The Structure of the Cyclodextrin Complex. III. The Crystal Structure of the α-Cyclodextrin–Sodium Benzenesulfonate Complex

Kazuaki HARATA

Research Institute for Polymers and Textiles, Sawatari-4, Kanagawa-ku, Yokohama 221

(Received December 25, 1975)

The crystal structure of the α-cyclodextrin–sodium benzenesulfonate complex, which has a channel-type structure, was determined by X-ray analysis. The crystals were orthorhombic with the space group of $P2_12_12$, cell dimensions of $a=21.832(3)$, $b=16.529(2)$, and $c=8.356(1)$ Å, and $Z=2$. The structure was determined on the basis of 2894 diffractometer data and refined by the block-diagonal least-squares methods to the final R-value of 0.069. The benzenesulfonate anion is arranged in the channel which is formed by the stack of α-cyclodextrin rings along the c axis. The benzene ring is located in the cavity, while the sulfonato group is hydrogen-bonded to the primary hydroxyl groups of the adjacent α-cyclodextrin molecule. The space outside the channel is filled with water molecules and sodium ions, and the hydrogen-bonding network is formed. The energy of the complex formation was calculated for two possible structures of the 1 : 1 complex in an aqueous solution.

α-Cyclodextrin(α-CDx) forms a number of crystalline adducts with a variety of "guest" molecules.[1] Several types of crystal structures have been investigated by the X-ray method.[2-9] The cage-type structure[2-6] is formed when the "guest" molecule is sufficiently small to be enclosed in the cavity, both sides of which are blocked by adjacent α-CDx molecules. In the case of the *p*-iodoaniline complex,[7] the "guest" molecule is too large to be enclosed in the interior of the cavity; as a result, the amino group protrudes from an open end of the cavity.

In the channel-type structure,[8,9] the α-CDx molecules are stacked along two-fold axes to form endless channels and the "guest" molecules in the channels are hydrogen-bonded to the primary hydroxyl groups of α-CDx. A long molecule as well as a small molecule can be included in the channel. In the potassium acetate complex,[8] the acetate anion is so small that the two water molecules are located in the empty space of the cavity. In the Methyl Orange complex,[9] the "guest" molecule is twice as long as the cavity. Therefore, the "guest" molecule extends through two α-CDx rings. Sodium benzenesulfonate(BS) also forms an α-CDx complex with a channel-type structure. The benzenesulfonate anion is a part of the Methyl Orange anion, and it consists of hydrophobic and hydrophilic groups. It is of interest to know which group is included in the cavity, and whether or not the hydrophilic group forms hydrogen bonds with primary hydroxyl groups. In this paper we will present the crystal and molecular structure of the α-cyclodextrin–sodium benzenesulfonate (1 : 1) complex. The energy of the complex formation in an aqueous solution was also calculated in order to investigate the binding force of the complex.

TABLE 1. CRYSTAL DATA

$C_{36}H_{60}O_{30}\cdot C_6H_5O_3SNa\cdot 10H_2O$,		Orthorhombic
Molecular weight		1333.2
Cell dimensions	a	21.832(3) Å
	b	16.529(2)
	c	8.356(1)
Cell volume	V	3015.3 Å^3
Space group		$P2_12_12$
	Z	2
Density	D_m	1.47 g·cm^{-3}
	D_x	1.47

Experimental

Crystals which are colorless prisms elongated along the c axis were obtained by letting stand an aqueous solution containing α-CDx and BS with 1 : 1 molar ratio. The

TABLE 2. THE FINAL ATOMIC PARAMETERS ($\times 10^4$)

The anisotropic thermal factors are of the form: $\exp[-(B_{11}h^2+B_{22}k^2+B_{33}l^2+B_{12}hk+B_{23}kl+B_{31}lh)]$.

