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The Crystal and Molecular Structure of 1-Naphthyl 2′,3′,4′,6′-Tetra-*O*-acetyl-β-D-glucopyranoside

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The crystal and molecular structure of 1-naphthyl 2′,3′,4′,6′-tetra-*O*-acetyl-β-D-glucopyranoside was determined by application of direct methods of structure analysis. For the crystal, of space group $P2_12_12_1$, with unit-cell parameters $a = 16{\cdot}423$ (2), $b = 21{\cdot}832$ (3), $c = 6{\cdot}876$ (2) Å and $Z = 4$ molecules per unit cell, intensity data were collected with a four-circle diffractometer and reduced to a unique set of 2018 reflections. Block-diagonal least-squares refinement with anisotropic temperature factors for nonhydrogen atoms and a weighting scheme based on counting statistics gave a final R value of 0·0677. In general, the bond lengths and valency angles are consistent with those of other carbohydrate structures, but the stereochemical relationships of the pyranose ring and glycosidic C—O bonds are not identical to those observed for alkyl-substituted β-D-glucopyranosides. The pyranose ring exhibits a minimally distorted chair configuration, and the structural data of the acetylated side chains provide precise stereochemical values for bond lengths and valency angles of ester functional groups. With no solvent molecules of crystallization, the crystal structure has no hydrogen bonds, in contrast to other carbohydrate structures.

Introduction

The aryl β-D-glucosides constitute a class of carbohydrate derivatives widely employed in enzymological and histochemical investigations. In comparison with the structural information available on β(alkyl)-substituted carbohydrates, there are, in general, considerably less data on the stereochemistry of aromatic substituted glycosides, and the mechanism of hydrolysis of aryl-substituted glycosides may be different from that of the corresponding alkyl derivatives. Since the stereochemical relationships of the glycosidic linkage of substituted glycosides undoubtedly account for their chemical properties in solution, more complete structural data are necessary for a thorough understanding of differences in the stereochemical properties and chemical reactivity of the hemiacetal group.

In the course of a series of structural and spectroscopic investigations of lysozyme-substrate interactions, we have synthesized a variety of aryl-substituted D-glucopyranoside derivatives with a β configuration at the anomeric C atom (Makinen, 1976). Since in the course of these studies the aryl-substituted derivatives were readily crystallized, the structure of the peracetylated 1-naphthyl β-D-glucopyranoside derivative was determined by application of direct methods of structural analysis. As a result of peracetylation of the glucose side-chain positions, the crystal packing is not subject to the usual hydrogen-bonding arrangements observed with most other carbohydrates, and significantly no hydrogen bonds are formed with the glycosidic or ring O atoms. In general, the crystal structures of carbohydrates exhibit a maximum number of hydrogen bonds, thought to produce perturbations on the stereochemistry of carbohydrates (Strahs, 1970). Therefore, comparison of this structure with those of other D-glucose derivatives should help to define the stereochemical properties of the glucose ring in the absence of such perturbing hydrogen-bonding networks.

Experimental

1-Naphthyl 2′,3′,4′,6′-tetra-*O*-acetyl-β-D-glucopyranoside (hereafter referred to as NGTA)‡ was synthesized by the method of Bretschneider & Beran (1949). Suitable crystals for diffraction studies were obtained by slow evaporation of saturated solutions of NGTA in dimethyl sulfoxide at ambient temperature. For data collection an elongated prismatic crystal, 0·1 × 0·15 × 0·5 mm, was mounted with the c axis (largest dimension) parallel to the φ axis of a computer-controlled Hilger & Watts four-circle diffractometer. The unit-cell dimensions were obtained from a least-squares refinement of the diffractometer-measured

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‡ Other abbreviations used in the text are: GlcNAc, *N*-acetyl-α-D-glucosamine; and GlcNAc-PN, *p*-nitrophenyl 2-acetamido-2-deoxy-β-D-glucopyranoside.

setting angles of fourteen general reflections. The unit-cell volume and empirical chemical formula of the carbohydrate suggested $4{\cdot}0 \pm 0{\cdot}3$ molecules in the unit cell according to the empirical correlation of Kempster & Lipson (1972). Therefore, only the approximate density of crystals was measured by flotation in solutions of ammonium sulfate of known density to confirm within approximate limits the number of molecules in the unit cell. Fundamental crystal properties are given in Table 1.

