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THE CRYSTAL STRUCTURE OF A NONALKENIC, CYCLIC TRIMER OF LEVOGLUCOSENONE

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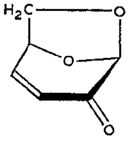
ABSTRACT

A single-crystal, X-ray diffraction study was performed on a nonalkenic, cyclic trimer ($C_{18}H_{18}O_9$, **4**) of levoglucosenone, in order to confirm its chemical structure. Crystals of **4** are orthorhombic, with unit-cell parameters of a = 792.20, b = 1874.35, c = 2383.02 pm, space group $P2_12_12_1$, and $z = 8$. The structure was solved by direct methods, and refined by least-squares to R = 0.032, based on 2990 unique reflections. Each asymmetrical unit contains two symmetry-independent molecules of **4** and one of acetone. The previously assigned chemical structure and stereochemistry of **4** were found to be correct.

INTRODUCTION

Levoglucosenone (**1**, 1,6-anhydro-3,4-dideoxy-β-D-*glycero*-hex-3-enopyranos-2-ulose) has been synthesized by the pyrolysis of cellulose and such cellulosic wastes as newsprint[1], and many aspects of its chemical reactivity have been investigated[2]. The carbon–carbon double bond has been shown to undergo base-catalyzed Michael additions readily[2], and recently, levoglucosenone was found to form oligomers *via* this process[3]. A dimer (**2**), and two cyclic trimers, one alkenic (**3**) and one nonalkenic (**4**), have been isolated, and their chemical structures tentatively identified by spectro-



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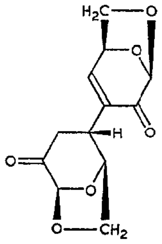

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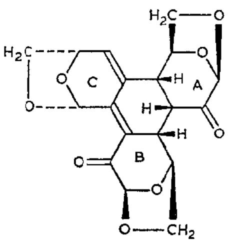

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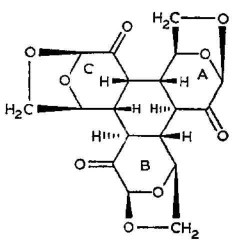

