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Note

The crystal structure of an epoxide* of a levoglucosenone–cyclopentadiene adduct

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Levoglucosenone (1,6-anhydro-3,4-dideoxy-β-D-*glycero*-hex-3-enopyranos-2-ulose, **1**) is readily obtained from the pyrolysis of acid-treated, waste paper[1], and many aspects of its properties in synthesis have been investigated[1,2]. The reaction of **1** with cyclopentadiene yields the [4 + 2] cycloaddition product (**2**), whose structure was determined by spectroscopic methods[3]. However, the stereochemistry at C-3 and C-4 of **2** could not be definitively assigned from the ^{1}H-n.m.r. spectrum. The reaction of **2** with *m*-chloroperoxybenzoic acid has now been investigated. A single product was obtained in 86% yield, and determined by spectroscopic and X-ray diffraction methods to be epoxide **3**.

For **3**, a stereoscopic drawing derived from the X-ray data is shown in Fig. 1, and atomic coordinates are listed** in Table I. Fig. 1 shows a residue of **1** to which is fused a norbornyl epoxide moiety at C-3 and C-4. The hydrogen atoms attached to these asymmetric centers project in the same direction as the 1,6-anhydro bridge, with the levoglucosenone residue in the D-*ribo* configuration. The methylene carbon atom (C-11) of the norbornyl epoxide moiety is *exo*, with C-8 and C-9 directly "below" the pyranoid ring. The stereochemistry at each of C-3, 4, 7, and 10 of **3** is consistent with that previously assigned to **2**, and thus confirms its structure. The oxygen atom (O-8) of the epoxide group lies *exo* to the rest of the

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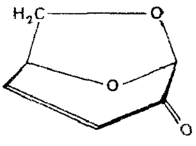
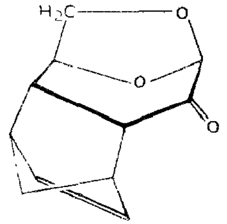
*Systematic name: (1aα,2β,2aβ,4α,7α,7aβ, 8β,8aα)-Octahydro-4,7-epoxy-2,8-methanooxireno-[*h*][3]benzoxepin-3(4*H*)-one.

**Supplementary data: Calculated hydrogen atomic coordinates (Table V), hydrogen and non-hydrogen thermal parameters (Table VI), and observed and calculated structure factors (Table VII) 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/25/*Carbohydr Res.*, 118 (1983) 261–268.



1



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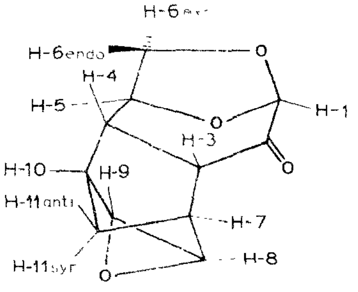

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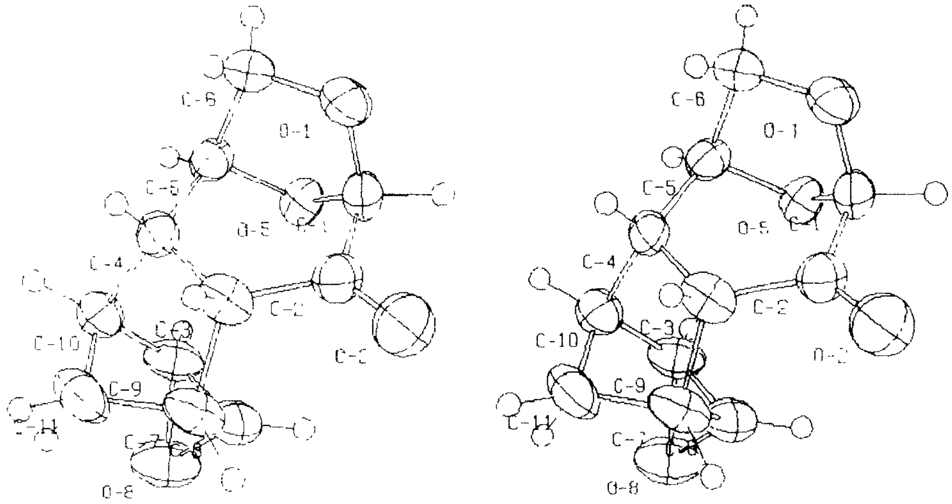

Fig. 1. Stereoview[10] of **3** from the X-ray data. [Thermal ellipsoids for carbon and oxygen atoms are at the 50% probability level. Labelling of hydrogen atoms is the same as that of formula **3**.]

molecule, with the plane defined by this three-membered ring at an angle of 52° to the plane of the pyranoid ring. Epoxidation of **2** occurs at the *exo* face, and this is consistent with reaction from the less-hindered side of the carbon–carbon double bond, as has been observed with epoxidation of norbornene[4,5].

