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Hydrogen bonding in the crystal structure of α,β-panose

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ABSTRACT

The crystal structure of panose, *O*-α-D-glucopyranosyl-(1→6)-*O*-α-D-glucopyranosyl-(1→4)-D-glucose, $C_{18}H_{32}O_{16}$, has been refined using low-temperature, 123 K, Cu*K*α X-ray data. Difference syntheses and least-squares refinement showed a 16% substitution of α-panose by the β anomer. All the hydrogen atoms were located on difference synthesis with the exception of one attached to the low occupancy (β) O-1″. The final *R*-factor was 0.036 for 2135 observed structure amplitudes. The molecular conformation is stabilized by two interresidue intramolecular hydrogen bonds. All the hydroxyls and glycosidic oxygen atoms are involved in the hydrogen bonding, which is a two-dimensional network formed from finite and infinite chains.

INTRODUCTION

The crystal structure of panose, *O*-α-D-glucopyranosyl-(1→6)-*O*-α-D-glucopyranosyl-(1→4)-D-glucose, was determined at room temperature using Cu*K*α radiation, with the hydrogen atoms approximately located on successive difference Fourier syntheses[1]. Our examination of the hydrogen bonding, based on these coordinates, revealed some unacceptably close nonbonded hydrogen to hydrogen distances, and no rational bonding scheme could be deduced. We have collected X-ray diffraction data at 123 K in order to resolve these problems, using a crystal kindly provided by Dr. S. Perez and Dr. A. Imberty of the Institut National de la Recherche Agronomique, Nantes, France. During the course of this refinement, it was observed that this crystal was a mixture of α and β epimers in the ratio 0.84:0.16. Crystallization of the anomeric mixture is not uncommon in di- and tri-saccharides[2].

EXPERIMENTAL

X-Ray diffraction data, given in Table I, were obtained on a CAD-4 diffractometer at 123 K using Ni-filtered Cu*K*α radiation. Coordinates of the oxygen and carbon atoms were taken from the previous room-temperature study[1], with the exception of those for O-1″. Coordinates for O-1″α, O-1″β, and for the hydrogen atoms, were determined from difference syntheses. A full-matrix, least-squares refinement was carried out using UPALS[3], with anisotropic thermal parameters for the carbon and oxygen atoms and fixed isotropic thermal parameters for the hydrogen atoms. The hydrogen atoms were assigned the isotropic temperature factors of the atoms to which

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TABLE I

Crystal data and structure determination and refinement data for panose at 123 K

Crystal data

$C_{18}H_{32}O_{16}$, mol. wt. 504.4, $P2_1$, $Z = 2$
Cell dimensions, $a = 9.6306(9)$ [9.662(3)]^a, $b = 8.4889(9)$ [8.505(3)],
$c = 12.894(1)$ [12.955(5)] Å, $\beta = 102.217(9)$ [102.4(1)]°
$V = 1030.3$ [1040] Å^3; $D_x = 1.626$ [1.612] g cm^{-3}, $D_o =$ [1.63] g cm^{-3}
$F000 = 536$

Structure determination and refinement data

Crystal dimensions, 0.10 × 0.33 × 0.10 mm^3
Radiation Cu$K\alpha$ ($\lambda = 1.5418$ Å), Ni filtered; $\mu_{CuK\alpha} = 12.62$ cm^{-1}
Absorption correction, max. 1.297 cm^{-1}, min. 1.113 cm^{-1}
2301 intensities measured on a CAD-4 diffractometer with ω-2θ scans;
2135 with $F_o > 2\sigma(F_o)$
2θ limits, $2° < 2\theta < 144°$; range of hkl, $0 < h < 11$, $0 < k < 10$, $-15 < l < 15$
413 parameters; refinement using UPALS[b], minimizing $w(k|F_o| - |F_c|)^2$, where $w = 1/\sigma^2(F)$
Final refinement values, $R(F) = 0.036$, $R_w(F) = 0.035$

[a] Values in square brackets are from ref. 1 (at 295 K). [b] Ref. 3.