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TABLE I

FRACTIONAL ATOMIC COORDINATES[a] FOR **4**

Atom	*Molecule 1*			*Molecule 2*		
	x	y	z	x	y	z
C-1A	6312(5)	4971(2)	2517(2)	−585(4)	2971(2)	1898(1)
C-2A	7601(5)	4788(2)	2972(1)	728(4)	3472(2)	1646(1)
C-3A	7449(4)	4031(1)	3189(1)	1971(4)	3109(1)	1260(1)
C-4A	5563(4)	3857(2)	3266(1)	2537(4)	2432(2)	1584(1)
C-5A	4497(5)	4145(2)	2765(1)	997(4)	2008(2)	1807(1)
C-6A	3680(5)	4870(2)	2891(2)	735(5)	2116(2)	2430(1)
O-1A	5001(3)	5375(1)	2769(1)	−30(3)	2819(1)	2459(1)
O-2A	8582(4)	5224(1)	3150(1)	817(3)	4093(1)	1793(1)
O-5A	5591(3)	4342(1)	2308(1)	−552(3)	2323(1)	1601(1)
C-1B	10908(5)	3291(2)	4408(1)	5560(4)	4376(2)	434(1)
C-2B	9111(4)	2999(2)	4443(1)	6226(4)	3674(2)	678(1)
C-3B	8144(4)	3083(1)	3897(1)	4831(4)	3144(1)	787(1)
C-4B	8386(4)	3880(2)	3735(1)	3487(4)	3572(1)	1122(1)
C-5B	10299(4)	4057(2)	3732(1)	3017(4)	4261(2)	793(1)
C-6B	10792(5)	4504(2)	4232(1)	3774(5)	4926(2)	1053(2)
O-1B	10894(3)	3981(1)	4674(1)	5508(3)	4892(1)	876(1)
O-2B	8540(3)	2770(1)	4877(1)	7704(3)	3605(1)	794(1)
O-5B	11296(3)	3425(1)	3837(1)	3878(3)	4277(1)	256(1)
C-1C	5776(5)	1767(2)	3083(1)	4650(5)	1247(2)	412(1)
C-2C	5676(4)	2555(2)	2913(1)	3224(4)	1584(2)	752(1)
C-3C	5303(4)	3058(1)	3395(1)	3855(4)	1995(1)	1259(1)
C-4C	6307(4)	2831(1)	3926(1)	5406(4)	2456(1)	1083(1)
C-5C	6244(4)	2013(2)	3982(1)	6574(4)	2019(2)	702(1)
C-6C	4450(4)	1711(2)	3937(1)	7043(4)	1295(2)	951(1)
O-1C	4248(3)	1561(1)	3340(1)	5701(3)	831(1)	762(1)
O-2C	5847(3)	2732(1)	2432(1)	1756(3)	1528(1)	611(1)
O-5C	7047(3)	1701(1)	3492(1)	5649(3)	1810(1)	202(1)
H-1A	680(4)	525(2)	223(1)	178(4)	318(1)	188(1)
H-3A	781(3)	377(1)	292(1)	129(4)	301(1)	91(1)
H-4A	514(4)	413(1)	367(1)	314(3)	257(1)	188(1)
H-5A	361(4)	381(2)	262(1)	111(4)	152(1)	168(1)
H-6A*endo*	324(5)	490(2)	328(2)	181(5)	211(2)	265(1)
H-6A*exo*	263(4)	499(2)	265(1)	1(4)	178(1)	256(1)
H-1B	1188(4)	294(1)	463(1)	631(4)	456(1)	9(1)
H-3B	874(3)	281(1)	362(1)	429(4)	303(1)	40(1)
H-4B	785(3)	417(1)	402(1)	403(3)	370(1)	150(1)
H-5B	1071(4)	426(1)	336(1)	179(4)	429(1)	73(1)
H-6B*endo*	987(4)	490(1)	431(1)	370(4)	491(1)	140(1)
H-6B*exo*	1191(4)	469(1)	418(1)	327(3)	536(1)	88(1)
H-1C	606(5)	141(2)	276(1)	410(4)	92(2)	6(1)
H-3C	399(4)	299(1)	350(1)	423(4)	157(1)	153(1)
H-4C	567(3)	303(1)	427(1)	615(4)	256(1)	145(1)
H-5C	687(4)	183(1)	438(1)	750(4)	226(1)	54(1)
H-6C*endo*	354(3)	208(1)	407(1)	710(4)	132(1)	139(1)
H-6C*exo*	425(4)	123(1)	414(1)	817(4)	114(2)	80(1)

[a] $\times 10^4$ for C and O, and $\times 10^3$ for H (standard deviation in parentheses).

scopic methods. In addition, the structure of trimer **3** has been confirmed by X-ray crystallography[4]. In order to confirm the structure of the nonalkenic, cyclic trimer **4**, an X-ray crystallographic study was undertaken, and the results are reported herein.

RESULTS AND DISCUSSION

Trimer **4** ($C_{18}H_{18}O_9$) crystallized with two molecules of **4** and one of acetone per asymmetrical unit. The atomic coordinates of the two crystallographically independent molecules of **4** are listed* in Table I. A stereochemical drawing of **4**, showing the atomic labelling and thermal ellipsoids, is given in Fig. 1, which shows the three residues of levoglucosenone (A, B, and C) with three C-3–C-4 linkages joining them to form a central, cyclohexane ring. This structure, including the stereochemistry, is consistent with the chemical-structure determination reported previously[3].

Calculation of puckering parameters[5,6] showed that the deviations in conformations between the two symmetry-independent molecules are small (see Table