The bond lengths and angles for **3** are respectively shown in Figs. 2 and 3. The C–O bonds of the anhydro ring show the typical pattern observed in most other 1,6-anhydrohexopyranoses, where C-6–O-1 and C-5–O-5 are longer than the mean, C–O bond-length, and C-1–O-1 and C-1–O-5 are shorter than the mean[6]. The epoxide ring forms an equilateral triangle having C–O bond-lengths of 145.7 pm, and the C–C length is 146.2 pm. The carbon bond-angles are 59.9°, and the oxygen angle is 60.2°. There is evidence for strain in other areas of the fused-ring system, particularly at the bridge-head positions (with the short C-4–C-5 bond-length of 150.1 pm) and C-11 (with a bond angle of 95.5°).

Although the model refined well (R = 0.041), not all of the hydrogen atoms refined to chemically reasonable locations. Carbon–hydrogen bond-lengths ranged

TABLE I

FRACTIONAL ATOMIC COORDINATES[a] FOR **3**

Atom	*x*	*y*	*z*	*Atom*	*x*	*y*	*z*
C-1	3826(5)	1720(6)	10431(6)	O-8	8446(4)	−1300(5)	10288(5)
C-2	4612(6)	1226(6)	11472(6)	H-1	390(7)	300(8)	1027(5)
C-3	4864(6)	−0463(6)	11603(6)	H-3	454(8)	−096(7)	1210(5)
C-4	4356(5)	−1445(5)	10621(6)	H-4	375(6)	−206(6)	1084(4)
C-5	3597(5)	−0585(5)	9710(6)	H-5	396(7)	−124(7)	885(6)
C-6	2011(5)	−0050(6)	10002(7)	H-6*endo*	171(5)	−064(5)	1058(4)
C-7	6557(6)	−0924(7)	11781(6)	H-6*exo*	141(6)	003(6)	938(4)
C-8	7388(6)	−0248(7)	10800(7)	H-7	715(8)	−038(7)	1255(7)
C-9	6904(5)	−1177(7)	9869(6)	H-8	753(4)	086(5)	1078(3)
C-10	5840(5)	−2329(6)	10324(6)	H-9	683(6)	−102(5)	915(4)
C-11	6465(7)	−2587(7)	11484(8)	H-10	558(7)	−337(8)	977(6)
O-1	2267(4)	1394(4)	10541(6)	H-11*anti*	630(11)	−347(11)	1205(8)
O-2	4959(5)	2134(5)	12174(6)	H-11*syn*	723(6)	−313(6)	1142(4)
O-5	4366(4)	0871(4)	9548(5)				

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

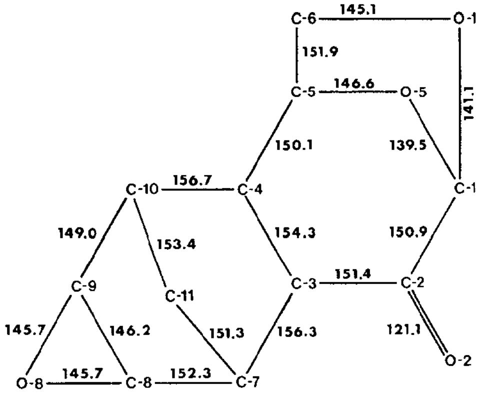

Fig. 2. Bond lengths (pm) for **3**. [Bond lengths involving hydrogen atoms are not included. Standard deviations ranged from 0.6 to 1.1 pm.]

from 80 to 124 pm, and bond angles involving hydrogen ranged from 76 to 134°. As a result, the positions of hydrogen atoms were calculated from the carbon and oxygen positions[7], based on C–H bond-lengths of 105 pm, and these calculated, hydrogen-atom positions were used to calculate the proton dihedral angles shown in Table II.