The intensities of 7743 reflections of the equivalent classes *hkl*, *hkl̄* were measured with Ni-filtered Cu K radiation to a $\sin\theta/\lambda$ limit of $0{\cdot}61$ Å^{-1}. Operation was in the $\omega/2\theta$ step-scan mode. The scan range of $0{\cdot}8°$ in θ was sampled in 40 equal steps with a counting time of 1 s per step. Integrated peak and background intensities were estimated by an ordinate-analysis method. Three monitor reflections, measured *ca* every four hours, showed no sign of radiation damage over the period of data collection. The data were corrected for Lorentz and polarization effects, and the empirical absorption correction of North, Phillips & Mathews (1968) was applied. The largest such correction factor was 1·037. The agreement between measurements of equivalent reflections was 0·051 (based on I). Of the 2891 unique reflections, 2018 with $I \geq 3S(I)$ were used in subsequent calculations, where $S(I)$ is the standard deviation of the measured intensity estimated as $S(I) = (N_{\text{background}} + N_{\text{peak}})^{1/2}$.

Table 1. *Crystal data*

1-Naphthyl 2′,3′,4′,6′-tetra-*O*-acetyl-β-D-glucopyranoside, $C_{24}H_{28}O_{10}$, $M_r = 476{\cdot}49$, orthorhombic, space group $P2_12_12_1$ from systematic absences for $h00$, $0k0$, $00l$ when h, k, or $l = 2n + 1$.

a	16·423 (2) Å*	D_m	1·23–1·33 g cm^{-3}
b	21·832 (3)	D_c	1·28
c	6·876 (2)	$F(000)$	1008
V	2465·4 Å^3	μ(Cu $K\alpha$)	8·535 cm^{-1}
Z	4		

* The numbers in parentheses are the standard deviations referred to the last decimal position.

Structural determination and refinement

The structure was determined by application of the direct-methods procedure described by Kennard *et al.* (1971). Table 2 lists the starting set of reflections employed in the multi-solution tangent-formula calculations. For these calculations 218 reflections with $|E| > 1{\cdot}6$ were used. Of the 32 phase sets calculated, one had a significantly low R_K value (Karle & Karle, 1966) of 0·231 with 207 of the 218 data phased.

From an E map calculated with these phased E values as coefficients, a fragment of the structure consisting of 25 atoms could be recognized. The conventional R value was 0·408 based on the coordinates of these 25 atoms. From a subsequent electron density map the positions of the remaining nine atoms in the structure were determined, bringing the conventional R value to 0·233. Assignment of O and methyl C atoms of the acetyl groups was made on the basis of calculated bond lengths and angles. Full-matrix least-squares refinement with individual isotropic temperature factors and unit weights reduced R to 0·172. Inspection of calculated and observed structure factors indicated that 21 reflections of high intensity had been systematically underestimated. These were assumed to be influenced by secondary extinction and were removed from the data list.

Table 2. *Data for selection of origin- and enantiomorph-defining reflections and symbolic reflections*

Reflection and type	$\|E\|$	NT*	$K = \sigma_3\sigma_2^{-3/2}\|E_h\|\Sigma\|E_k\|\|E_{h-k}\|$	K/NT	φ_{initial}	
(g 0 u) 6 0 5	3·27	21	50·77	2·42	$\pi/2$	Fixed for origin definition
(0 u g) 0 15 4	3·26	25	62·59	2·50	$\pi/2$	
(u u 0) 5 1 0	2·46	40	79·97	1·99	$\pi/2$	
(0 g u) 0 18 3	2·40	14	28·66	2·05	0	Fixed for enantiomorph definition
Σ_1 relations						
0 6 6	3·57	15	40·97	2·73	0	
Symbolic reflections						
9 2 2	2·67	26	55·86	2·15	$\pm\pi/4, \ldots$	Systematically assigned values
5 15 3	2·65	20	40·60	2·03	$\pm\pi/4, \ldots$	
4 0 1	2·30	34	75·55	2·22	$\pm\pi/2$	

* Number of triplet relationships; see Kennard *et al.* (1971) for definition of parameters.