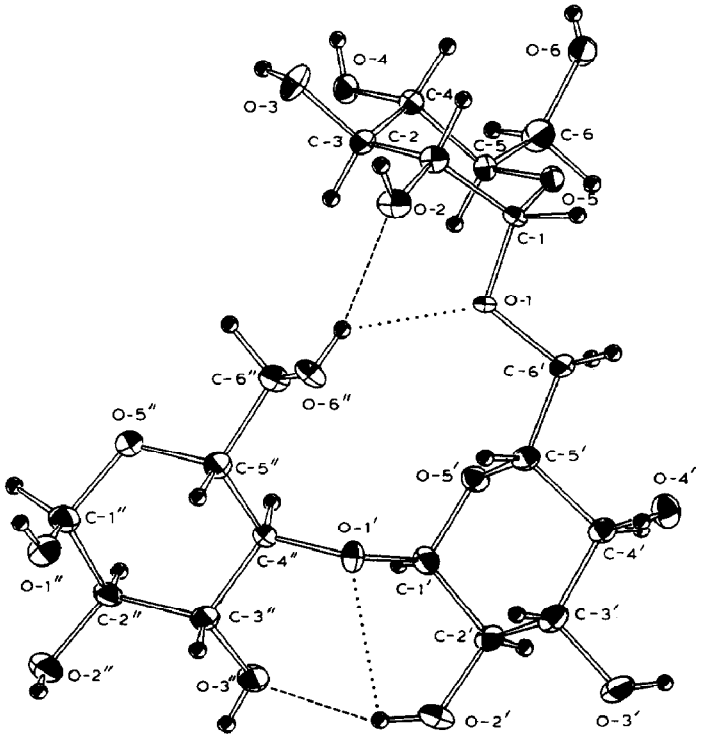


Fig. 1. Atomic notation and thermal ellipsoids (50% probability) for α-panose. Intramolecular hydrogen bonds are dashed (H---O < 2.2 Å) and dotted (H···O) > 2.2 Å. The nonstandard notation is that used in the original room-temperature analysis[1].

they are bonded. Occupancy parameters for O-1″α and O-1″β were refined and normalized to 0.84 and 0.16, respectively. The refinement data are given in Table I and the final atomic parameters in Table II. The atomic notation, thermal ellipsoids, and intramolecular hydrogen bonds are shown in Fig. 1*.

TABLE II

Atomic positional parameters and equivalent isotropic thermal parameters for panose at 123 K[a]