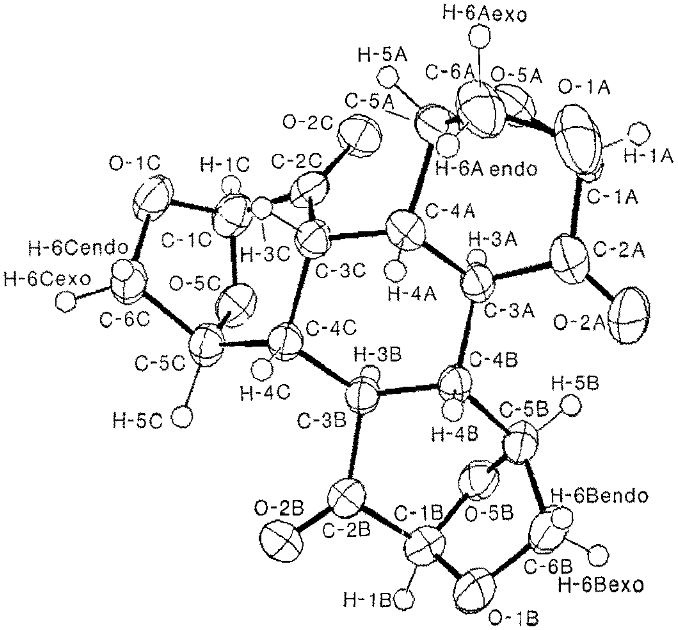

Fig. 1. ORTEP[16] drawing of molecule 1 of **4**, showing atomic labelling and thermal ellipsoids at the 50% probability level. (Thermal parameters for hydrogen atoms are not depicted.)

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*Supplementary data: Hydrogen and non-hydrogen thermal parameters (Table V), bond lengths (Table VI) and angles (Table VII) involving hydrogen, atomic parameters of the acetone molecule (Table VIII), and observed and calculated structure factors (Table IX) can be obtained from Elsevier Scientific Publishing Company, BBA Deposition, P.O. Box 1527, Amsterdam, The Netherlands. Reference should be made to No. BBA/DD/235/*Carbohydr. Res.*, 112 (1983) 179–187.

TABLE II

PUCKERING PARAMETERS FOR **4**

Residue	Q *(pm)*	θ *(°)*	ϕ *(°)*
Pyranose rings			
A	81.3	98.3	180.6
A′[a]	85.1	95.0	183.5
B	87.6	93.6	183.6
B′	87.8	93.8	184.1
C	63.9	159.2	171.0
C′	64.9	160.9	180.9
[b]	64.8	161.0	174.1
Central cyclohexane rings[c]			
D	57.5	170.8	282.5
D′	55.8	176.2	305.2
Anhydro rings[d]			
A	43.5		47.7
A′	45.6		56.1
B	45.7		53.9
B′	46.9		54.6
C	40.5		36.8
C′	41.4		41.9

[a] Prime refers to molecule 2. [b] Residue A of **3**[1]. [c] C-3C is atom 1; C-4A, atom 2, *etc*. [d] C-1 is atom 1; O-5, atom 2, *etc*.

II), and are similar to those reported for 1,6-anhydro-β-D-galactopyranose[7]. The pyranoid residues A and B are in the $B_{3,O}$ conformation, with some distortion toward the *sofa*$_O$ conformation (5 carbon atoms coplanar). Residue C is in the ${}^1C_4$ conformation, with some distortion toward the *sofa*$_O$ form. This conformation is typical of monomeric 1,6-anhydrohexoses having all members of the pyranose ring in the sp^3-hybridized state[6]. Residue C of **4** and residue A of the alkenic trimer **3** are structurally the same, including the stereochemistry of the substituents at C-3 and C-4, and their conformations are almost identical (see Table II). The central cyclohexane ring D of **4** assumes a conformation very close to the ${}^{C\text{-}4A}C_{C\text{-}3B}$ form. The conformations of all of the anhydro rings are either near to the ${}^{C\text{-}5}T_{O\text{-}5}$ (ϕ = 54°), or lie between the ${}^{C\text{-}5}T_{O\text{-}5}$ and the $E_{O\text{-}5}$ (ϕ = 36°). This is typical of other 1,6-anhydropyranoses[8].

Molecules of **4** have a rigid, fused-ring structure, with no freely-rotating, functional groups. As a result, the differences between the two symmetry-independent molecules are small. The largest bond-length differences ($>4\sigma$) are C-5A–C-6A (2.2 pm) and C-1A–O-1A (1.7 pm; see Fig. 2). The greatest bond-angle differences are C-2A–C-3A–C-4A (3.7°), C-3A–C-4B–C-5B (2.4°), and C-2A–C-3A–C-4B (2.2°, see Fig. 3). When molecules 1 and 2 of **4** were superimposed and the fit was refined by least-squares[9] (with hydrogen atoms excluded), the mean difference be-

