	**−0.01**	**0.06**	**−0.06**
O-3(n)···O-2($n+1$)	2.76(1)	2.85(1)	2.79(1)	2.84(1)	2.82(1)	2.76(1)	2.69(1)
	2.77(1)	**2.83(1)**	**2.79(1)**	**2.76(1)**	**2.73(1)**	**2.70(1)**	**2.82(1)**
O-3(n)_1···O-2(m)_2 [g]	2.94(1)	3.15(1)	2.99(1)	3.05(1)	3.00(1)	3.11(1)	3.11(1)
O-3(n)_1···O-3(m)_2 [g]	3.12(1)	3.10(1)	2.88(1)	2.81(1)	2.79(1)	2.89(1)	2.85(1)
O-2(n)_1···O-2(m)_2 [g]	3.16(1)	3.42(1)	3.27(1)	3.04(1)	2.96(1)	3.08(1)	3.11(1)
O-2(n)_1···O-3(m)_2 [g]	2.90(1)	3.31(1)	3.11(1)	3.11(1)	2.96(1)	3.05(1)	3.02(1)
Torsion angle							
C-4–C-5–C-6–O-6	61.0(9)	50.3(9)	50.5(10)	54.0(8)	56.5(8)	179.0(8) [h], 50.3(12) [h]	54.8(9)
	57.6(8)	**61.2(7)**	**55.3(10)**	**57.3(8)**	**61.7(10)**	**57.9(8)**	**56.1(8)**
O-5–C-5–C-6–O-6	−61.9(8)	−71.3(9)	−69.4(8)	−67.7(8)	−65.2(7)	59.0(10) [h], −69.8(11) [h]	−66.0(8)
	−62.9(7)	**−60.0(7)**	**−67.3(9)**	**−61.6(7)**	**−62.8(9)**	**−65.5(7)**	**−65.1(8)**

[a] Cremer–Pople puckering amplitude.[15]
[b] Indicates the deviation from the theoretical chair conformation (ideal value: $\theta = 0$).
[c] Torsion angles ϕ and ψ at glycosidic O-4, defined as O-5(n)–C-1(n)–O-4($n-1$)–C-4($n-1$) and C-1(n)–O-4($n-1$)–C-4($n-1$)–C-3($n-1$), respectively.
[d] Tilt angles, defined as the angles between the O-4 plane and the planes through C-1(n), C-4(n), O-4(n) and O-4($n-1$).
[e] Angle at each glycosidic O-4: O-4($n+1$)–O-4(n)–O-4($n-1$).
[f] Deviation of O-4 atoms from the least-squares plane through the seven O-4 atoms.
[g] Intradimeric hydrogen bonds between O-2, O-3 of glucose unit n (β-CD # 1) and of glucose unit m (β-CD # 2).
[h] Values for twofold disordered O-66_1 with the occupancy factors 0.5 for both sites A and B.
[i] Bold numbers are the values of β-CD # 2.

in Table 2. All C-6–O-6 bonds are directed 'away' from the β-CD cavities and are hydrogen bonded with neighboring water sites and O-6–H groups (Figs. 3, 5 and 6), as shown by torsion angles C-4–C-5–C-6–O-6 and O-5–C-5–C-6–O-6 in the ranges 50.3–61.7° and −60.0 to −71.3°, respectively (Table 2). Except for O-66A_1 that points 'toward' the cavity and hydrogen bonds to water sites W-9, W-21, W-23 and O-2Z_1, Fig. 6. The corresponding torsion angles are 179.0 and 59.0°, Table 2.