	x	y	z	B_{11}	B_{22}	B_{33}	B_{12}	B_{23}	B_{31}
C(1,G1)	1533(3)	2428(4)	3405(8)	8(1)	20(2)	77(10)	-6(3)	9(9)	1(6)
C(2,G1)	1269(3)	2821(4)	4882(8)	9(1)	22(2)	66(10)	-4(3)	-8(9)	-4(6)
C(3,G1)	595(3)	2557(4)	5051(9)	10(1)	22(2)	59(9)	3(3)	-5(8)	6(6)
C(4,G1)	252(3)	2770(4)	3518(8)	8(1)	18(2)	49(9)	-5(3)	3(8)	0(6)
C(5,G1)	564(3)	2389(4)	2070(8)	9(1)	22(2)	57(9)	-3(3)	8(9)	5(6)
C(6,G1)	284(3)	2644(4)	490(8)	14(2)	32(3)	56(10)	5(4)	-8(10)	4(7)
O(2,G1)	1618(2)	2621(3)	6265(6)	11(1)	34(2)	67(7)	2(3)	-15(7)	-20(5)
O(3,G1)	313(2)	2963(3)	6364(6)	11(1)	39(2)	54(7)	10(3)	-35(7)	-3(5)
O(4,G1)	-348(2)	2434(3)	3681(6)	6(1)	18(2)	73(7)	2(2)	14(6)	2(4)
O(5,G1)	1204(2)	2642(3)	2023(6)	9(1)	24(2)	58(7)	0(2)	18(6)	2(4)
O(6,G1)	538(2)	2213(3)	-816(6)	18(1)	39(2)	48(7)	2(3)	-14(8)	6(5)
C(1,G2)	2492(3)	-528(4)	3310(9)	8(1)	25(3)	91(11)	4(3)	29(10)	12(7)
C(2,G2)	2659(3)	-6(5)	4730(8)	10(1)	22(2)	80(10)	6(3)	9(10)	1(6)
C(3,G2)	2177(3)	644(4)	4950(9)	11(1)	23(3)	76(11)	3(3)	5(10)	-7(7)
C(4,G2)	2099(3)	1136(4)	3410(9)	10(1)	21(2)	69(11)	7(3)	8(9)	11(6)
C(5,G2)	2003(3)	576(4)	1954(9)	15(2)	22(3)	65(10)	10(3)	-4(9)	11(7)
C(6,G2)	2051(4)	1050(5)	373(9)	28(2)	23(3)	71(12)	14(4)	0(10)	-11(8)
O(2,G2)	2727(2)	-493(3)	6137(6)	17(1)	31(2)	84(8)	7(3)	35(7)	-18(6)
O(3,G2)	2332(2)	1196(3)	6201(6)	15(1)	27(2)	65(7)	5(3)	-11(7)	-11(5)
O(4,G2)	1541(2)	1584(3)	3639(6)	8(1)	19(2)	77(7)	3(2)	3(6)	8(5)
O(5,G2)	2468(2)	-32(3)	1909(5)	15(1)	19(2)	69(7)	8(3)	13(7)	29(5)
O(6,G2)	1903(4)	530(4)	-912(7)	46(3)	50(3)	77(9)	9(5)	-9(10)	6(9)
C(1,G3)	863(3)	-2936(4)	3359(9)	10(1)	20(2)	90(11)	4(3)	-4(9)	9(7)
C(2,G3)	1291(3)	-2872(4)	4788(9)	11(1)	28(3)	63(10)	4(3)	18(9)	0(6)
C(3,G3)	1507(3)	-2005(4)	4991(9)	10(1)	26(3)	60(10)	3(3)	21(9)	-4(7)
C(4,G3)	1811(3)	-1718(4)	3442(8)	10(1)	25(3)	41(9)	-3(3)	9(8)	-1(6)
C(5,G3)	1375(3)	-1840(4)	2014(8)	11(1)	25(3)	41(9)	1(3)	-9(9)	14(6)
C(6,G3)	1693(4)	-1663(5)	424(9)	19(2)	38(4)	56(11)	-13(4)	4(10)	14(7)
O(2,G3)	981(2)	-3156(3)	6205(6)	11(1)	39(2)	83(8)	-5(3)	59(8)	-1(5)
O(3,G3)	1934(2)	-1925(3)	6273(6)	12(1)	40(2)	51(7)	-9(3)	15(7)	-15(5)
O(4,G3)	1907(2)	-866(3)	3638(6)	8(1)	21(2)	74(7)	2(2)	3(6)	15(5)
O(5,G3)	1176(2)	-2676(3)	1958(6)	12(1)	22(2)	56(7)	-1(2)	-11(6)	8(5)
O(6,G3)	1281(3)	-1717(4)	-864(7)	22(1)	49(3)	74(9)	-8(4)	-8(9)	-10(6)
C(1,BS)	0(-)	0(-)	7088(12)	13(2)	31(4)	64(14)	10(6)	0(-)	0(-)
C(2,BS)	547(4)	-94(8)	6290(11)	10(2)	85(6)	128(14)	3(6)	-11(19)	-6(9)
C(3,BS)	538(4)	-87(9)	4619(11)	17(2)	91(7)	121(15)	9(7)	32(20)	37(10)
C(4,BS)	0(-)	0(-)	3797(14)	26(3)	44(5)	90(18)	12(8)	0(-)	0(-)
S(BS)	0(-)	0(-)	9206(3)	26(1)	26(1)	72(4)	7(2)	0(-)	0(-)
O(1,BS)	606(8)	-261(9)	9687(14)	49(5)	68(8)	63(17)	58(11)	-23(20)	-70(17)
O(2,BS)	-504(8)	-593(8)	9663(17)	57(6)	35(6)	152(25)	-40(10)	-7(20)	67(21)
O(3,BS)	-178(6)	832(7)	9708(14)	27(3)	33(5)	110(18)	7(6)	-22(17)	-6(13)
Na	1472(3)	4867(4)	9344(8)	22(2)	31(3)	108(10)	10(3)	-3(9)	16(7)
O(W1)	1170(6)	4885(7)	2255(14)	92(5)	86(6)	425(27)	38(11)	9(25)	-287(21)
O(W2)	0(-)	5000(-)	3634(17)	145(11)	56(6)	241(27)	35(16)	0(-)	0(-)
O(W3)	1377(3)	6306(4)	9145(8)	41(2)	40(3)	129(11)	31(4)	-7(10)	-26(9)
O(W4)	1712(3)	3383(4)	9290(7)	26(2)	45(3)	114(10)	-38(4)	4(10)	18(7)
O(W5)	1130(7)	4796(9)	9326(19)	31(4)	60(8)	22(29)	-9(10)	-37(28)	11(20)
O(W6)	303(7)	4571(9)	6846(22)	32(4)	53(7)	304(37)	16(9)	-1(31)	-45(24)
O(W6')	832(7)	4645(9)	7149(21)	28(4)	47(7)	271(34)	5(8)	-56(27)	-61(20)

	x	y	z	B		x	y	z	B
H(1,G1)	2029	2592	3166	1.8	H(6A,G2)	2518	1279	224	2.9
H(2,G1)	1299	3483	4838	1.9	H(6B,G2)	1733	1563	393	2.9
H(3,G1)	558	1912	5325	1.8	H(1,G3)	698	-3554	3101	1.9
H(4,G1)	218	3427	3360	1.7	H(2,G3)	1682	-3279	4631	2.5
H(5,G1)	529	1732	2207	2.2	H(3,G3)	1124	-1616	5353	2.1
H(6A,G1)	364	3293	310	2.2	H(4,G3)	2250	-2005	3216	2.1
H(6B,G1)	-209	2550	525	2.2	H(5,G3)	977	-1443	2166	2.1
H(1,G2)	2807	-1033	3056	2.4	H(6A,G3)	2067	-2080	250	2.8
H(2,G2)	3105	282	4580	2.4	H(6B,G3)	1888	-1047	465	2.8
H(3,G2)	1754	357	5329	1.8	H(2,BS)	969	-186	6964	4.4
H(4,G2)	2488	1540	3206	2.1	H(3,BS)	963	-145	3936	5.3
H(5,G2)	1560	287	2073	2.5	H(4,BS)	0	0	2485	4.2

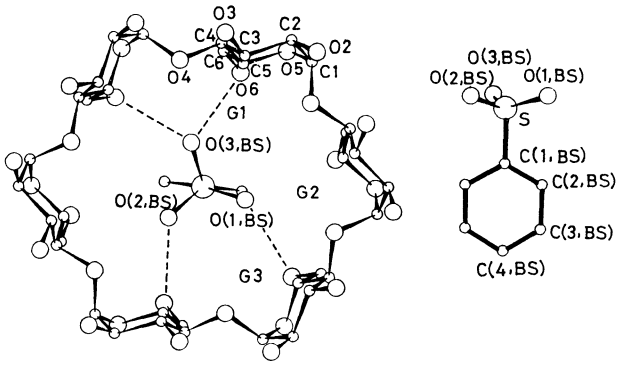

Fig. 1. The structure and numbering scheme of the complex. Dashed lines indicate hydrogen bonds between the sulfonato group and α-cyclodextrin.