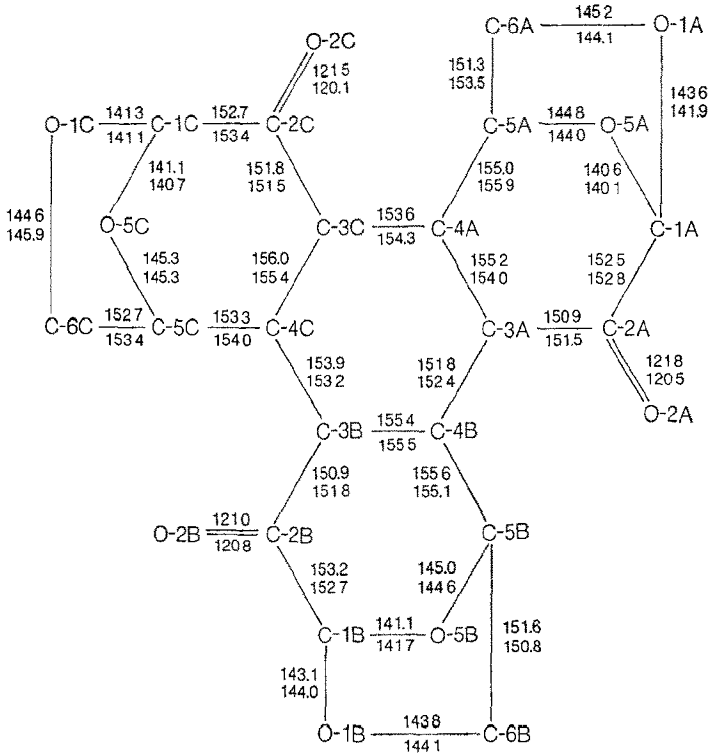

Fig. 2. Bond lengths (pm) for **4**. The upper numbers correspond to molecule 2. (Standard deviations ranged from 0.3 to 0.6 pm. Bond lengths involving hydrogen atoms have been omitted.)

tween equivalent, non-hydrogen atoms was 13 pm, with a minimum difference of 5 pm (C-4B and C-4C), and a maximum of 43 pm (O-2A). The difference between proton positions ranged from 4 (H-4B) to 43 pm (H-5A), with an average of 23 pm.

The C-5–O-5–C-1–O-1–C-6 atom sequence of 1,6-anhydropyranoses consists of four sequential, C–O bonds. It had been observed[10] that the two outer bonds (C-5–O-5 and O-1–C-6) are systematically long, and the two inner bonds (O-5–C-1 and C-1–O-1), systematically short, when compared to the average, C–O bond-length of this sequence; this has been attributed[11] to the "anomeric effect". A similar, long–short–short–long, bond-length sequence is present in **4** (see Table III), and is most prevalent in residue C. In residue A, this effect is somewhat less pronounced, the C-1–O-1 bond-length being close to the average length. In residue B, however, the sequence begins with the typical, long-outer and short-inner bond, but the next two O-1–C bonds lengths are both close to the average. This was not expected, as residues A and B are almost identical, both chemically and conformationally (see Table II). However, these bond-length differences are small ($2\ \sigma = \sim 1$ pm), and caution should be used in interpreting these results.

Hydrogen atomic parameters refined properly, with the resulting bond-lengths involving hydrogen atoms ranging from 83 to 114 pm, and bond angles from 101 to