Least-squares refinement was continued using a block-diagonal scheme based on 1997 F's with anisotropic temperature factors and weighting according to the expressions $w = 1/\sigma^2$ and $\sigma = [\Sigma w_i S_i(I)^2/\Sigma w_i]^{1/2}$, where w_i is a weight based on a Gaussian distribution assigned to each contributing measurement of the reflection. H atoms located from a ΔF map were kept at fixed positions and assigned isotropic temperature factors. The final agreement factors were $R = 0{\cdot}0677$ and $R_w = 0{\cdot}0743$.* Least-squares refinement using a weighting scheme based on a Chebyshev polynomial (Rollett, 1965), calculated for comparative purposes, resulted in identical values for R and R_w and equivalent values for bond lengths and valency angles. A final difference electron density synthesis showed no spurious features except that one of the H(C2″) atoms was not observed. There was no difference in the final agreement factors for refinement with observed H atoms at fixed positions or with all H atoms included at their calculated positions. The unrefined bond lengths for the observed positions of H atoms ranged from 0·78 to 1·26 Å. The fractional positional parameters are given in Table 3 for nonhydrogen atoms.

The atomic scattering factors for C and O were from *International Tables for X-ray Crystallography* (1962); those for H were from Stewart, Davidson & Simpson (1965).

* Lists of structure factors and anisotropic thermal parameters have been deposited with the British Library Lending Division as Supplementary Publication No. SUP 32997 (12 pp.). Copies may be obtained through The Executive Secretary, International Union of Crystallography, 13 White Friars, Chester CH1 1NZ, England.

Table 3. *Final atomic parameters*

The estimated standard deviations given in parentheses refer to the last decimal positions of the respective values.

	x	y	z
O(1)	0·2132 (5)	0·2605 (4)	0·2855 (16)
O(2)	0·2082 (4)	0·0249 (3)	0·1657 (12)
O(3)	0·4621 (4)	0·0665 (2)	−0·1156 (7)
O(4)	0·6330 (4)	0·0367 (3)	0·1321 (10)
O(1′)	0·3685 (3)	0·2419 (2)	0·5858 (7)
O(2′)	0·2312 (3)	0·1741 (2)	0·4491 (8)
O(3′)	0·2803 (3)	0·1093 (2)	0·1020 (7)
O(4′)	0·4231 (3)	0·0324 (2)	0·1773 (7)
O(5′)	0·4512 (3)	0·1638 (2)	0·4973 (7)
O(6′)	0·5859 (3)	0·1223 (2)	0·2676 (8)
C(1)	0·3965 (4)	0·2645 (3)	0·7641 (10)
C(2)	0·4391 (5)	0·2304 (3)	0·8975 (11)
C(3)	0·4631 (6)	0·2584 (4)	1·0686 (13)
C(4)	0·4453 (6)	0·3176 (4)	1·1097 (14)
C(5)	0·3816 (6)	0·4160 (3)	1·0050 (17)
C(6)	0·3436 (6)	0·4488 (3)	0·8668 (17)
C(7)	0·3199 (5)	0·4232 (4)	0·6858 (16)
C(8)	0·3358 (5)	0·3625 (3)	0·6511 (13)
C(9)	0·3772 (4)	0·3266 (3)	0·7900 (11)
C(10)	0·4018 (5)	0·3532 (3)	0·9718 (13)
C(1′)	0·3709 (5)	0·1784 (3)	0·5489 (10)
C(2′)	0·3148 (4)	0·1690 (3)	0·3763 (11)
C(3′)	0·3242 (4)	0·1061 (3)	0·2863 (10)
C(4′)	0·4131 (4)	0·0947 (2)	0·2475 (10)
C(5′)	0·4600 (4)	0·1010 (3)	0·4366 (10)
C(6′)	0·5484 (5)	0·0870 (3)	0·4222 (11)
C(1″)	0·1878 (6)	0·2230 (4)	0·3903 (18)
C(2″)	0·1060 (6)	0·2223 (5)	0·4853 (21)
C(3″)	0·2206 (5)	0·0682 (4)	0·0705 (13)
C(4″)	0·1749 (6)	0·0855 (5)	−0·1110 (17)
C(5″)	0·4492 (5)	0·0245 (3)	−0·0089 (11)
C(6″)	0·4594 (6)	−0·0421 (4)	−0·0566 (14)
C(7″)	0·6258 (5)	0·0900 (4)	0·1308 (13)
C(8″)	0·6592 (6)	0·1333 (5)	−0·0216 (17)

Description of the structure

The molecular geometry

The molecular conformation and atomic numbering scheme of NGTA are illustrated in Fig. 1. The absolute configuration was not determined, but as the synthesis of the molecule proceeded from a β-D-glucose derivative, the structure has been chosen to conform to the D form for a right-handed coordinate axis system. The glucose ring is in the $C1$ chair configuration with the side groups in equatorial positions (Reeves, 1950). The relevant torsion angles are given in Table 4.