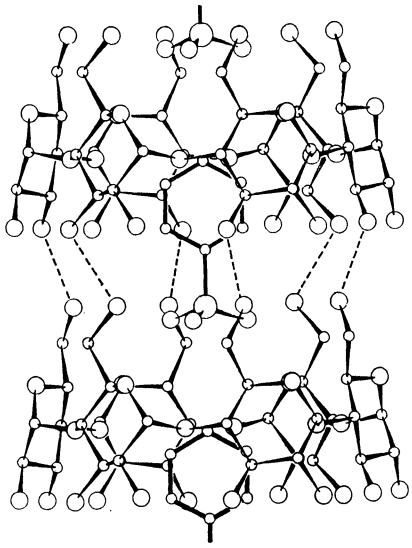

Fig. 2. The stacking feature of α-cyclodextrin rings. Dashed lines indicate O(3)---O(6) hydrogen bonds.

density was measured by the flotation method in a mixture of chloroform and dioxane. The crystal data are given in Table 1. The intensity data were collected on a Rigaku automated four-circle diffractometer using graphite monochromatized Cu$K\alpha$ radiation and the 2θ-ω scan technique. The crystal was enclosed in a quartz capillary with a small amount of water, since the crystal decomposes in air. 3064 independent reflections were obtained up to 150° in 2θ by using a specimen with dimensions of $0.4\times0.4\times0.4$ mm. 170 reflections with $|F_o|<3\sigma(F)$ were considered to be unobserved; $\sigma(F)$ is the standard deviation estimated according to the counting statistics. No corrections were made for absorption and extinction.

Determination and Refinement of the Structure

The structure was elucidated by assuming the same type of framework as that in the channel-type crystal. The positions and orientations of glucose residues were refined by the rigid-body least-squares method. A Fourier map calculated by using phases based on the glucose residues revealed the locations of BS and water molecules. The occupancy of 0.5 was assigned to the sodium ion, since there are only two BS molecules in the unit cell in spite of there being four equivalent positions. The BS anion was found on the two-fold axis with the statistical disorder of the sulfonato group. A water molecule (O(W5)) was found near the position of the sodium ion. The Na---O(W5) distance, however, is unreasonably short (Fig. 5). Therefore, O(W5) seems to occupy the position when the sodium ion is absent, having the average population of 0.5. O(W6) and O(W6′) are statistically disordered, and the distances of O(W5)---O(W6′) and O(W6)---O(W6′) are also absurdly short. These short distances can reasonably be explained by assigning 0.5 to the respective occupancies of O(W6) and O(W6′). The refinement of atomic parameters was carried out by the block-diagonal least-squares method. The positions of the hydrogen atoms attached to the carbon atoms were calculated and included in the structure factor calculation; the isotropic thermal factors used were equal to those of the carbon atoms to which the hydrogen atoms are bonded. The final R-value was 0.069. The quantity minimized was $\Sigma w(|F_o|-|F_c|)^2$, with $w=1.0$ for all reflections used. The atomic scattering factors were taken from "International Tables for X-ray Crystallography."[10] The atomic parameters are given in Table 2. The observed and calculated structure factors are listed in Table 3*.

Table 4. Bond distances (l/Å), angles (ϕ/°), and conformation angles (ϕ/°) in α-cyclodextrin
An asterisk (*) indicates the atom in the adjacent glucose residue.

	G1	G2	G3	AVERAGE
C(1)-C(2)	1.527(9)	1.512(10)	1.520(10)	1.520
C(1)-O(5)	1.429(8)	1.429(8)	1.422(8)	1.427
C(1)-O(4*)	1.408(8)	1.421(8)	1.422(8)	1.417
C(2)-C(3)	1.541(9)	1.514(10)	1.518(10)	1.524
C(2)-O(2)	1.424(8)	1.433(9)	1.442(9)	1.433
C(3)-C(4)	1.525(9)	1.531(10)	1.529(9)	1.528
C(3)-O(3)	1.425(8)	1.428(9)	1.426(8)	1.426
C(4)-C(5)	1.524(9)	1.543(10)	1.541(9)	1.536
C(4)-O(4)	1.430(7)	1.438(8)	1.432(8)	1.433
C(5)-C(6)	1.515(10)	1.539(11)	1.527(10)	1.527
C(5)-O(5)	1.458(8)	1.430(9)	1.448(8)	1.445
C(6)-O(6)	1.416(9)	1.412(11)	1.406(10)	1.411

	G1	G2	G3	AVERAGE
C(2)-C(1)-O(5)	109.3(5)	108.9(5)	109.3(5)	109.2
C(2)-C(1)-O(4*)	107.5(5)	106.8(5)	107.2(5)	107.2
O(5)-C(1)-O(4*)	110.3(5)	110.5(5)	111.1(5)	110.6
C(1)-C(2)-C(3)	110.0(5)	109.4(6)	110.2(6)	109.9
C(1)-C(2)-O(2)	109.8(5)	110.4(6)	109.5(6)	109.9
C(3)-C(2)-O(2)	111.9(5)	111.8(6)	111.3(6)	111.7
C(2)-C(3)-C(4)	109.0(5)	110.6(6)	109.5(6)	109.7
C(2)-C(3)-O(3)	110.4(5)	112.0(6)	112.0(6)	111.5
C(4)-C(3)-O(3)	109.1(5)	107.6(5)	108.9(5)	108.5
C(3)-C(4)-C(5)	110.6(5)	111.0(6)	110.3(5)	110.6
C(3)-C(4)-O(4)	106.2(5)	104.8(5)	105.8(5)	105.6
C(5)-C(4)-O(4)	109.0(5)	107.3(5)	107.9(5)	108.1
C(4)-C(5)-C(6)	113.4(5)	111.2(6)	111.5(6)	112.0
C(4)-C(5)-O(5)	109.3(5)	110.2(6)	109.6(5)	109.7
C(6)-C(5)-O(5)	106.5(5)	106.6(6)	106.9(5)	106.7
C(5)-C(6)-O(6)	111.9(6)	109.1(6)	111.2(6)	110.7
C(1)-O(5)-C(5)	114.8(5)	114.0(5)	113.9(5)	114.2
C(1)-O(4*)-C(4*)	118.3(5)	119.7(5)	118.7(5)	118.9