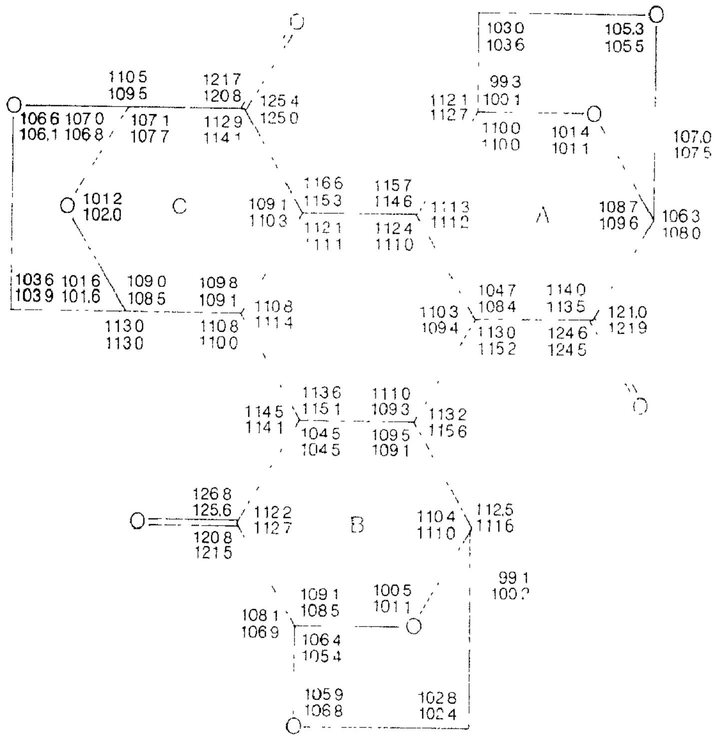

Fig. 3. Bond angles (°) for **4**. The upper numbers correspond to molecule 2. (Standard deviations ranged from 0.2 to 0.4°. Bond angles involving hydrogen atoms have been omitted.)

TABLE III

VARIATIONS IN C–O BOND-LENGTH IN **4**

Residue	*Difference from the mean C–O distance (pm)*				*Mean C–O length (pm)*
	C-5 — O-5	*O-5 — C-1*	*C-1 — O-1*	*O-1 — C-6*	
A	+1.5	−2.4	0.6	+1.6	142.5
A′[a]	+1.2	3.0	0.0	+1.6	143.6
B	+1.0	1.9	0.4	+0.5	143.6
B′	+1.7	2.2	−0.2	+0.5	143.3
C	+2.0	−2.6	−2.2	+2.6	143.3
C′	+2.2	2.0	1.8	1.5	143.1

[a] Prime refers to molecule 2.

116°. The isotropic, thermal parameters (U) for all hydrogen atoms of **4** ranged from 190 to 1070 pm^2, and averaged 469 pm^2.

The acetone molecule has large, apparent, thermal motion, with anisotropic, thermal parameters (U_{11}) ranging from 350 to 3010 pm^2 for non-hydrogen atoms. Despite the high thermal motion, the hydrogen atoms were visible, with the value of

TABLE IV

PROTON DIHEDRAL-ANGLES AND ^{1}H-N.M.R. COUPLING-CONSTANTS

Protons involved	Dihedral angle (°) Molecule no.		Avg.	Coupling constant (Hz) Interpretation	
	1	*2*		*1*	*2*[a]
3A, 4A	170	180	175	12.0	
3A, 4B	176	173	175	12.0	
3B, 4B	177	178	178	12.0	
3B, 4C	168	171	169	12.0	
4B, 5B	119	118	118	2.8	
5B, 6B*exo*	38	41	40	3.3	
5A, 6A*endo*	89	83	86	∼0	
5B, 6B*endo*	88	86	87	∼0	
5C, 6C*endo*	98	104	101	∼0	
4A, 5A	105	115	110	1.6	3.0
4C, 5C	60	70	65	3.0	1.6
3C, 4A	58	60	59	6.1	4.3
3C, 4C	41	45	43	4.3	6.1
5A, 6A*exo*	28	42	35	5.3	∼3.5
5C, 6C*exo*	28	17	22	∼3.5	5.3

[a] When different from 1.

U ranging from 1060 to 2980 pm^2, C–H bond-lengths from 77 to 126 pm, and bond angles from 86 to 126°. The large apparent, thermal motion probably stems from the absence of strong, intermolecular interactions between acetone and **4**. No strong hydrogen-bonds are possible, due to the lack of O–H groups. The smallest distance between acetone and **4** is 231 pm from an acetone proton to O-1A′, and this is the only H···O distance that is less than 250 pm.

The structure of **4** was originally determined by ^{1}H-n.m.r. spectroscopy, and the stereochemistry by the spin–spin coupling-constants of the protons in the central cyclohexane ring[3]. Four of the six coupling constants associated with this ring were 12.0 Hz, resulting from spin coupling of *trans*-diaxial protons. Fig. 1 and Table IV show that protons 4A, 3A, 4B, 3B, and 4C are, indeed, arranged *trans*-axially, with dihedral angles ranging from 168 to 180°. H-3C is in the equatorial position ($J_{3C,4}$ 6.1 and 4.3 Hz) with proton dihedral-angles of ∼59 and 43°.