Two β-CD molecules form a dimer where their O-2–H, O-3–H groups are engaged in intermolecular O-2(*n*)_1/O-3(*n*)_1···O-2(*m*)_2/O-3(*m*)_2 hydrogen bonds with O···O distances 2.79–3.16 Å, except O22_1···O26_2 (3.42 Å), O-22_1···O-35_2 (3.31 Å), and O-23_1···O-25_2 (3.27 Å), Table 2. Such feature has been observed frequently in crystal structures of β-CD.[3] Since the X-ray data at room temperature of the present structure did not permit the H-atom positions to be determined, the detailed hydrogen bonding in the β-CD dimer could not be obtained. However, the recent study of β-CD–1,12-dodecanedioic acid inclusion complex using synchrotron high-resolution data (0.65 Å) at 100 K[16] allowed the accurate location of H-atoms of the β-CD O–H groups to be verified. The results showed that only O-3–H groups of a β-CD monomer are involved in the intermolecular hydrogen bonds at the O-2-, O-3-sides of the β-CD dimer.

3.2. Inclusion geometry of BA molecules

Fig. 4 shows that both BA molecules are placed in the central cavities of β-CD molecules. The two aromatic ring centers of BA are shifted from the O-4-plane centers to the O-6-sides of β-CD by approx 1.0 Å (distance *d*), see Figs. 2 and 3. The two aromatic ring planes are inclined 52° with respect to the O-4 plane (angle τ) and make an angle of 13° with respect to each other. The BA molecules protrude with their COOH groups at the β-CD O-6-sides and are maintained in positions by hydrogen bonding to the surrounding O-6–H groups and water molecules, Figs. 2–4. They are almost in the same environment as their COOH groups are coordinated via six O–H···O hydrogen bonds (O···O distances 2.58–3.35 Å), except for O-2Z_1 that is additionally hydrogen bonded to O-66A_1, Fig. 4. The inclusion geometry of BA in the present structure agrees with those proposed by previous studies[5,8] as the