Atom	x/a	y/b	z/c	B_{eq} (Å^2)
O-1	2913(3) × 10^{-4}	9594(0) × 10^{-4}	6310(2) × 10^{-4}	104(6) × 10^{-2}
O-2	3099(3)	12465(5)	5422(2)	148(7)
O-3	1332(3)	14319(5)	6452(2)	179(8)
O-4	−328(3)	12512(5)	7703(2)	133(7)
O-5	433(3)	9598(5)	5806(2)	124(6)
O-6	−2376(3)	9702(6)	6126(3)	237(8)
C-1	1718(4)	10148(6)	5580(3)	118(9)
C-2	1739(4)	11954(6)	5577(3)	125(10)
C-3	1394(4)	12644(6)	6571(3)	132(10)
C-4	−1(4)	11954(6)	6728(3)	112(9)
C-5	147(4)	10166(6)	6788(3)	124(9)
C-6	−1179(5)	9336(7)	6956(4)	191(11)
O-1′	6724(3)	8678(5)	8575(2)	134(7)
O-2′	8091(3)	5855(5)	8997(2)	206(8)
O-3′	7282(3)	4245(5)	6986(3)	182(8)
O-4′	5042(3)	5646(5)	5441(2)	177(8)
O-5′	4530(3)	7495(5)	7917(2)	126(6)
C-1′	5867(4)	7339(6)	8625(3)	133(9)
C-2′	6664(4)	5866(6)	8369(3)	144(10)
C-3′	6650(4)	5700(6)	7192(3)	141(10)
C-4′	5130(4)	5875(6)	6552(3)	128(10)
C-5′	4594(4)	7508(6)	6808(3)	117(9)
C-6′	3141(4)	7921(6)	6183(3)	150(10)
O-1″α	8893(4)	13050(5)	10111(3)	165(9)
O-1″β	7603(19)	13847(30)	11107(21)	203(42)[b]
O-2″	9305(3)	11051(5)	11837(2)	173(7)
O-3″	8090(3)	8183(5)	10673(2)	201(8)
O-5″	6441(3)	12566(5)	9716(2)	152(7)
O-6″	5552(3)	11714(5)	7008(2)	163(7)
C-1″	7734(5)	12633(7)	10528(3)	167(10)
C-2″	8028(4)	11010(6)	11060(3)	136(10)
C-3″	8040(4)	9724(6)	10225(3)	142(10)
C-4″	6684(4)	9815(6)	9382(3)	120(9)
C-5″	6517(4)	11452(6)	8882(3)	138(10)
C-6″	5147(4)	11627(6)	8028(3)	152(10)
H-O-2	304(5) × 10^{-3}	1326(6) × 10^{-3}	496(4) × 10^{-3}	
H-O-3	116(7)	1472(9)	685(5)	
H-O-4	−102(6)	1307(7)	763(4)	

(contd.)

* Lists of anisotropic thermal parameters and observed and calculated structure amplitudes have been deposited with, and can be obtained from, Elsevier Science Publishers B.V., BBA Data Deposition, P. O. Box 1527, Amsterdam, The Netherlands. Reference should be made to No. BBA/DD/475/*Carbohydr. Res.*, 222 (1991) 47–55.

Atom	x/a	y/b	z/c	B_{eq} ($Å^2$)
H-O-6	−295(5)	1008(6)	613(4)	
H-O-2′	844(7)	660(8)	945(4)	
H-O-3′	667(4)	354(6)	692(3)	
H-O-4′	573(5)	610(6)	522(4)	
H-O-1″	888(7)	1384(9)	992(5)	
H-O-2″	997(6)	1111(9)	1166(4)	
H-O-3″	872(7)	791(8)	1128(5)	
H-O-6″	476(5)	1172(5)	663(3)	
H-C-1	171(4)	966(6)	475(3)	
H-C-2	97(4)	1230(6)	490(3)	
H-C-3	219(4)	1242(6)	716(3)	
H-C-4	−74(4)	1218(5)	603(3)	
H-C-5	89(5)	989(6)	743(3)	
H-C-6	−140(4)	964(6)	769(3)	
H′-C-6	−102(5)	808(7)	694(4)	
H-C-1′	561(3)	727(4)	933(2)	
H-C-2′	613(4)	500(5)	867(3)	
H-C-3′	720(4)	650(5)	699(3)	
H-C-4′	441(4)	505(5)	677(3)	
H-C-5′	519(4)	830(5)	668(3)	
H-C-6′	240(5)	727(7)	646(4)	
H′-C-6′	309(5)	770(6)	538(3)	
H-C-1″	719(7)	1351(9)	1117(6)	
H-C-2″	718(4)	1073(5)	1141(3)	
H-C-3″	898(4)	987(5)	985(3)	
H-C-4″	571(4)	970(5)	972(3)	
H-C-5″	756(5)	1178(6)	862(4)	
H-C-6″	457(4)	1267(5)	821(3)	
H′-C-6″	438(5)	1073(6)	828(3)	

[a] E.s.d. values given in parentheses refer to the least significant digit. $B_{eq} = 4/3\ (\Sigma_{ij} B_{ij} a_i a_j)$, calculated from the refined, anisotropic, thermal parameters. [b] Isotropic thermal parameter.