The endocyclic torsion angles vary from 51·0 to 66·5°, comparable with the range of 50·8 to 66·3° for β-D-glucose (Chu & Jeffrey, 1968). The exocyclic torsion angles exhibit similar close agreement. The C(6′)—O(6′) bond has a *gauche–gauche* or synclinal

Table 4. *Conformation angles* (°) *of NGTA*

Conformation angles are defined according to the convention of Klyne & Prelog (1960). The sequence of atoms is given only for exocyclic bonds.

Endocyclic	NGTA	β-D-Glucose*
C(1′) → C(2′)	+51·9	+53·7
C(2′) → C(3′)	−51·0	−50·8
C(3′) → C(4′)	+57·2	+53·4
C(4′) → C(5′)	−63·9	−59·8
C(5′) → O(5′)	+66·8	+66·3
O(5′) → C(1′)	−60·5	−62·8
Exocyclic		
C(1)–[O(1′) → C(1′)]–C(2′)	+163·7	–
C(1)–[O(1′) → C(2′)]–O(5′)	−79·4	–
O(5′)–[C(1′) → C(2′)]–O(2′)	+169·9	+175·0
O(1′)–[C(1′) → C(2′)]–O(2′)	−75·1	−69·2
C(1′)–[C(2′) → C(3′)]–O(3′)	−168·2	−170·5
O(2′)–[C(2′) → C(3′)]–O(3′)	+74·2	+68·9
C(2′)–[C(3′) → C(4′)]–O(4′)	+175·0	+173·1
O(3′)–[C(3′) → C(4′)]–O(4′)	−70·6	−67·5
C(3′)–[C(4′) → C(5′)]–C(6′)	+176·3	+179·0
O(4′)–[C(4′) → C(5′)]–C(6′)	+58·1	+59·6
C(6′)–[C(5′) → O(5′)]–C(1′)	−169·3	−169·6
C(5′)–[O(5′) → C(1′)]–O(1′)	−174·1	−179·4
O(5′)–[C(5′) → C(6′)]–O(6′)	−66·0	−60·4

* Calculated from Chu & Jeffrey (1968).

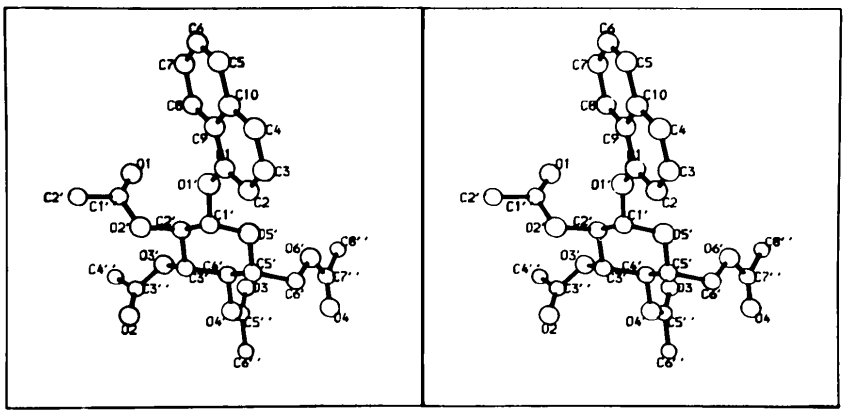

Fig. 1. Stereoscopic drawing of the structure of NGTA illustrating the atomic numbering scheme employed in the text. The numbering scheme C1, C1′, ... corresponds to the standard system of notation C(1), C(1′), ... employed in the text.

orientation (Klyne & Prelog, 1960), which is one of the favored arrangements in glucopyranosides. The C—O and C=O bonds of each acetylated side chain are in a *cis* configuration, this relationship corresponding to the configuration of least strain in an ester linkage (Mathieson & Welsh, 1965). The valence-bond angle at the glycosidic O is 119·7 (0·5)°, nearly identical to that of 120·0 (0·5)° observed in GlcNAc-PN (Brehm & Moult, 1975). Ham & Williams (1970) have pointed out that bulky substituents of the glycosidic O increase the valence-bond angle from that observed for a methyl group (~113°).