	G1	G2	G3	AVERAGE
C(1)-C(2)-C(3)-C(4)	-56.3	-55.5	-56.3	-56.0
C(2)-C(3)-C(4)-C(5)	55.8	50.8	54.1	53.6
C(3)-C(4)-C(5)-O(5)	-55.7	-50.8	-54.4	-53.6
C(4)-C(5)-O(5)-C(1)	59.2	58.5	59.6	59.1
C(5)-O(5)-C(1)-C(2)	-60.1	-63.6	-61.7	-61.8
O(5)-C(1)-C(2)-C(3)	57.3	60.4	59.0	58.9
O(4*)-C(1)-C(2)-O(2)	61.1	64.5	61.1	62.2
O(2)-C(2)-C(3)-O(3)	61.5	61.9	61.3	61.6
O(3)-C(3)-C(4)-O(4)	-65.4	-71.0	-66.7	-67.7
O(4)-C(4)-C(5)-C(6)	69.2	77.2	72.4	72.9
O(5)-C(5)-C(6)-O(6)	66.3	65.3	64.7	65.4
C(4)-C(5)-C(6)-O(6)	-173.5	-174.5	-175.5	-174.5
C(2)-C(1)-O(4*)-C(4*)	-129.0	-130.7	-129.6	-129.8
O(5)-C(1)-O(4*)-C(4*)	111.9	111.0	112.0	111.6
C(1)-O(4*)-C(4*)-C(3*)	127.6	130.3	130.5	129.5
C(1)-O(4*)-C(4*)-C(5*)	-114.3	-111.7	-110.2	-112.1

* Table 3 is kept as Document at the office of The Chemical Society of Japan. (Document No. 7626).

Description and Discussion of the Structure

The structure and numbering scheme of the complex are shown in Fig. 1. Bond distances, angles, and conformation angles in α-CDx(Table 4) are in good agreement with those of the Methyl Orange complex[9] and the potassium acetate complex.[8] The bond distances and angles of the BS anion are given in Table 5; they are in agreement with those observed in Methyl Orange.[11] The benzene ring has a good planarity (Table 6).

The geometrical data of the complex are shown in Table 7. The macro-cyclic conformation of the α-CDx ring is nearly the same as that in the Methyl Orange complex. The C(6)–O(6) bonds show a *gauche-trans* conformation, as is commonly observed in channel-type crystal. In the α-CDx cavity, the benzene ring is located at the same position as in the *p*-iodoaniline complex. The O(4, G3)---C(3, BS)

Table 5. Bond distances and angles in benzenesulfonate anion

(1) Bond distance (l/Å)			
C(1, BS)-C(2, BS)	1.376(14)	S(BS)-O(1, BS)	1.449(15)
C(2, BS)-C(3, BS)	1.396(15)	S(BS)-O(2, BS)	1.522(16)
C(3, BS)-C(4, BS)	1.369(16)	S(BS)-O(3, BS)	1.488(12)
C(1, BS)-S(BS)	1.770(10)		
(2) Bond angles (ϕ/°)			
C (1, BS) - C (2, BS) - C (3, BS)	118.2(9)		
C (2, BS) - C (3, BS) - C (4, BS)	120.9(10)		
C (2, BS) - C (1, BS) - S (BS)	119.0(8)		
C (2-BS) - C (1, BS) - C (2, BS)*	122.0(9)		
C (3, BS) - C (4, BS) - C (3, BS)*	119.7(11)		
C (1, BS) - S (BS) - O (1, BS)	106.1(8)		
C (1, BS) - S (BS) - O (2, BS)	104.5(8)		
C (1, BS) - S (BS) - O (3, BS)	106.4(6)		
O (1, BS) - S (BS) - O (2, BS)	113.6(9)		
O (1, BS) - S (BS) - O (3, BS)	115.7(8)		
O (2, BS) - S (BS) - O (3, BS)	109.5(8)		

Table 6. Least-squares planes and deviations of atoms (d/Å)

An asterisk(*) indicates the symmetry related atom by the two-fold axis.

(1) Six O(4) atoms			
$0.0000X + 0.0000Y + 1.0000Z = 3.0517$			
O (4, G1)	0.024	O (4, G1)*	0.024
O (4, G2)	−0.012	O (4, G2)*	−0.012
O (4, G3)	−0.013	O (4, G3)*	−0.013
(2) Benzenesulfonate anion			
$0.1246X + 0.9922Y + 0.0000Z = 0.0000$			
C (1, BS)	−0.000	S (BS)	−0.000
C (2, BS)	−0.005	C (2, BS)*	0.005
C (3, BS)	0.005	C (3, BS)*	−0.005
C (4, BS)	0.000		

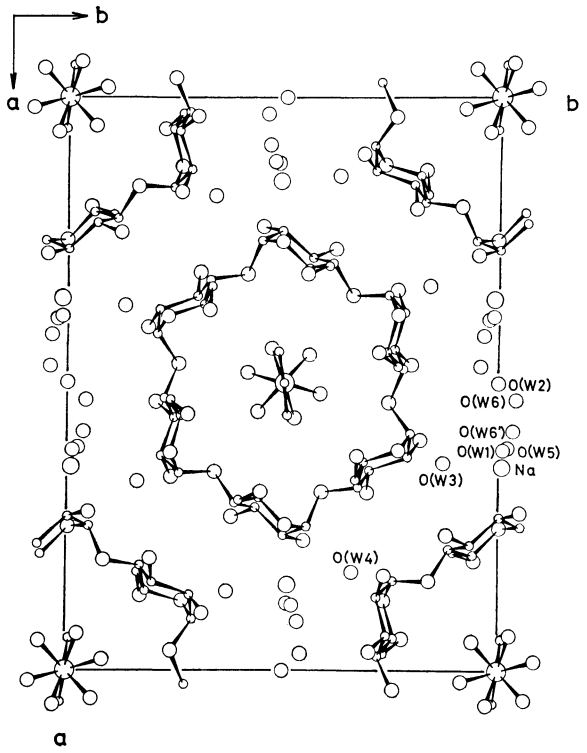

Fig. 3. The projection of the crystal structure along the c axis.

Table 7. Geometrical data for the complex (l/Å)

An asterisk(*) indicates the symmetry related atom by the two-fold axis.