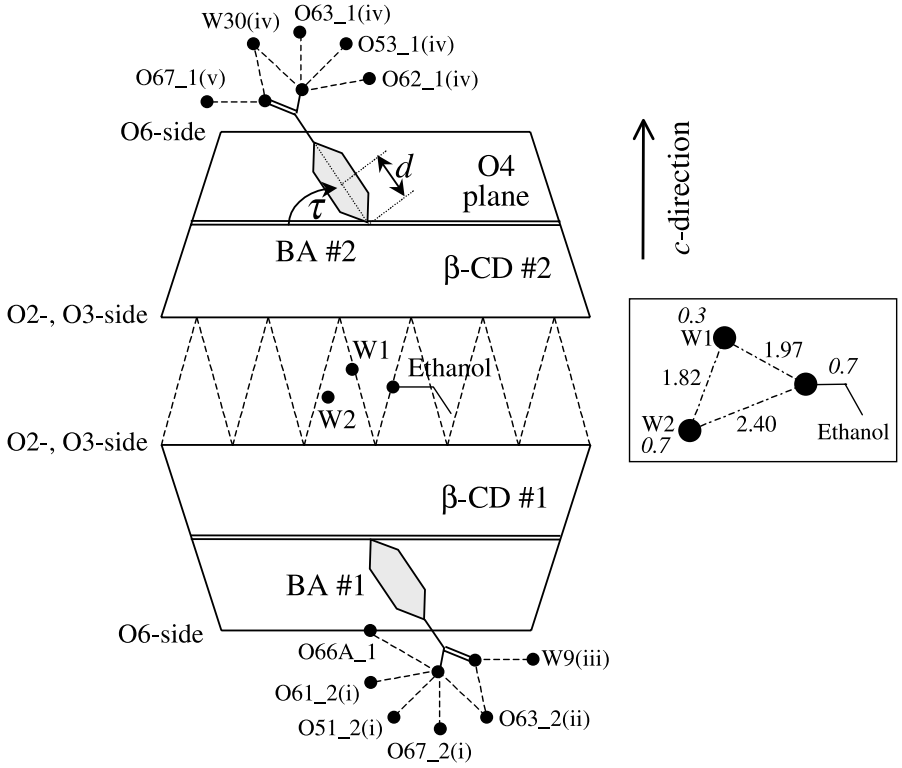


Fig. 4. Schematic presentation of the inclusion geometry of the BA molecules in the β-CD cavities. Aromatic rings of the two BA molecules are represented with gray hexagons. *d* defined as the center-to-center distance of the BA aromatic ring to β-CD O-4 plane. Angle τ showing inclination of the BA molecular axis (dotted line) with respect to the glycosidic O-4 plane (double line). Filled circles indicate oxygen atoms and dashed lines intermolecular O–H···O hydrogen bonds. Dashed lines linked between the β-CD monomer show O-2(*m*)_1/O-3(*m*)_1···O-2(*n*)_2/O-3(*n*)_2 hydrogen bonds in the β-CD dimer. Connection of water sites W-1, W-2, and ethanol molecule is depicted in the framed area. Symmetry operations: (i) $x, y, z-1$; (ii) $x+1, y, z-1$; (iii) $x+1, y-1, z-1$; (iv) $x, y, z+1$; (v) $x-1, y, z+1$.

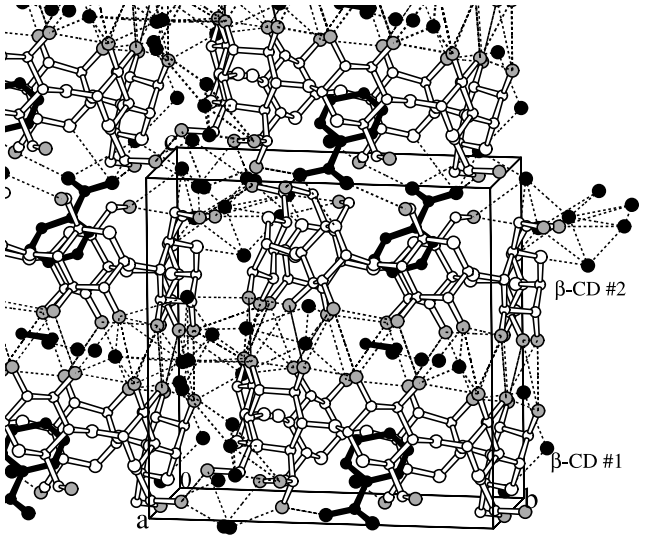


Fig. 5. Crystal packing of the 2β-CD·2BA·0.7C_2H_5OH·20.65H_2O inclusion complex in channel mode that is stabilized by O-2(m)_1/O-3(m)_1···O-2(n)_2/O-3(n)_2 (tail-to-tail), O-6(m)_1···O_W···O-6(n)_2 (head-to-head) hydrogen bonds (dashed lines) between β-CD #1 and #2. O-2_{CD}, O-3_{CD}, O-6_{CD} and O_W. are represented with gray and black spheres, respectively. The BA molecules are black and H-atoms not shown. Drawn with program MOLSCRIPT.[23]

BA COOH group is directed to the narrower rim of the cone.

It is worth comparing the present structure with the β-CD complexes with BA derivatives crystallized in the triclinic space group $P1$.[17–19] Although the host β-CD molecules have the same dimeric structures as found in the present structure, the inclusion geometries are different. In the complex of 4-*t*-butylbenzoic acid,[17] the host–guest ratio is 2:2 and the two guest molecules are in different environments in the β-CD cavities. The aromatic ring of one guest molecule is included in the β-CD cavity while that of the other one is in the channel of the β-CD dimer. In the complex of 3,5-dimethylbenzoic acid,[18] the guest molecules are extensively disordered. For the guest sites in the β-CD cavities, their COOH groups point to the O-2-, O-3-side while some are in the channel of the β-CD dimer. In the complex of acetylsalicylic acid–salicylic acid,[19] the aromatic rings of two acetylsalicylic acid molecules are embedded in each β-CD cavity and the salicylic acid is in the channel of the β-CD dimer.