The nonhydrogen atoms of the acetyl side chains including the carbohydrate O atom are each uniformly coplanar [$\chi^2 = 0{\cdot}72, 0{\cdot}98, 0{\cdot}05$, and 0·00 for the C(2′), C(3′), C(4′), and C(6′) substituents]. There is some distortion of the naphthyl ring indicating that the 10 aromatic C atoms are not coplanar ($\chi^2 = 18{\cdot}4$), and the glycosidic O deviates 0·056 Å from the calculated mean plane of the naphthyl ring. As demonstrated in a recent re-evaluation of GlcNAc (Mo & Jensen, 1975), the glucose ring atoms O(5′), C(1′), C(3′), and C(4′) are also coplanar in NGTA ($\chi^2 = 0{\cdot}19$). This plane is nearly perpendicular (82·8°) to a plane through the atoms C(5′), C(6′), and O(6′) and makes an angle of 61·4° with the mean plane of the aromatic ring. An angle of 6·15° is calculated between the normals of the planes defined by the C(3′), C(4′), C(5′) and C(2′), C(1′), O(5′) groups of atoms.

Bond lengths and angles

Bond lengths and valency angles with their estimated standard deviations are given in Tables 5 and 6. The mean standard deviations are 0·009 Å for C—C bonds, 0·007 Å for C—O bonds, and 0·7° for the valence angles of the molecule as a whole.

Within the glucose ring, the mean C—C bond length is 1·513 (8) Å with a maximum deviation of 0·012 Å. Corresponding values for β-D-glucose and cellobiose are 1·520 (2) and 1·522 (2) Å respectively (Chu & Jeffrey, 1968). The C(5′)—C(6′) bond length is 1·486 (9) Å, shorter than the average ring C—C bond distance by 2·3σ. Although shortening of this bond in NGTA is not significantly marked, Ham & Williams (1970) first observed that the corresponding C—C bond length is shortened in a variety of carbohydrate structures. Shortening of this bond distance as a true structural feature of pyranose compounds is established by a rigid-body analysis of GlcNAc (Mo & Jensen, 1975).

There is, in general, a larger spread among corresponding C—O bond lengths of carbohydrate structures than among C—C bonds, probably as a result of their increased sensitivity to bonding and crystal interactions. Chu & Jeffrey (1967) have outlined 'characteristic' stereochemical features of the glycosidic linkage on the

Table 5. *Intramolecular bond lengths* (Å) *of carbon and oxygen atoms of NGTA*

The estimated standard deviations given in parentheses refer to the last decimal positions of the respective values.

C(1)—C(2)	1·373 (9)	O(5′)—C(1′)	1·403 (7)
C(2)—C(3)	1·383 (9)	C(5′)—C(6′)	1·486 (9)
C(3)—C(4)	1·354 (9)	C(2′)—O(2′)	1·466 (7)
C(4)—C(10)	1·420 (10)	C(3′)—O(3′)	1·460 (7)
C(10)—C(5)	1·430 (9)	C(4′)—O(4′)	1·453 (6)
C(5)—C(6)	1·343 (12)	C(6′)—O(6′)	1·450 (8)
C(6)—C(7)	1·418 (12)	O(2′)—C(1″)	1·347 (8)
C(7)—C(8)	1·373 (9)	O(3′)—C(3″)	1·347 (8)
C(8)—C(9)	1·410 (9)	O(4′)—C(5″)	1·361 (8)
C(9)—C(1)	1·404 (8)	O(6′)—C(7″)	1·345 (8)
C(9)—C(10)	1·436 (10)	C(1″)—O(1)	1·167 (10)
C(1)—O(1′)	1·399 (7)	C(3″)—O(2)	1·168 (8)
O(1′)—C(1′)	1·410 (6)	C(5″)—O(3)	1·192 (7)
C(1′)—C(2′)	1·516 (8)	C(7″)—O(4)	1·169 (7)
C(2′)—C(3′)	1·513 (8)	C(1″)—C(2″)	1·494 (12)
C(3′)—C(4′)	1·505 (8)	C(3″)—C(4″)	1·505 (11)
C(4′)—C(5′)	1·517 (8)	C(5″)—C(6″)	1·501 (9)
C(5′)—O(5′)	1·440 (6)	C(7″)—C(8″)	1·515 (11)

Table 6. *Intramolecular bond angles* (°) *of carbon and oxygen atoms of NGTA*

The standard deviations in degrees are given in parentheses.