(1) Diagonal distances of the cavity.				
O (4, G1)---O (4, G1)*	8.185		C (3, G1)---C (3, G1)*	8.837
O (4, G2)---O (4, G2)*	8.523		C (3, G2)---C (3, G2)*	9.739
O (4, G3)---O (4, G3)*	8.805		C (3, G3)---C (3, G3)*	9.337
O (6, G1)---O (6, G1)*	7.680		C (5, G1)---C (5, G1)*	8.269
O (6, G2)---O (6, G2)*	8.493		C (5, G2)---C (5, G2)*	8.950
O (6, G3)---O (6, G3)*	7.965		C (5, G3)---C (5, G3)*	8.544
(2) Distances between benzenesulfonate anion and α-CDx.				
C (3, G2)---C (3, BS)	3.785		O (6, G1)---O (3, BS)	2.800
C (3, G2)---C (2, BS)	3.925		O (6, G3)---O (1, BS)	2.857
C (3, G3)---C (2, BS)	3.943		O (6, G1)*---O (2, BS)	2.708
C (3, G3)---C (3, BS)	3.823		O (6, G3)*---O (3, BS)	2.857
O (4, G3)---O (2, BS)	3.919		O (6, G2)*---O (2, BS)	3.093
O (4, G3)---C (3, BS)	3.356		O (6, G2)---O (1, BS)	3.158

Table 8. Intermolecular distances (l/Å) less than 3.0 Å
Letters in the parentheses indicate the symmetry operation.

O (2, G1) -O (W4)		2.83	O (3, G3) -O (6, G3)	(b)	2.81
O (3, G1) -O (W6)		2.69	Na -O (W1)	(b)	2.52
O (W1) -O (W2)		2.81	O (6, G1) -O (3, BS)	(c)	2.80
O (W3) -O (W5)		2.56	O (6, G3) -O (3, BS)	(c)	2.86
Na -O (W3)		2.39	O (5, G1) -O (W4)	(c)	2.82
Na -O (W6′)		2.34	O (W1) -O (W5)	(c)	2.45
Na -O (W4)		2.51	O (5, G3) -O (W3)	(d)	2.92
O (W2) -O (W6)		2.85	O (W6) -O (W6′)	(e)	2.81
O (W5) -O (W6)		2.77	O (6, G1) -O (2, BS)	(f)	2.71
O (W4) -O (W5)		2.66	O (6, G3) -O (3, BS)	(f)	2.86
O (2, G3) -O (W3)	(a)	2.75	O (2, G2) -O (W1)	(g)	2.83
O (3, G1) -O (6, G1)	(b)	2.71	O (5, G2) -Na	(g)	2.55
O (3, G2) -O (6, G2)	(b)	2.81			

Symmetry code	Symmetry operator		
	x,	y,	z
a	x,	$-1+y$,	z
b	x,	y,	$1+z$
c	x,	y,	$-1+z$
d	x,	$-1+y$,	$-1+z$
e	$-x$,	$1-y$,	z
f	$-x$,	$-y$,	$-1+z$
g	$1/2-x$	$-1/2+y$,	$1-z$

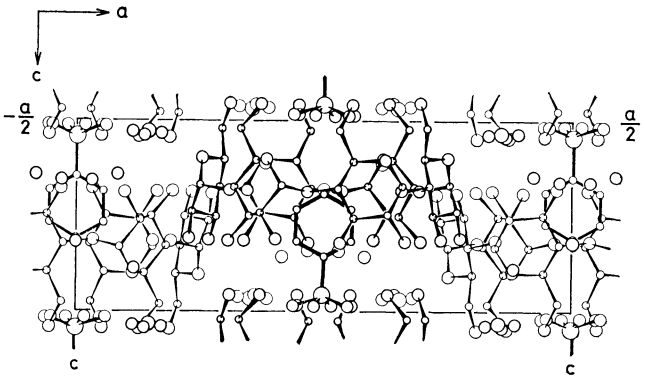

Fig. 4. The projection of the crystal structure along the b axis.

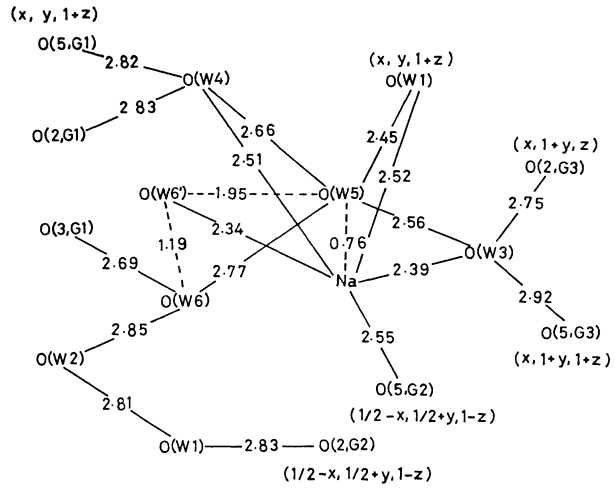

Fig. 5. The hydrogen-bonding scheme in the crystal. Dashed lines indicate the distances between the disordered atoms.

distance is 3.356 Å, while the corresponding distances are 3.25 and 3.35 Å in the *p*-iodoaniline complex.[7] The sulfonato group protrudes from the O(2), O(3) side of the cavity and is hydrogen-bonded to the primary hydroxyl groups of the adjacent α-CDx molecule; the distances of O(6, Gl)---O(3, BS), O(6, G3)---O(1, BS), O(6, Gl)*---O(2, BS), and O(6, G3)*---O(3, BS) are in the range of 2.708—2.857 Å, while the distances between the sulfonato group and the G2 residue are greater than 3.0 Å. In the water complex[4] and the 1-propanol complex,[6] which have cage-type structures, the hydrogen bonds are observed between the primary hydroxyl groups and the included "guest" molecule, and the hydroxyl groups involved in the hydrogen bonds have a *gauche-trans* conformation.