RESULTS AND DISCUSSION

Comparison with the room-temperature analysis. — As shown in Table I, there is a 1% reduction in unit cell volume at the lower temperature, with the greatest change in the *c* axis. For the nonhydrogen atoms, the greatest difference between the two analyses was 0.09 Å in the atomic coordinates. For the nonhydrogen bond lengths, the greatest and mean differences were 0.048 and 0.009 Å, respectively. For the linkage torsion angles, the greatest and mean differences were 3.9 and 2.2°, respectively. The values of the bond lengths, valence and torsion angles, and ring puckering parameters for the 123 K analysis are given in Table III. The α,β disorder of O-1″ is indicated in the room-temperature analysis by a larger isotropic equivalent temperature factor for O-1″ than for the other oxygen atoms.

The intramolecular hydrogen bond between O-2′ and O-3″ reported in the room-temperature analysis is observed, but the direction, O-2′-H– ––→O-3″, is the reverse of that previously deduced. Similarly, the direction of O-6″-H– ––→O-2 is the

TABLE III

Molecular geometry of panose at 123 K

Bond lengths (Å)		*Unprimed*	*Primed*	*Double-primed*	
C-1–C-2		1.533(6)	1.539(6)	1.539(6)	
C-2–C-3		1.509(6)	1.521(6)	1.535(6)	
C-3–C-4		1.518(6)	1.528(6)	1.514(6)	
C-4–C-5		1.525(6)	1.540(6)	1.526(6)	
C-5–C-6		1.514(7)	1.501(6)	1.537(6)	
C-1–O-1		1.405(5)	1.414(5)	1.383(6)	1.30(2)[a]
C-1–O-5		1.410(5)	1.418(5)	1.448(6)	
C-2–O-2		1.434(6)	1.440(6)	1.413(6)	
C-3–O-3		1.430(6)	1.426(6)	1.426(5)	
C-4–O-4		1.439(5)	1.429(5)	1.426(5)[b]	
C-5–O-5		1.435(5)	1.445(5)	1.446(5)	
C-6–O-6		1.431(6)	1.452(5)[c]	1.450(6)	
Bond angles (°)					
O-1–C-1–C-2		109.1(3)	108.7(3)	108.4(4)	119(1)[a]
O-1–C-1–O-5		112.4(3)	110.8(3)	111.8(4)	106(1)[a]
C-2–C-1–O-5		110.1(3)	111.4(3)	109.6(4)	
C-1–C-2–C-3		112.4(4)	112.9(4)	110.6(4)	
C-1–C-2–O-2		108.4(3)	110.2(3)	110.1(4)	
C-3–C-2–O-2		111.9(4)	111.5(4)	112.4(4)	
C-2–C-3–C-4		108.9(4)	109.6(4)	109.5(4)	
C-2–C-3–O-3		107.9(4)	110.6(4)	111.9(4)	
C-4–C-3–O-3		112.3(4)	112.4(4)	106.7(3)	
C-3–C-4–C-5		108.4(4)	107.4(3)	110.4(3)	
C-3–C-4–O-4		110.7(3)	112.1(4)	109.7(3)[b]	
C-5–C-4–O-4		108.6(3)	112.7(3)	108.9(3)[b]	
C-4–C-5–C-6		113.5(4)	114.4(4)	112.9(4)	
C-4–C-5–O-5		108.9(3)	107.0(3)	107.4(3)	
C-6–C-5–O-5		107.2(4)	107.6(3)	107.4(3)	
C-5–C-6–O-6		111.2(4)	108.3(3)[c]	107.4(4)	
C-1–O-5–C-5		114.4(3)	114.5(3)	113.1(3)	
Glycosidic angles (°)					
C-1–O-1–C-6′	112.0(3)				
C-1′–O-1′–C-4″	113.9(3)				
Selected torsion angles (°)					
Endocyclic					
O-5–C-1–C-2–C-3		51.6(5)	46.5(5)	53.9(5)	
C-1–C-2–C-3–C-4		−53.4(5)	−50.0(5)	−52.8(5)	
C-2–C-3–C-4–C-5		57.6(4)	58.9(4)	56.9(5)	
C-3–C-4–C-5–O-5		−61.3(4)	−65.0(4)	−61.1(4)	
C-4–C-5–O-5–C-1		62.6(4)	65.0(4)	64.1(4)	
C-5–O-5–C-1–C-2		−56.6(4)	−55.1(5)	−61.1(4)	
Exocyclic					
C-5–O-5–C-1–O-1		65.2(4)	66.0(4)	59.1(5)	169(1)[a]
O-1–C-1–C-2–O-2		52.0(4)	49.6(4)	56.5(5)	
O-2–C-2–C-3–O-3		62.2(4)	60.9(5)	65.5(5)	
O-3–C-3–C-4–O-4		−64.0(5)	−53.5(5)	−61.8(4)[b]	
O-4–C-4–C-5–C-6		59.2(5)	52.1(5)	60.3(5)[b]	
O-5–C-5–C-6–O-6		−61.9(5)	74.7(4)[c]	132.7(3)	
C-4–C-5–C-6–O-6		58.2(5)	−166.6(3)[c]	−109.2(4)	