C(1)–C(2)–C(3)	118·3 (0·7)	O(1′)–C(1′)–O(5′)	107·2 (0·6)	C(2′)–O(2′)–C(1″)	116·9 (0·6)
C(2)–C(3)–C(4)	122·6 (0·8)	O(1′)–C(1′)–C(2′)	104·9 (0·5)	C(3′)–O(3′)–C(3″)	117·9 (0·6)
C(3)–C(4)–C(10)	119·4 (0·8)	C(1′)–C(2′)–C(3′)	112·4 (0·6)	C(4′)–O(4′)–C(5″)	117·8 (0·5)
C(4)–C(10)–C(5)	122·4 (0·8)	C(2′)–C(3′)–C(4′)	108·8 (0·5)	C(6′)–O(6′)–C(7″)	116·2 (0·5)
C(4)–C(10)–C(9)	120·1 (0·7)	C(3′)–C(4′)–C(5′)	109·0 (0·5)	O(2′)–C(1″)–O(1)	123·5 (0·9)
C(10)–C(5)–C(6)	120·4 (0·9)	C(4′)–C(5′)–O(5′)	106·4 (0·5)	O(3′)–C(3″)–O(2)	125·3 (0·8)
C(5)–C(6)–C(7)	122·6 (0·7)	C(5′)–O(5′)–C(1′)	112·6 (0·5)	O(4′)–C(5″)–O(3)	122·5 (0·6)
C(6)–C(7)–C(8)	118·7 (0·8)	C(1′)–C(2′)–O(2′)	107·0 (0·6)	O(6′)–C(7″)–O(4)	124·4 (0·6)
C(7)–C(8)–C(9)	120·7 (0·8)	C(2′)–C(3′)–O(3′)	105·2 (0·5)	O(2′)–C(1″)–C(2″)	109·7 (0·9)
C(8)–C(9)–C(10)	120·1 (0·6)	C(3′)–C(4′)–O(4′)	108·9 (0·5)	O(3′)–C(3″)–C(4″)	109·3 (0·7)
C(8)–C(9)–C(1)	124·0 (0·6)	C(4′)–C(5′)–C(6′)	114·8 (0·6)	O(4′)–C(5″)–C(6″)	111·3 (0·6)
C(1)–C(9)–C(10)	116·0 (0·6)	O(2′)–C(2′)–C(3′)	107·7 (0·5)	O(6′)–C(7″)–C(8″)	109·5 (0·7)
C(9)–C(10)–C(5)	117·5 (0·8)	O(3′)–C(3′)–C(4′)	109·5 (0·5)	O(1)–C(1″)–C(2″)	126·8 (1·0)
C(9)–C(1)–C(2)	123·6 (0·6)	O(4′)–C(4′)–C(5′)	108·2 (0·5)	O(2)–C(3″)–C(4″)	125·4 (0·9)
C(9)–C(1)–O(1′)	112·2 (0·6)	O(5′)–C(1′)–C(2′)	110·1 (0·5)	O(3)–C(5″)–C(6″)	126·2 (0·7)
C(2)–C(1)–O(1′)	124·2 (0·6)	O(6′)–C(6′)–C(5′)	110·7 (0·6)	O(4)–C(7″)–C(8″)	126·2 (0·7)
C(1)–O(1′)–C(1′)	119·7 (0·5)	C(6′)–C(5′)–O(5′)	108·3 (0·5)		

basis of structural data for alkyl-substituted D-glucosides. By these criteria it is expected that an equatorial C(1′)–O(1′) bond is short (2–7σ), compared with the mean equatorial C–O bond length at the other side-chain positions, irrespective of whether the H atom on O(1′) is substituted or not. In NGTA the C(1′)–O(1′) bond length constituting the glycosidic linkage is 1·410 (6) Å, shorter by only 1·9σ than the mean equatorial C–O bond length of 1·425 (2) and 1·420 (2) Å for *β*-D-glucose and cellobiose (Chu & Jeffrey, 1968). In NGTA the mean equatorial C–O bond length, excluding the anomeric glycosidic linkage, is 1·457 (7) Å and is, as expected, longer than in the nonacetylated glucosides. The ring C(5′)–O(5′) bond length of 1·440 (6) Å is nearly identical to the mean equatorial C–O bond while the C(1′)–O(5′) bond length of 1·403 (7) Å is shorter than the other ring C–O bond distance at a significance level of 5·4σ. Parallel relationships for the ring C–O bond lengths are observed in GlcNAc-PN (Brehm & Moult, 1975). The C(1)–O(1′) bond distance is 1·399 (7) Å, consistent with the aromatic C–O bond lengths of 1·38 (1) Å in 1,2-diphenoxyethane (Yasuoka, Ando & Kurijabashi, 1967) and 1·377 (8) Å for the corresponding bond length in GlcNAc-PN (Brehm & Moult, 1975).