α-CDx molecules are stacked along the c axis with six O(3)---O(6) hydrogen bonds forming endless channels (Fig. 2). The BS anions are arranged in the channel, while the sodium cations are located outside the channel at nearly the same positions as those found in the other channel-type crystals (Figs. 3 and 4). The sodium ion is surrounded by O(W1), O(W3), O(W4), O(W6′), and O(5, G2), with Na---O distances between 2.34 and 2.55 Å. In the potassium acetate complex, a distorted octahedral coordination has been observed. In the Methyl Orange complex, five oxygen atoms are found around the sodium ion, but four of the Na---O distances are 2.86—2.90 Å, showing weak coordination. The hydrogen-bonding scheme is shown in Fig. 5. Intermolecular distances less than 3.0 Å are given in Table 8. The space outside the channel is filled with water molecules and sodium ions. Water molecules and hydroxyl groups

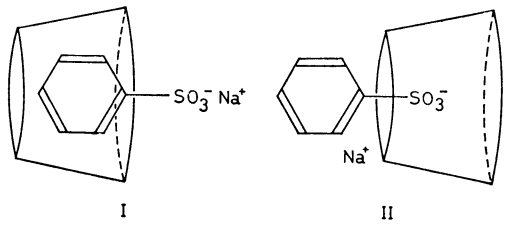

Fig. 6. Two possible structures of the 1 : 1 complex in an aqueous solution.

form the hydrogen-bonding network; O(W4) is hydrogen-bonded to O(2) and O(5) atoms of the Gl residue; O(W3) forms hydrogen bonds with O(2, G3) and O(5, G3); O(W6) and O(Wl) are also hydrogen-bonded to O(3, Gl) and O(2, G2) respectively. These four water molecules are linked to O(W5) by hydrogen bonds.

Formation Energy of the Complex in Aqueous Solution

In the crystalline state, the BS anion extends through two α-CDx rings. In an aqueous solution, the two structures shown in Fig. 6 are possible for the 1 : 1 complex. In the complex I, the hydrophobic benzene ring is located in the α-CDx cavity, while the hydrophilic sulfonato group is hydrogen-bonded to primary hydroxyl groups in the complex II. It has been emphasized[12,13] that the effect of solvation is important as well as the interaction between α-CDx and the "guest" molecule. The formation energy of the complex was calculated for these two complexes by using structural data in order to examine which structure is stable in an aqueous solution. That is, the heat of formation was estimated for the equilibrium in an aqueous solution;

$$\alpha\text{-CDx} + \text{BS} \rightleftharpoons \text{complex}. \tag{1}$$

The complex formation energy is expressed as follows:

$$\Delta E = E(\text{complex}) - E(\alpha\text{-CDx}) - E(\text{BS}) \tag{2}$$

$$E(\alpha\text{-CDx}) = E^{\text{sol}}(\alpha\text{-CDx}) \tag{2a}$$

$$E(\text{BS}) = E^{\text{sol}}(\text{BS}) \tag{2b}$$

$$E(\text{complex}) = E^{\text{sol}}(\text{complex}) + E^{\text{int}}(\text{complex}) \tag{2c}$$

E^{sol} is the solvation energy of the solute, and E^{int} is the interaction energy between α-CDx and the "guest" molecule. The solvation energy was calculated according to Halicioğlu and Sinanoğlu:[14,15]

$$E^{\text{sol}} = E^{\text{sol}}_{\text{cav}} + E^{\text{sol}}_{\text{e.s.}} + E^{\text{sol}}_{\text{vdw}} \tag{3}$$

where $E^{\text{sol}}_{\text{cav}}$, $E^{\text{sol}}_{\text{e.s.}}$, and $E^{\text{sol}}_{\text{vdw}}$ are the cavity term, the electrostatic term, and the van der Waals term respectively. The procedure of evaluating each term will be explained below.

Cavity Term. $E^{\text{sol}}_{\text{cav}}$ is the energy needed to create a cavity which will accomodate a solute molecule, A:

$$E^{\text{sol}}_{\text{cav}} = 4.836\kappa^{\text{e}}(\phi_{1\text{A}})V_{\text{A}}^{2/3}\gamma\left(1-\frac{\partial \ln\gamma}{\partial \ln T}-\frac{2}{3}\frac{1}{v}\frac{\partial v}{\partial T}T\right) \tag{4}$$

$$\kappa^{\text{e}}(\phi_{1\text{A}}) = 1 + \phi_{1\text{A}}^{2/3}(\kappa^{\text{e}}(1)-1) \tag{4a}$$

$$\phi_{1\text{A}} = V_1/V_{\text{A}} \tag{4b}$$

where V_1 and V_{A} are the molecular volumes of water and the solute A respectively, γ and $\kappa^{\text{e}}(1)$ are the surface tension and the cavity factor for water respectively. The values of $\kappa^{\text{e}}(1)$, γ, $\partial\ln\gamma/\partial\ln T$, and $1/v\ \partial v/\partial T$ were taken from Halicioğlu and Sinanoğlu.[14] The V_{A} of α-CDx was estimated from the X-ray data, and the volumes of a water molecule and the BS anion were estimated by means of the van der Waals volumes of atoms and molecules.[16] The parameters used are given in Table 9.

Table 9. Parameters for the calculation of solvation energy

Refractive index	n	1.333
Dielectric constant	ε	77.46
Surface tension	γ	72.00 dyn cm^{-3}
	$\frac{\partial \ln \gamma}{\partial \ln T}$	−0.157
Expansion coefficient	$\frac{1}{v}\frac{\partial v}{\partial T}$	0.257×10^{-3} K^{-1}
Cavity coefficient	κ^{e} (1)	1.277
Molecular volume		
Water		20.6 Å^3
BS anion		129.7
α-CDx		1330.0
Complex I		1381.0
Complex II		1376.0

Electrostatic Term. The electrostatic interaction energy between solute and solvent molecules was calculated by means of the following equation:

$$E^{\text{sol}}_{\text{e.s.}} = -\frac{D_{\text{d}}}{2}\sum_i \frac{\mu^2_{\text{A}i}}{V_{\text{A}i}(1-\bar{\alpha}_{\text{A}i}/r^3_{\text{A}i})} \tag{5}$$

$$D_{\text{d}} = \frac{2(\varepsilon-1)}{2\varepsilon+1} \tag{5a}$$

$$r^3_{\text{A}i} = \frac{3V_{\text{A}i}}{4\pi} \tag{5b}$$

where $\mu_{\text{A}i}$, $\bar{\alpha}_{\text{A}i}$, and $V_{\text{A}i}$ are the dipole moment, the average polarizability, and the volume of the i-th group in the solute molecule A, respectively, and where ε is the dielectric constant of the solvent. $\bar{\alpha}_{\text{A}i}$ was estimated as a sum of the atomic polarizabilities of the constituent atoms, while $V_{\text{A}i}$ was calculated by means of the van der Waals volumes of atoms and groups. Only the hydroxyl groups of α-CDx and the sulfonato group of BS were included in the calculation because these groups are in contact with solvent molecules. The effect of the sodium cation was neglected. The parameters are given in Table 10.