(contd.)

Linkage bonds			
O-5–C-1–O-1–C-6′	70.8(4)	O-5′–C-1′–O-1′–C-4″	96.8(4)
C-1–O-1–C-6′–C-5′	167.3(3)	C-1′–O-1′–C-4″–C-5″	−134.8(4)
O-1–C-6′–C-5′–O-5′	74.7(4)	C-1′–O-1′–C-4″–C-3″	104.3(4)
C-6′–C-5′–O-5′–C-1′	−171.6(3)	O-1′–C-4″–C-5″–O-5″	178.5(3)

Cremer-Pople puckering parameters[8,9]

Ring	Q(Å)	θ (°)	φ (°)
Unprimed	0.58	7	262
Primed	0.59	13	270
Double-primed	0.59	5	299

[a] O-1″β. [b] O-4″ ≡ O-1′. [c] O-6′ ≡ O-1.

reverse of that previously reported. The unusual, partially eclipsed orientation of the primary hydroxymethyl group is attributed to the formation of this intramolecular interresidue hydrogen bond[1], which is a component of an infinite chain of hydrogen bonds. These hydrogen bonds are the major components of three- and four-center bonds, with minor components to the linkage oxgyens O-1′ and O-1, as shown in Figs. 1 and 2. Of the ten hydrogen-bond interactions reported in the room-temperature analysis[1], only three were confirmed at the lower temperature.

The hydrogen bonding. — The principal hydrogen bonding consists of infinite chains in the direction of the *b* axis, —→O-6″-H— —→O-2-H— —→O-6-H— —→O-6″-H— —→, intersecting at O-6″ with a finite chain which originates at O-3-H, as shown in Fig. 3. The finite chains are cross linked by the secondary components of three-center bonds