3.3. Disordered water molecules

Water molecules (20.65) are distributed over 30 positions (W-3–W-7, W-12, W-18–W-20, W-22, W-23, W-30 are fully occupied while the others have occupancies in the ranges 0.25–0.75) in the interstices between β-CD macrocycles, except for the water sites W-1, W-2 that are in the channel of the β-CD dimer, Figs. 2, 4 and 5. Water site W-1 is too close to the ethanol OH group (1.97 Å) and water site W-2 (1.82 Å), i.e., they are not in hydrogen bonding distance indicating that water site W-1 cannot be occupied simultaneously with water site W-2 and ethanol (their occupancies sum up to one). The W-2–ethanol distance 2.40 Å accounts for hydrogen bond interaction showing that water site W-2 and ethanol may coexist (Fig. 4). In addition, short interatomic distances among water sites W-9–W-10 (1.22 Å), W-14–W-15 (1.63 Å), W-24–W-26 (1.57–1.74 Å), and W-27–W-29 (1.07–1.64 Å) suggest that the water sites in each cluster are not coexistent. Water sites play an important role in stabilizing the crystal structure as they contribute to hydrogen bonding as bridges, e.g., at O-2-, O-3-side: O-21_1···W-19···O-36_2, O-22_1···W-16···O-35_2, O-32_1···W-26···O-25_2, O-23_1···W-3···O-25_2; at O-6-side: O-61_1···W-18···O66_2, O-61_1···W-7···O-64_2, O-62_1···W-11···W-23···O-62_2, O-65_1···W-21···O-65_2, O-66A_1···W-9···O-65_2 (Fig. 6). The hydrogen-bonding network in the present structure is complicated since there are many partially occupied water sites (Fig. 6).

3.4. Crystal packing

The β-CD molecules are stacked along the crystallographic c-axis, in the alternative head-to-head and tail-to-tail channel mode[20] as frequently observed in the β-CD crystal structures[3] (Fig. 5). The glycosidic O-4 planes of the β-CD #1, 2 are almost parallel. They are slightly inclined approx 11.1, 9.8° to the ab-plane, and make an angle of 2.8° with respect to each other. The distance from O-4-plane center of β-CD #1 to #2 is 7.17 Å. Both O-4-plane centers are not lined vertically but are shifted 2.89 and 1.33 Å in a- and b-directions, respectively. The molecular arrangement is stabilized at one end of β-CD (in the same column) by intermolecular O-2(m)_1/O-3(m)_1···O-2(n)_2/O-3(n)_2 hydrogen bonds (O···O distances 2.79–3.42 Å), Figs. 2 and 5, Table 2. At the other end, the O-6–H groups are not directly hydrogen bonded to the O-6–H groups of adjacent β-CD but linked by one or two bridging water molecules, e.g., O-61_1···W-18···O-66_2, O-62_1···W-11···W-23···O-62_2, O-65_1···W-21···W-7···O-64_2. In addition, a number of O_{CD}···O_{CD}, O_{CD}···O_W···O_{CD}, O_{CD}···O_W···O_W···O_{CD} hydrogen bonds found between neighboring β-CD columns contribute to the stability of the crystal structure (Figs. 5 and 6).

In comparison with the complexes of BA derivatives, the complex of 4-*t*-butylbenzoic acid[17] and of 3,5-dimethylbenzoic acid[18] show similar packing patterns as the present crystal structure. This contrasts with the complex of acetylsalicylic acid–salicylic acid[19] in which β-CD dimers are stacked in layers like bricks in a wall.

After the β-CD–BA inclusion complex has been characterized both in solution and gas phase by various