The presence of the rigid, norbornyl moiety of **3** results in a flattening of the pyranoid ring. Calculation of ring-puckering parameters[8,9] from the X-ray data (see Table III) shows that the pyranoid moiety of **3** assumes a *sofa*$_0$ conformation (five atoms coplanar). A "perfect" *sofa*$_0$ conformer would have[9] the parameters θ

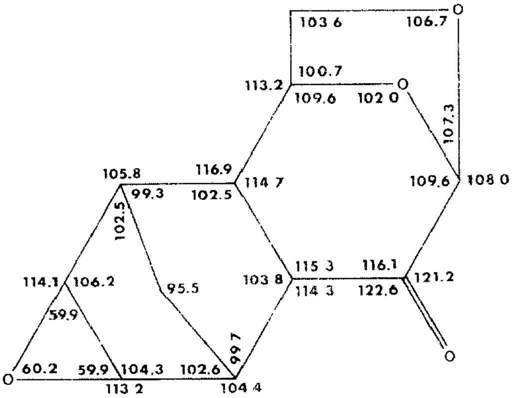

Fig. 3 Bond angles (degrees) for **3** [Angles involving hydrogen atoms are not included. Standard deviations ranged from 0.4 to 0.6°.]

TABLE II

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

Protons involved	*Dihedral angle (°)*	*Coupling constant (Hz)*
3,4	2	10.3
4,5	75	~0
5,6*endo*	88	~0
5,6*exo*	38	3.9
3,7	42	4.7
4,10	77	3.7
7,8	50	~0
9,10	42	small[b]
7,11*anti*	72	~0
10,11*anti*	103	~0
7,11*syn*	63	1.9
10,11*syn*	32	1.9
8,9	0	5.6

[a]Derived from carbon atomic positions from X-ray data, and calculated hydrogen atomic coordinates (Table IV). [b]Observed as a sharpening of the resonance for H-9 upon spin–spin decoupling.

TABLE III

PUCKERING PARAMETERS FOR **3**

Ring	*Q (pm)*	*θ (°)*	*ϕ (°)*	*Atom no.*		
				1	*2*	*3*
Pyranoid	62.5	127.0	179.3	O-5	C-1	C-2
Anhydro	41.1		46.3	C-1	O-5	C-5
Cyclohexane	98.6	89.2	119.9	C-4	C-3	C-7
Cyclopentane	61.1		1.6	C-11	C-10	C-4
Cyclopentane	52.4		0.5	C-11	C-7	C-8

TABLE IV

RING TORSION-ANGLES FOR **3**[a]

Atom				*Angle (degrees)*
1	*2*	*3*	*4*	
C-1	C-2	C-3	C-4	3.1(7)
C-1	C-2	C-3	C-7	123.3(6)
C-2	C-3	C-4	C-5	−3.7(7)
C-2	C-3	C-4	C-10	124.2(5)
C-2	C-3	C-7	C-8	−55.5(7)
C-2	C-3	C-7	C-11	−161.3(6)
C-3	C-4	C-5	C-6	−72.3(6)
C-3	C-4	C-5	O-5	39.3(6)
C-3	C-7	C-8	C-9	−71.2(5)
C-3	C-7	C-8	O-8	−134.3(5)
C-3	C-7	C-11	C-10	57.6(6)
C-4	C-3	C-7	C-8	70.9(6)
C-4	C-3	C-7	C-11	−34.9(7)
C-4	C-5	C-6	O-1	86.6(6)
C-4	C-5	O-5	C-1	−76.4(5)
C-4	C-10	C-11	C-7	−58.8(5)
C-5	C-6	O-1	C-1	6.8(7)
C-5	O-5	C-1	C-2	76.0(5)
C-5	O-5	C-1	O-1	−41.1(5)
C-6	C-5	O-5	C-1	43.2(6)
C-6	O-1	C-1	C-2	−96.9(6)
C-6	O-1	C-1	O-5	21.2(6)
C-7	C-3	C-4	C-5	−129.4(5)
C-7	C-3	C-4	C-10	−1.6(6)
C-7	C-8	C-9	C-10	0.0(5)
C-7	C-8	C-9	O-8	−108.8(5)
C-7	C-8	O-8	C-9	93.6(6)
C-8	C-7	C-11	C-10	−49.7(5)
C-8	C-9	C-10	C-4	71.7(6)
C-8	C-9	C-10	C-11	−31.9(5)
C-8	O-8	C-9	C-10	−95.4(6)
C-9	C-10	C-4	C-3	−69.0(6)
C-9	C-10	C-4	C-5	57.4(6)
C-9	C-10	C-11	C-7	49.8(5)
C-10	C-4	C-5	C-6	167.6(4)
C-10	C-4	C-5	O-5	−80.8(6)
C-11	C-7	C-8	C-9	32.4(6)
C-11	C-7	C-8	O-8	−30.6(7)
C-11	C-10	C-4	C-3	37.0(5)
C-11	C-10	C-4	C-5	163.4(4)
O-1	C-1	C-2	C-3	76.2(5)
O-1	C-1	C-2	O-2	−100.9(6)
O-2	C-2	C-3	C-4	−179.8(5)
O-2	C-2	C-3	C-7	−59.6(8)
O-5	C-1	C-2	C-3	−40.4(6)
O-5	C-1	C-2	O-2	142.5(5)
O-5	C-5	C-6	O-1	−30.4(7)
O-8	C-8	C-9	C-10	108.8(5)
O-8	C-9	C-10	C-4	135.4(6)
O-8	C-9	C-10	C-11	31.9(7)