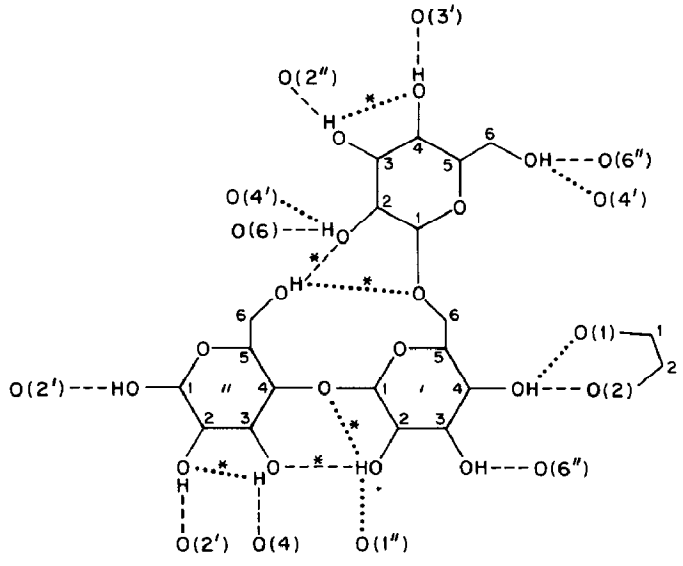


Fig. 2. Hydrogen-bond interactions in the α-panose molecule in the crystal structure at 123 K.

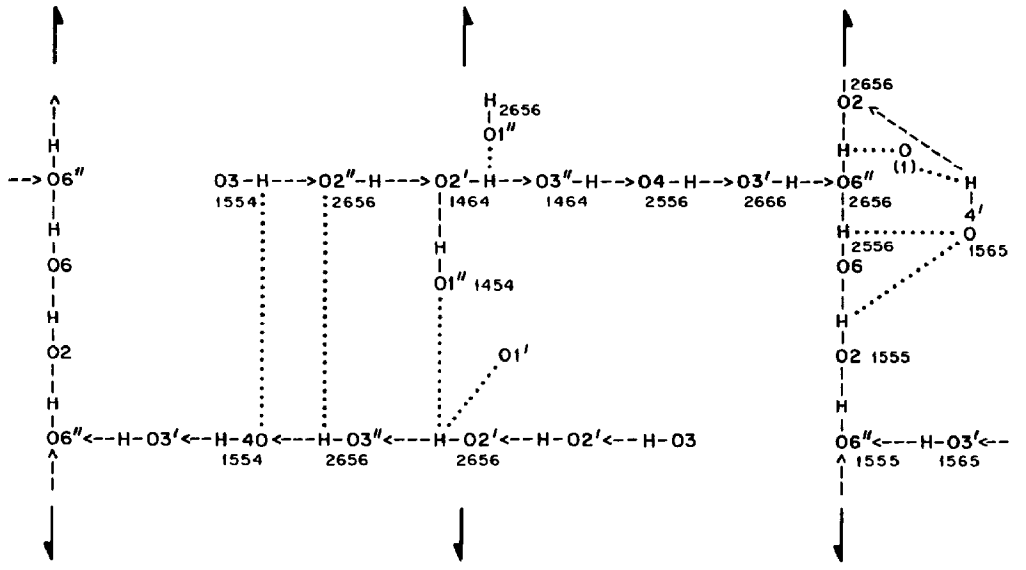


Fig. 3. Hydrogen-bonding scheme in the crystal structure of panose at 123 K. Symmetry code as in Table IV.

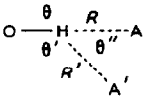
to form a network. Hydrogen O-4'-H forms a separate primary bond to O-2. The direction of the hydrogen bonding in the infinite chains is parallel to the direction of the polar axis, but the finite chains are antiparallel. All the glycosidic oxygens are included in the hydrogen bonding through the minor components of three- and four-center bonds. None of the ring oxygens are hydrogen-bond acceptors. There are four two-center bonds, six three-center bonds, and one four-center bond, the geometries of which are shown in Table IV. The bond lengths are consistent with those observed in other carbohydrate crystal structures[4]. The hydrogen atom attached to O-1″β, with 0.16 occupancy, could not be located. An intermolecular separation of O-1″β– –→0.5′ of 2.866 Å could correspond to a hydrogen bond.

This hydrogen bonding scheme is consistent with those observed in the mono- and di-saccharides, and in the more recent low-temperature studies of raffinose pentahydrate[5] and stachyose tetrahydrate[6]. The homo- and hetero-dromic cycles found in the cyclodextrin hydrates[7] are not found in this structure.