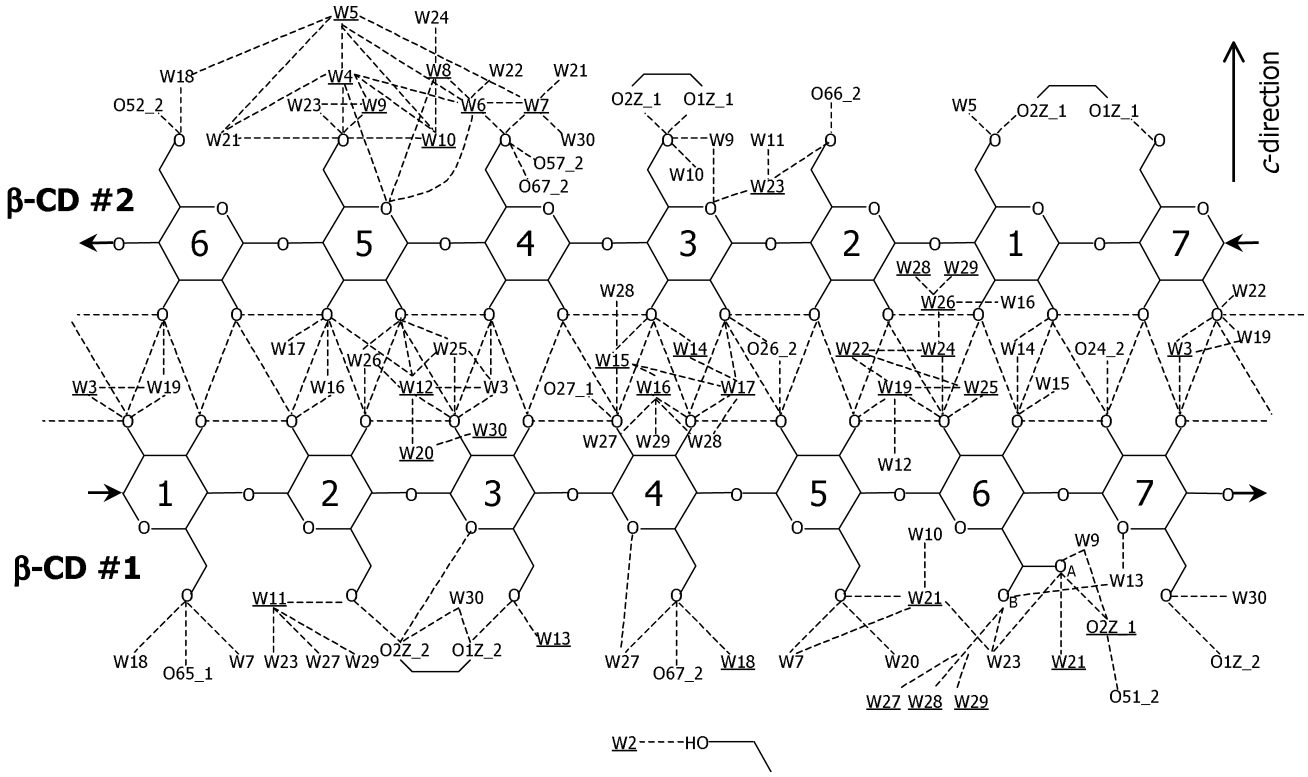


Fig. 6. O–H···O hydrogen bonds (dashed lines) in the 2β-CD·2BA·0.7C_2H_5OH·20.65H_2O inclusion complex with O···O distance within 3.5 Å. Underlined atomic names indicate atoms in the general position x, y, z; the others are in symmetry related positions. Arrows show connection of glucose units in β-CD.

techniques since 25 years ago,[21] its structural evidence in crystalline state is finally reported in the present paper. The previous results forecasted a 1:1 host–guest stoichiometry and orientation of BA with its aromatic ring parallel to the CD molecular axis and the COOH group points to the CD O-6-side. This agrees well with the crystallographic results. However, X-ray analysis reveals deeper details of BA inclusion geometry. The stoichiometry is 2:2 and the BA aromatic ring is in fact, not parallel but slanted to the β-CD molecular axis. BA is maintained in position by hydrogen bonds to the surrounding O-6–H groups and water molecules.

The present finding is not consistent with the inclusion complexes of β-CD with other BA derivatives both in terms of stoichiometry and inclusion geometry as mentioned above. Since the functional groups attached to the aromatic ring have different hydrogen bonding donor/acceptor functionality and bulkiness, they are oriented differently in the β-CD cavity to be energetically stable. Therefore, a general direction for predicting the authentic CD inclusion complexes is not possible and these complexes needed to be investigated case by case.

Supplementary material

Crystallographic data (excluding structure factors) have been deposited with the Cambridge Crystallographic Data Center as supplementary publication No. CSD-191347. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html or from The Director, CCDC, 12 Union Road, Cambridge, CB2 1EZ, UK (Tel.: +44-1223-336-408; fax: +44-1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

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