[a] Standard deivation in parentheses.

= 125.3° and $\phi = 180.0°$. The deviations of the six atoms of the pyranoid ring from the least-squares plane[10] defined by the five carbon atoms of this ring also demonstrate existence of the *sofa*$_0$ conformation. The five carbon atoms are coplanar, with maximum, and average, absolute deviations of 1.9 and 1.2 pm, respectively, and the ring-oxygen atom, O-5, lies well "below" the plane (81.9 pm). The ring torsion-angles for **3** are listed in Table IV. The anhydro ring has a conformation lying between an envelope ($E_{O\text{-}5}$, where $\phi = 36°$) and a twist ($^{C\text{-}5}T_{O\text{-}5}$, where $\phi = 54°$), as is typically observed in 1,6-anhydrohexopyranoses[11]. The conformation of the cyclohexane ring is a boat ($^{7,10}B$, where $\theta = 90°$ and $\phi = 120°$) and the conformation of each of the two cyclopentane rings is an envelope (^{11}E, where $\phi = 0°$).

Evidence of flattening of the pyranoid ring in solution was also observed by ^{1}H-n.m.r. spectroscopy (see Table II), where the spin–spin coupling between H-3 and H-4 is large (10.1 Hz), indicating a small dihedral angle between these *cis* atoms (calculated to be 2° in the crystalline state). In other 1,6-anhydropyranoses in a chair conformation, $J_{3,4}$ (axial-equatorial) is usually[12] within the range of 4.2–5.8 Hz. In addition, $J_{4,5}$ of **3** is unusually small (~0 Hz), indicating a large dihedral angle (calculated to be 75° in the crystalline state), whereas 1.5–2.5 Hz would be expected for a chair conformation[12].

The ^{1}H-n.m.r. spectrum of **3**, interpreted with the aid of spin–spin decoupling experiments, is consistent with the spectral data for related compounds[13]. Two doublets, at δ 3.47 and 3.08, were observed, and determined to be the resonances for the epoxide H-9 and H-8, respectively. Both are shifted downfield from the equivalent resonance of *exo*-norbornene epoxide (2.90 p.p.m.)[14]. The dihedral angle formed by these hydrogen atoms of the epoxide was found to be 0° in the solid phase, and, in solution, $J_{8,9}$ 3.6 Hz is within the range of 3.0–4.5 Hz found in steroid *cis*-epoxides[15]. Coupling between H-8 and 9 of the epoxide and their vicinal atoms (H-7 and 10, respectively) is small, with $J_{7,8}$ indiscernible, and $J_{9,10}$ only observed as a sharpening at 3.47 p.p.m. when H-9 was spin–spin-decoupled from H-10. The solid-phase dihedral-angles for these hydrogen atoms were found to be 50 and 42°, respectively. Similarly, in other epoxycyclopentanes, *vicinal* coupling has been found to violate the Karplus equation, and was only observed[16] at dihedral angles of <50°.