Although the stereochemistry of **4** could be determined from the ^{1}H-n.m.r. spectrum, the cyclic nature of **4** precluded an unambiguous interpretation of the complete spectrum. Two different interpretations were possible[3], both fully consistent with all of the spin–spin decoupling experiments. Although the majority of the proton coupling-constants for **4** were the same for both interpretations, there were three instances where the assigned coupling-constants could be interchanged, depending on the interpretation chosen. For instance, $J_{4A,5A}$ was either 1.6 or 3.0 Hz, and $J_{4C,5C}$ either 3.0 or 1.6 Hz, for interpretations 1 and 2, respectively.

A comparison of the dihedral angles found in the solid phase and the coupling constants for **4** in solution provided evidence to indicate which ^{1}H-n.m.r. interpretation is correct (see Table IV). The average, proton dihedral angles were compared to the diagrams derived from two equations that correlate dihedral angles with coupling constants[12,13]. In each of the three pairs, where the coupling constants differed depending on the interpretation, this indicated which of the two dihedral angles should result in the larger and the smaller coupling constant. In all cases, this led to the choice of interpretation 2, suggesting that this interpretation is the correct one. A comparison of the similarities between residue C of **4** and residue A of **3** also supports this interpretation. The choice of 6.1 Hz for $J_{3C,4C}$ of **4** agrees well with $J_{3A,4A}$ (6.9 Hz) of **3**. Both residues have pyranose rings with identical substitution-patterns, conformations (see Table II), and H-3–H-4 dihedral angles (~43° for residue C of **4**, and 45° for residue A of **3**).

Two crystalline forms of **4** have been observed. The crystals used in this study were obtained by using acetone as the crystallization solvent[3], and they contain one molecule of acetone in each asymmetrical unit. Acetone was also observed by ^{1}H-n.m.r. spectroscopy of the dissolved crystals, where a three-proton singlet was observed at 2.1 p.p.m. When crystals of **4** were prepared without the use of acetone (method "b", ref. 3), ^{1}H-n.m.r. spectroscopy showed no resonance for acetone, and Weissenberg photography showed them to be monoclinic, space group either $P2$ or $P2_1$, $Z = 4$, with cell parameters a = 1240, b = 780, and c = 1790 pm, and $\beta = 113°$.

EXPERIMENTAL

Crystals of **4** were obtained as colorless plates from a previous study[3]; the spectral properties were reported therein. Weissenberg and precession photographs showed them to be orthorhombic, space group $P2_12_12_1$ (systematic absences for h00, 0k0, and 00l reflections when h, k or l is odd); z = 8. X-Ray intensity data were collected from a single crystal (0.5 × 0.3 × 0.1 mm), mounted on a computer-controlled, four-circle diffractometer. Cell constants obtained from 10 centered reflections were a = 792.20(7), b = 1874.35(15), and c = 2383.02(18) pm, $\rho_{calc} = 1.530$, $\rho_{meas} = 1.527$. Data were collected in the $\omega - 2\theta$ mode, scan width 1.2°, scan rate 2°·min.$^{-1}$, $\lambda = 154.18$ pm, maximum $2\theta = 120°$, with 10-s backgrounds measured on both sides of each reflection. Six standard reflections remeasured after every 300 reflections provided a deterioration correction, and multiple measurements of a $\chi = 90°$ reflection yielded an applicable absorption correction[14]. A correction for coincidence loss was made, based on measurements of about 450 reflections at reduced beam intensity.

Initial attempts to determine the structure using MULTAN78[15] were not successful, but a more recent version of the program, MULTAN80, run with default input parameters, found the locations of 53 of the 54 non-hydrogen atoms in the two molecules of **4** per asymmetrical unit. The remainder of the structure, including an acetone molecule, was located by using conventional Fourier and least-squares methods[16]. The temperature factors were refined anisotropically for the carbon and oxygen atoms, and isotropically for hydrogen atoms. The blocked, least-squares refinement converged to an R ($= \Sigma||F_0| - |F_c||/\Sigma|F_0|$) of 0.032 for 2990 reflections with $F_0 > 4\sigma\ (F_0)$. Eighty reflections had $F < 4\sigma\ (F_0)$. The weighted R is 0.036, and the goodness of fit is 3.239. The maximum shift/error in the last refinement cycle was 0.45.

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