Table 10. Dipole moments, average polarizabilities, and volumes of C-SO_3^- and C-OH groups

	μ(Debye)	$\bar{\alpha}$	V
C-SO_3^-	5.07[a]	6.23 Å^3	51.3 Å^3
C-OH	1.69[b]	1.94	20.5

a) The value of the BS anion calculated on the basis of atomic charges. b) The value of methanol.

van der Waals Term. The van der Waals energy of solute-solvent interaction was expressed as follows:

$$E_{vdw}^{sol} = B_{1A}U_{1A} \tag{6}$$

$$B_{1A} = 1 - \frac{3}{4}D_r \tag{6a}$$

$$D_r = \frac{n^2-1}{n^2+1} \tag{6b}$$

where n is the refractive index of the solvent and U_{1A} the potential function used to express van der Waals interaction energy. Halicioğlu and Sinanoğlu[14] used the semi-empirical Kihara potential, but we have used the Lennard-Jones potential because it has an analytical form which is convenient for numerical calculation. We assumed that the molecules of the solute or solvent are rigid spheres. The energy of the interaction between a water molecule and the i-th atom in the solute molecule A (Fig. 7) is expressed as follows:

$$U_{1Ai} = \frac{\pi}{V_A}\int_{-l_i^0}^{l_i^0}\left[\frac{a_{1Ai}}{r_{1Ai}^{12}} - \frac{c_{1Ai}}{r_{1Ai}^{6}}\right](l_i^{02}-l^2)\mathrm{d}l \tag{6c}$$

$$l_i^0 = R_A - l_{Ai} \tag{6d}$$

$$r_{1Ai} \approx R - l \tag{6e}$$

where a_{1Ai} and c_{1Ai} are coefficients of the potential function. By integrating from R_0 to ∞, the total van der Waals energy is found to be:

$$U_{1A} = \frac{4\pi}{V_1}\int_{R_0}^{\infty}(\sum_i U_{1Ai})R^2\mathrm{d}R \tag{6f}$$

where $R_0 = R_A + R_1$. This integral equation was solved numerically.

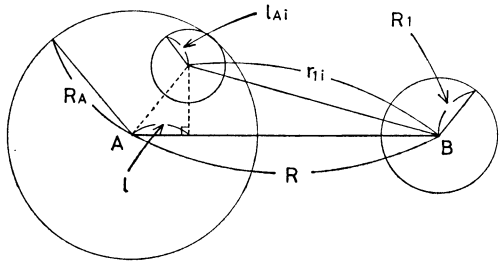

Fig. 7. A schematic drawing of interaction between water(B) and i-th atom in the solute(A).

α-CDx-"Guest" Interaction Term. In the calculation of the α-CDx-"guest" interaction energy, the non-bonded interaction betwwn non-hydrogen atoms was taken into account:

$$E^{int} = E_{e.s.}^{int} + E_{vdw}^{int} \tag{7}$$

$$E_{e.s.}^{int} = \sum_{i,j}\frac{q_iq_j}{\varepsilon r_{ij}} \tag{7a}$$

$$E_{vdw}^{int} = (1-K)\sum_{i,j}\left[\frac{a_{ij}}{r_{ij}^{12}} - \frac{c_{ij}}{r_{ij}^{6}}\right] \tag{7b}$$

$$K = \frac{3}{2}\left(\frac{n^2-1}{n^2+1}\right) \tag{7c}$$

where q_i and q_j are the atomic charges of the i-th and j-th atoms respectively. The atomic charges of the glucose residues and the BS anion were calculated by the CNDO/2 MO method[17] (Table 11). The charges of the C–H and O–H groups were used as those of the carbon and oxygen atoms respectively.

Table 11. Atomic charges

Glucose residue					
C (1)	0.24	C (2)	0.11	C (3)	0.11
C (4)	0.14	C (5)	0.14	C (6)	0.14
O (2)	−0.11	O (3)	−0.12	O (4)	−0.25
O (5)	−0.25	O (6)	−0.11		
BS anion					
C (1)	0.03	C (2)	0.01	C (3)	−0.03
C (4)	−0.04	S	0.52	O (1)	−0.49
O (2)	−0.49	O (3)	−0.49		

Coefficients of Potential Function. The coefficients of a_{ij} and c_{ij} were calculated by means of the following equation:[18]

$$c_{ij} = \frac{3e\hbar\alpha_i\alpha_j}{2m[(\alpha_i/N_i)^{1/2}+(\alpha_j/N_j)^{1/2}]} \tag{8}$$

$$a_{ij} = c_{ij}(r_{0i}+r_{0j})^6 \tag{8a}$$

where α_i and α_j are the atomic polarizabilities of the i-th and j-th atoms respectively, N_i and N_j are the numbers of electrons in the outer subshell, e and m are the charge and mass of the electron respectively, $\hbar$ is the Plank constant, and r_{0i} and r_{0j} are the van der Waals radii.[16] The values of α, N, and r_0 are given in Table 12, while a_{ij} and c_{ij} are listed in Table 13.

Table 12. Parameters for van der Waals potential function

Atom	N	r_0	α
C	4	1.70 Å	0.93 Å
O (Hydroxyl)	6	1.52	0.59
O (Ether)	6	1.52	0.64
O (Carbonyl)	6	1.52	0.84
S	6	1.80	3.09

Table 13. Coefficients for van der Waals potential function

		$a\times10^5$ mol/(kcal Å^{12})	$c\times10^2$ mol/(kcal Å^6)
C	C	4.948	3.203
C	O (H)[a]	2.745	2.463
C	O (E)[b]	2.930	2.628
C	O (C)[c]	3.632	3.258
C	S	15.73	8.555
O (H)	O (H)	1.565	1.982
O (H)	O (E)	1.663	2.107
O (H)	O (C)	2.032	2.574
O (H)	S	8.456	6.314
O (E)	O (E)	1.768	2.240
O (E)	O (C)	2.163	2.740
O (E)	S	9.058	6.764
O (C)	O (C)	2.658	3.368
O (C)	S	11.37	8.491
S	S	51.72	23.76

a) Oxygen atom in a hydroxyl group. b) Oxygen atom in ether. c) Oxygen atom in a carboxyl group.