EXPERIMENTAL

Synthesis of **3**. — An 85% solution of *m*-chloroperoxybenzoic acid (0.80 g, 4.0 mmol) in chloroform (~9 mL) was slowly added to a solution of compound[3] **2** (0.48 g, 2.5 mmol) in chloroform (7 mL). The solution was stirred for 17 h at room temperature, t.l.c. then showed complete depletion of **1** and the appearance of a single product, R_F 0.43, on Baker-flex silica gel IB2-F with 1:1 hexane–ethyl acetate. The solution was cooled to 0°, and the precipitate of *m*-chlorobenzoic acid was removed by filtration, and washed three times with cold chloroform. The extract and washings were combined, washed three times with saturated aqueous sodium hydrogencarbonate and once with distilled water, dried (sodium sulfate), and evaporated, to give **3** as a white solid (0.45 g, 86%). Recrystallization from ethyl acetate by slow evaporation gave colorless needles, m.p. 140–141°; ν_{max}^{KBr} 2968 (C–H stretch) and 1723 cm^{-1} (C=O); ^{1}H-n.m.r. (360 MHz, $CDCl_3$–Me_4Si): δ 5.04 (s, 1 H, H-1), 4.82 (d, 1 H, H-5), 3.86 (m, 2 H, H-6*endo*, H-6*exo*), 3.47 (d, 1 H, H-9), 3.08 (d, 1 H, H-8), 3.05 (br d, 1 H, H-7), 2.84 (dd, 1 H, H-3), 2.78 (m, 1 H, H-10), 2.31 (dd, 1 H, H-4), 1.51 (dm, 1 H, H-11*syn*, $J_{11syn,11anti}$ 10.1 Hz), and 0.75 (d, 1 H, H-11*anti*); ^{13}C-n.m.r. (90.6 MHz, $CDCl_3$–Me_4Si): δ 200.4 (C-2), 100.5 (C-1), 74.6 (C-5), 70.5 (C-6), 49.5 and 48.9 (C-8,9), 44.8 (C-7,10), 42.5 (C-3), 41.0 (C-4), and 26.2 (C-11).

Anal. Calc. for $C_{11}H_{12}O_4$: C, 63.5; H, 5.8. Found: C, 63.5; H, 6.0.

X-Ray structure determination. — Weissenberg photographs of crystals of **3** showed them to be tetragonal, space group $P4_1$ or $P4_3$ (001 reflections present for 1 = 4*n*); *z* = 4. X-Ray intensity data were collected from a single crystal (0.21 × 0.21 × 0.10 mm), mounted on a computer-controlled, four-circle diffractometer. Cell constants obtained from 18 centered reflections were a = b = 882.0 (1), c = 1217.5(3) pm. Data were collected in the $\omega - 2\theta$ mode, scan width 1.2°, scan rate 2°/min, λ 154.18 pm, maximum $2\theta = 120°$ (CuKα radiation), with 10-second backgrounds measured on both sides of each reflection. Six standard reflections measured periodically throughout the data collection indicated no deterioration of the crystal in the X-ray beam, and multiple measurements of a $\chi = 90°$ reflection showed no need for absorption correction. A correction for coincidence loss was used, based on measurements of 70 reflections at reduced beam-intensity.

The D configuration of the molecule was known from the chemical and synthetic work. The structure solution was carried out in space group $P4_1$, and resulted in a model having the (correct) D configuration, indicating the correct choice of space group. MULTAN80[16] (run with default input-parameters) revealed the locations of 13 of the 15 non-hydrogen atoms in the asymmetric unit. The remainder of the structure was elucidated by using conventional Fourier and least-squares programs of the XRAY76 system[10]. Atomic coordinates and anisotropic temperature-factors were refined for the carbon and oxygen atoms. After all of the hydrogen atoms had been located, four parameters per hydrogen atom, including isotropic temperature-factors, were refined. During the final cycles of refinement, three reflections with significant differences between their calculated and observed amplitudes were omitted from the data set. The 102 and 110 reflections were very intense, and had significant, coincidence losses, even at reduced beam intensity, and the background for 320 was abnormally low. The least-squares refinement converged to an R ($= \Sigma||F_o| - |F_c||/\Sigma|F_o|$) of 0.041 for 773 reflections with $F_o > 4\,\sigma(F_o)$. Eight reflections had $F_o < 4\,\sigma(F_o)$. The weighted R was 0.071, and the goodness of fit, 6.93. The maximum shift/error in the last refinement cycle was 0.90.

ACKNOWLEDGMENTS

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