There is in general only limited stereochemical data of high precision for bond lengths and valency angles of ester linkages. Therefore, the side chains of the carbohydrate ring are of added interest. The acetyl side chains exhibit a low degree of variation in structural detail, and these stereochemical details may be considered as characteristic values for an ester group, particularly in view of the *cis* configuration and absence of perturbing hydrogen-bonding networks. For the side groups the mean C=O bond length of 1·174 (8) Å is comparable with that of 1·19 (1) Å in succinic anhydride (Ehrenberg, 1965) and that of 1·18 (1) Å in acetylsalicylic acid (Wheatley, 1965). The mean C–O bond length of 1·352 (8) Å between the carboxylic C atom of the acetyl group and the carbohydrate O is equivalent to that of 1·36 (1) Å in acetylsalicylic acid, and the mean equatorial C–O bond length of 1·457 (7) Å is equivalent to that of 1·46 Å for the corresponding chemically equivalent bond length of methyl *p*-bromocinnamate (Leiserowitz & Schmidt, 1965). More recent stereochemical data for comparative purposes with regard to the structure of the ester linkage appear not to be reported.

The crystal structure and intermolecular contacts

The intermolecular contact distances less than 3·50 Å between adjacent molecules are listed in Table 7 and are illustrated in projection along the *c* axis in Fig. 2. There are nine contacts which are less than the sum of the van der Waals radii, based on the values of Bondi (1964) for corresponding chemical groups. Since the C···C interactions involve both aromatic and carbonyl

Table 7. *Intermolecular contacts in the NGTA crystal with interatomic distances less than* 3·5 Å

Standard deviations of the intermolecular distances are given in parentheses and refer to the last decimal positions of the respective values. The symbols *S*, *Tx*, *Ty*, and *Tz* indicate the *n*th molecule of the unit cell and the translational operations with respect to molecule 1 required to produce the intermolecular contacts.

	Distance (Å)	*S*	*Tx*	*Ty*	*Tz*
O(1)–C(8″)	3·074 (11)	3	−1	0	0
O(2)–C(4″)	3·443 (12)	4	1	0	0
–C(6″)	3·371 (11)	4	1	0	0
O(4)–C(6)	3·473 (10)	3	0	0	1
–C(7)	3·394 (10)	2	1	−1	0
–C(7)	3·428 (10)	3	0	0	1
O(4′)–C(4″)	3·366 (9)	4	0	0	0
C(7)–C(7″)	3·440 (10)	3	−1	0	1
C(7″)–C(7)	3·463 (7)	3	0	0	1

C atoms, no hydrophobic interactions are observed between hydrocarbon groups. The C···O interactions involve aromatic and methyl C atoms with carbonyl O atoms of the side chains, except for the O(4′)···C(4′) interaction. In view of the unsaturated chemical bonding structure of the groups involved, the O(4)···C(6), O(4)···C(7), and C(7)···C(7″) interactions may represent formation of an intermolecular π complex between a carbonyl group and the naphthalene ring.

The crystal structures of all carbohydrates described hitherto are characterized by formation of the maximum number of intermolecular hydrogen-bonding networks (Strahs, 1970). As a result of peracetylation of the equatorial side groups, the crystal structure of NGTA, therefore, differs significantly from other carbohydrates since the usual type of hydrogen bonding is not possible. In this respect the O(1)···C(8″) interaction may be of potential interest since it is a surprisingly short intermolecular contact. Unfortunately, our data do not permit an unambiguous assignment of the O(1)···C(8″) contact as an attractive C–H···O interaction, for the final difference electron density synthesis indicated smearing of the electron density features attributable to the H atoms bonded to C(8″). Although such intermolecular C–H···O interactions are expected for polyproline and related polymers (Ramachandran, Ramakrishnan & Venkatachalam, 1967; Krimm, Kuriowa & Relune, 1967), they provide only weak ($\leq$1 kcal mol^{-1}) attractive interactions (Poland & Scheraga, 1967) and cannot be expected to serve as the predominant crystal stabilizing force. It is, therefore, probable that the forces stabilizing the crystal structure derive mainly from intermolecular van der Waals interactions.