TABLE IV

The structural parameters of hydrogen bonds in panose at 123 K[a]

Bond type[b]	*Acceptor symmetry code*	R (Å)		θ (°)	Σθ (°)[c]
		H---O	*O---O*		
Two-center bonds					
O-4-H O-3′	1 465	1.79	2.723	160	
O-3′-H O-6″	1 545	1.77	2.720	167	
O-1″-H O-2′	1 565	1.89	2.801	156	
O-2″-H O-2′	2 757	1.98	2.915	168	
Three-center bonds					
O-2-H O-6	2 556	1.80	2.758	163	359
O-4′	1 565	2.74	2.772	116	
O-3-H O-2″	2 657	1.86	2.835	177	359
O-4	1 555	2.68	2.919	95	
O-6-H O-6″	1 455	2.16	3.010	148	360
O-4′	2 556	2.40	3.016	122	
O-4′-H O-2	2 646	1.82	2.772	165	351
O-1	2 646	2.84	3.400	119	
O-3″-H O-4	2 647	1.78	2.739	165	341
O-2″	1 555	2.79	2.970	91	
O-6″-H O-2	1 555	1.94	2.841	156	359
O-1	1 555	2.41	3.082	127	
Four-center bond					
O-1′	1 555	2.51	2.732	93	313
O-2′-H O-3″	1 555	2.07	2.935	146	
O-1″	2 747	2.74	2.801	130	360
O-1″β–H – – – O-5′ bond					
C-1″–O-1″β – – O-5′	2 657		2.866	96	
C-5′–O-5′ – – – O-1″β	2 647			128	
C-1′–O-5′ – – – O-1″β	2 647			113	

[a] O–H bond lengths are normalized to 0.97 Å. Symmetry code: The three digits give the unit cell translation in the *a*, *b*, and *c* directions with respect to 555; the first digit of the symmetry code specifies one of the following operations: 1, x, y, z; 2, $-x, 1/2 + y, -z$. [b] The following definitions are used[10]: two-center bonds, one oxygen only with H---O < 3.0 Å and angle O–H---O > 90°; three-center bonds, two oxygens with H---O < 3.0 Å, angles O–H---O > 90°, and $\Sigma\theta$ = 340–360°; four-center bond, three oxygens with H---O < 3.0 Å and angles O–H---O > 90°. [c] $\Sigma\theta = \theta + \theta' + \theta''$, as shown in 

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REFERENCES

1 A. Imberty and S. Perez, *Carbohydr. Res.*, 181 (1988) 41–55.
2 G. A. Jeffrey, *Acta Crystallogr., Sect. B*, 46 (1990) 89–103.
3 J. O. Lundgren, *UPALS, A Full Matrix Least Squares Refinement Program*, Institute of Chemistry, University of Uppsala, Sweden, 1978.
4 G. A. Jeffrey and J. Mitra, *Acta Crystallogr., Sect. B*, 39 (1983) 469–480.
5 G. A. Jeffrey and D. Huang, *Carbohydr. Res.*, 206 (1990) 173–182.
6 G. A. Jeffrey and D. Huang, *Carbohydr. Res.*, 210 (1991) 89–104.
7 K. Lindner and W. Saenger, *Acta Crystallogr., Sect. B*, 38 (1982) 203–210.
8 D. Cremer and J. A. Pople, *J. Am. Chem. Soc.*, 97 (1975) 1354–1358.
9 G. A. Jeffrey and J. H. Yates, *Carbohydr. Res.*, 74 (1979) 319–322.
10 G. A. Jeffrey, in W. Saenger (Ed.), *Nucleic Acids, Crystallographic and Structural Data II*, Vol. 1b of *Numerical Relationships in Science and Technology*, Landolt-Björnstein New Series, Group VII, Springer-Verlag, Berlin, 1989, Sect. 2.7, p. 314.