Atomic Polarizability. The atomic polarizabilities of carbon and oxygen atoms were taken from Ketelaar.[19] For the sulfur atom, it was calculated by the following equation:[20]

$$\alpha = \frac{4}{9a_0}\sum_i (\bar{r}^2)^2 \tag{9}$$

$$(\bar{r}^2) = \left[\frac{n_i^*}{2(Z-S_i)}\right]^2 (2n_i^*+1)(2n_i^*+2)a_0^2 \tag{9a}$$

where n_i^* and $Z-S_i$ are the effective quantum number and the effective nuclear charge respectively, and where a_0 is the Bohr radius. In the case of the chlorine atom, the calculated atomic polarizability was twice the observed value; $\alpha_{calcd}=4.57$ and $\alpha_{obsd}=2.28$ Å^3. Therefore, the factor of 0.5 was multiplied to the calculated value for the sulfur atom.

Results and Discussion

The results are given in Table 14. The calculated formation energy of the complex I is larger by 8.74 kcal M^{-1} than that of the complex II, indicating that the inclusion of the hydrophobic group gives a more stable complex. The major part of the energy difference is $\Delta E^{sol}_{e.s.}$ of 7.06 kcal M^{-1}; this may be ascribed to the fact that the $E^{sol}_{e.s.}$ term is greatly reduced when the sulfonato group is included in the α-CDx cavity. The interaction energy between α-CDx and BS is larger in the complex I than in the complex II.

The α-CDx-BS interaction may involve the electrostatic, van der Waals, and hydrogen-bonding contacts. The van der Waals force between α-CDx and BS is an important component of the binding force. However, the contribution of the elcetrostatic interaction to the stability of the complex is small, since the interior of the α-CDx cavity is a relatively non-polar environment compared with the water environment. The effects of hydrogen bonds may also be small. In the complex II, the sulfonato group forms hydrogen bonds with primary hydroxyl groups of α-CDx, but it is also hydrogen-bonded to water molecules in the uncomplexed state.

TABLE 14. CALCULATED ENERGY FOR THE COMPLEX FORMATION (× mol/kcal)

(1) Solvation energy

	E^{sol}_{cav}	$E^{sol}_{e.s.}$	E^{sol}_{vdw}	E^{sol}
BS	22.22	−7.06	−0.65	14.52
α-CDx	98.71	−28.68	−5.36	64.67
Complex I	101.77	−35.63	−5.40	60.03
Complex II	100.93	−28.68	−5.12	67.13

(2) Solvation effects on the complex formation

	ΔE^{sol}_{cav}	$\Delta E^{sol}_{e.v.}$	ΔE^{sol}_{vdw}	ΔE^{sol}
Complex I	−19.76	0.0	0.61	−19.15
Complex II	−20.00	7.06	0.89	−12.05

(3) Interaction energy between α-CDx and BS

	E^{int}_{vdw}	$E^{int}_{e.s.}$	E^{int}
Complex I	−4.59	−0.03	−4.62
Complex II	−2.92	−0.06	−2.98

(4) Total association energy

	E(α-CDx)	E(BS)	E(complex)	ΔE
Complex I	64.67	14.52	55.41	−23.78
Complex II	64.67	14.52	64.15	−15.04

The stability of the complex in solution is determined by the α-CDx-"guest" interaction energy and the solvation energy. It is noteworthy that the effect of solvation on the complex formation is remarkably large; the ΔE^{sol} values are −19.15 kcal M^{-1} in the complex I and −12.05 kcal M^{-1} in the complex II, while the α-CDx-BS interaction energies are −4.62 and −2.98 kcal M^{-1} in the complex I and the complex II respectively. This indicates that the stability of the complex is largely determined by the difference in the solvation energies between the complexed state and the uncomplexed state. The change of the solvation energy is mainly ascribed to the cavity term. The cavity energy is proportional to the surface area of the solute molecule, and the solvation energy decreases when the "guest" molecule is included in the cavity of α-CDx.

The author wishes to thank Dr. Hisashi Uedaira for supporting this study and for his useful discussions. The author also wishes to acknowledge the helpful discussions and critical comments on the manuscript of Professor Jiro Tanaka of Nagoya University. The computation was carried out on a HITAC 8450 computer in our laboratory.

References

1) J. A. Thoma and L. Stewart, "Starch: Chemistry and Technology," Vol. I, ed. by R. L. Whistler and E. F. Pashall, Academic Press, New York (1965), pp. 209—249.
2) R. K. McMullan, W. Saenger, J. Fayos, and D. Mootz, *Carbohyd. Res.*, **31**, 37 (1973).
3) R. K. McMullan, W. Saenger, J. Fayos, and D. Mootz, *Carbohyd. Res.*, **31**, 211 (1973).
4) P. C. Manor and W. Saenger, *J. Am. Chem. Soc.*, **96**, 3630 (1974).
5) W. Saenger and M. Noltemeyer, *Angew. Chem.*, **86**, 594 (1974).
6) W. Saenger, R. K. McMullan, J. Fayos, and D. Mootz, *Acta Crystallogr., B*, **30**, 2019 (1974).
7) K. Harata, *Bull. Chem. Soc. Jpn.*, **48**, 2409 (1975).
8) A. Hybl, R. E. Rundle, and D. E. Williams, *J. Am. Chem. Soc.*, **87**, 2779 (1965).
9) K. Harata, to be published. Part II of this series.
10) "International Tables for X-Ray Crystallography," Vol. III, Birmingham: Kynoch Press (1965), pp. 202—208.
11) A. W. Hanson, *Acta Crystallogr., B*, **29**, 454 (1973).
12) E. A. Lewis and L. D. Hansen, *J. Chem. Soc. Perkin Trans. 2*, **1973**, 2081.
13) D. W. Griffiths and M. L. Bender, "Advances in Catalysis," **23**, 209 (1973).
14) T. Halicioğlu and O. Sinanoğlu, *Ann. N. Y. Acad. Sci.*, **158**, 308 (1969).
15) O. Sinanoğlu, "Molecular Associations in Biology," ed. by B. Pullman, Academic Press, New York (1968), pp. 427—445.
16) A. Bondi, *J. Phys. Chem.*, **68**, 441 (1964).
17) J. A. Pople and D. L. Beveridge, "Approximate Molecular Orbital Theory," McGraw-Hill, New York (1970).
18) K. S. Pitzer, "Advances in Chemical Physics," Vol. II, ed. by I. Prigogine, Interscience Publishers, New York (1965), pp. 59—83.
19) J. Ketelaar, "Chemical Constitution," Elsevier Publishing Co., New York (1958), p. 91.
20) J. O. Hirschfelder, C. F. Curtis, and R. B. Bird, "Molecular Theory of Gases and Liquids," John Willy & Sons, New York (1954).