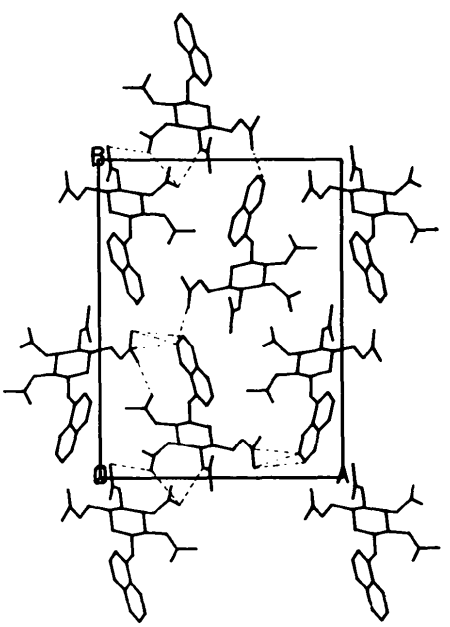

Fig. 2. Schematic illustration of the crystal structure of NGTA projected along the *c* axis. The structurally significant intermolecular contacts listed in Table 7 are indicated by broken lines. The origin (*O*), *a*-axis (*A*), and *b*-axis (*B*) directions are indicated.

Since hydrogen-bonding networks produce distortions of stereochemical relationships in other carbohydrate structures (Strahs, 1970), the ring structure of the glucose moiety in NGTA can be viewed as negligibly perturbed by the crystal environment, especially since the O(1′) and O(5′) atoms are not involved in intermolecular contacts. It is, furthermore, likely that the acetyl side chains are not significantly perturbed stereochemically by their environment in view of their *cis* configurations and the closely similar stereochemical values for bond lengths and valency angles which all the acetyl substituents exhibit.

Stereochemistry of the ring and glycosidic C–O *bonds*

The different stereochemical relationships of the hemiacetal group of substituted glucosides undoubtedly account for their chemical properties in solution, particularly with respect to acid-catalyzed hydrolysis. Since the mechanism of hydrolysis of alkyl- and aryl-substituted glycosides may be different, it is of interest to review some of the previously defined criteria (Chu & Jeffrey, 1967) of the structural relationships of the hemiacetal group of glucosides. By these criteria, an equatorial glycosidic C–O bond is expected to be short with no significant difference in the ring C–O bond lengths. In the case of 'unshortened' glycosidic bonds, as observed with alkyl substituents in an axial configuration, the ring C–O bond lengths are unequal, with that adjacent to the glycosidic linkage being the shorter. While shortened equatorial glycosidic C–O bonds have been reported previously for unsubstituted or alkyl-substituted carbohydrates, the glycosidic C–O bond length in NGTA appears not to be significantly shorter ($1{\cdot}9\sigma$) than the mean equatorial C–O bond length in β-D-glucose or cellobiose. The ring C–O bond lengths, however, are significantly different, as observed only in the case of unshortened glycosidic C–O bonds with *axial* substituents. On the other hand, the structure of GlcNAc-PN, to our knowledge the only other aromatic-substituted glucopyranoside reported in the literature, exhibits shortening of the glycosidic C–O bond ($3{\cdot}0\sigma$) with significantly different ($3{\cdot}3\sigma$) ring C–O bonds. We conclude that aromatic-substituted glucosides with the aglycone residue in an equatorial configuration exhibit significantly different ring C–O bonds independent of the glycosidic C–O bond length. In contrast, alkyl-substituted glucosides with a β configuration, always having a shortened glycosidic C–O bond, exhibit no significant differences in the ring C–O bond lengths. In view of these differences for β-substituted glucosides, the stereochemical relationships of axially substituted glucosides also might not conform

to the previously defined structural properties of the hemiacetal group. Structure determination of an aromatic-substituted glucoside with an α configuration at the anomeric C atom would help to define more completely the differential influence of alkyl and aromatic aglycone substituents on the stereochemical relationships of the hemiacetal group. These differences in stereochemical properties may underlie differences in their mechanism of hydrolysis in acidic media.

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