The Photochemistry of Ketones Derived from Carbohydrates. Part 10.[1] A Study of Stereochemical Influences on Photo-induced Rearrangements and Ring Expansions of 3-Oxacyclopentanones Using 1,2-O-Isopropylidenefuranos-3-ulose Derivatives

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U.v.-irradiation of the 3-oxacyclopentanone 5-deoxy-1,2-O-isopropylidene-β-D-*threo*-pentofuranos-3-ulose (9) in methanol gave at −60 °C, and to a small extent at +20 °C, [2S,3R,5S,6R]-2,3-isopropylidenedioxy-5-methoxy-6-methyl-1,4-dioxane (12), whereas in a benzene solution at +20 °C only the unsaturated lactones 2,2-dimethyl-5-[(Z)-prop-1-enyloxy]-1,3-dioxolan-4-one (13) and its (E)-isomer (14) were obtained. The photoproducts formed from (9) in methanol–diethyl ether (1:4) at −60 °C were a mixture of the dioxane (12) and the lactones (13) and (14). The isomeric *erythro*-ulose (20) gave only the lactones (13) and (14) when irradiated in either methanol–diethyl ether (1:4) at −60 °C or in benzene at +20 °C. The lactone mixtures from (9) and (20) possessed similar specific optical rotations.

U.v.-irradiation of a benzene solution of 1,2-O-isopropylidene-α-L-*glycero*-tetrofuranos-3-ulose (22) at +20 °C gave racemic 5-ethenyloxy-2,2-dimethyl-1,3-dioxolan-4-one (16). The optical activity exhibited by the lactone mixtures produced from ketones (9), (20) and (22) indicated that they were not formed *via* the respective oxacarbenes (11), (29) and (30), which are chiral, but through the intermediacy of the symmetric enals (31) from (9) and (20), and (32) from (22).
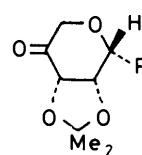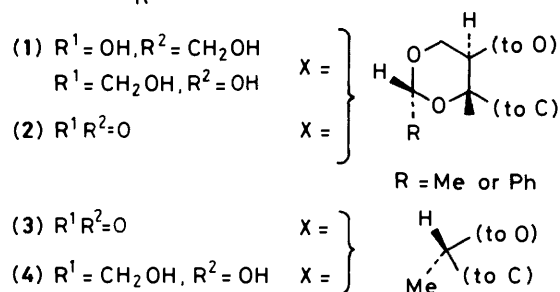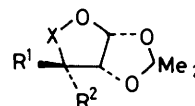
The uloses (9) and (20) formed hemiacetals (18), and (23) and (24) respectively, in methanolic solutions but only to a limited extent at low temperatures.

C-3-Hydroxymethyl branched-chain sugars (1) are formed at ambient temperatures by photo-induced cross-pinacolization of methanol with 1,2:4,6-diacetalated-*ribo*-hexopyranos-3-uloses (2).[2] When we subjected the 3-oxacyclopentanone 5-deoxy-1,2-O-isopropylidene-β-L-*threo*-pentofuranos-3-ulose (3)[3,†] to these reaction conditions as a potential route to the acetonide of dihydrostreptose (4), cross-pinacolization was not observed.[4] The only photoproduct detected, and isolated in low yield, was the ring-expanded 1,4-dioxane derivative [*i.e.* the enantiomer of (12)]. Although this reaction is not as striking as the conversion of the six-membered ring sugar ketones (5) and (6) into the seven-membered ring products (7)[4] and (8),[5] which occurs in low-temperature photoreactions, it did represent the first example of an oxacyclopentanone increasing its ring size. Previously, ring expansions[6] had only been observed when the cyclopentanones were part of bridged 2-norbornane ring systems,[7] or when their α-carbon atoms were incorporated into cyclopropane rings.[8] Subsequently, Yates and his co-workers[9] have reported ketone ring expansions for three monocyclic oxacyclopentanones.
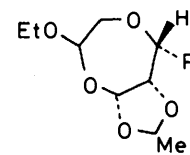
In this paper we exploit the array of stereoisomers offered by the carbohydrates to explore further the photoreactions of 3-oxacyclopentanones related to compound (3).[‡] The three 1,2-O-isopropylideneglycofuranos-3-uloses, (9), (20), and (22), with the β-D-*threo*-pentose, α-D-*erythro*-pentose, and α-L-*glycero*-tetrose structures, have been synthesized and photolysed.

Results and Discussion

Since the conversion of pyranos-4-ulose derivatives into ring-expanded products [*i.e.* (5) and (6) into (7) and (8)] occurs most efficiently in alcohol–diethyl ether mixture at low temperature,[4]

(1) R¹ = OH, R² = CH₂OH
    R¹ = CH₂OH, R² = OH   X = ⌐

(2) R¹R² = O   X = ⌐

R = Me or Ph

(3) R¹R² = O   X = ⌐
(4) R¹ = CH₂OH, R² = OH   X = ⌐

(5) R = H
(6) R = OMe

(7) R = H
(8) R = OMe

the D-*threo*-ulose (9)[10] was irradiated in a 1:4 combination of methanol and diethyl ether at −60 °C with the light from a medium-pressure 450-W lamp until most of the ulose (9) had reacted. G.l.c. analysis of the photolysate showed five product peaks, three of which were significant. Flash chromatography afforded these three materials, the structures of which were determined by elemental analysis and ¹H and ¹³C n.m.r. spectroscopy as described later.

The first fraction, with R_F 0.86, isolated in only 5% yield was a mixture of the two isomeric unsaturated lactones (13) and (14),

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† The compound was erroneously designated *erythro* in ref. 4.
‡ For the ketones derived from sugars, carbohydrate numbering is used; for the dioxanes, heterocyclic numbering is employed.

R_t 15 and 18 min. Quantitative ^{1}H n.m.r. spectroscopic analysis of the crude photolysate suggests that these lactones underwent some degradation during photolysis and upon chromatography. The second fraction obtained in 27% yield was the ring-expanded dioxane (12), R_t 26.3 min. In addition to these compounds column chromatography yielded some unchanged ulose (9) and three impure fractions, R_F 0.54, 0.23, and 0.14. The ^{1}H n.m.r. spectrum of the two polar fractions indicated that diethyl ether had combined with the sugar molecule, possibly to give cross-pinacolized adducts (17).

Irradiation of (9) in pure methanol at $-60\,^\circ$C produced a similar quantity of the 1,4-dioxane derivative (12), a trace of hemiacetal (18), but no lactones. Irradiation of a similar solution at $+20\,^\circ$C gave the same products, but the quantity of (12) produced was very small. Although ring expansion of furanos-3-ulose derivatives was first[4] detected * under the last set of conditions it is more satisfactory to work at low temperatures where loss of the ketone to the non-absorbing hemiacetal (18) is suppressed.
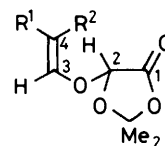
The isomeric D-*erythro*-ulose (20)[10] behaves differently from (9) when irradiated in methanol–diethyl ether (1:4) at $-60\,^\circ$C since although it affords lactones (13) and (14), and two hemiacetals (23) and (24) as expected, ring-expanded dioxanes could not be isolated from the crude photolysate or detected in it by ^{1}H n.m.r. spectroscopy.
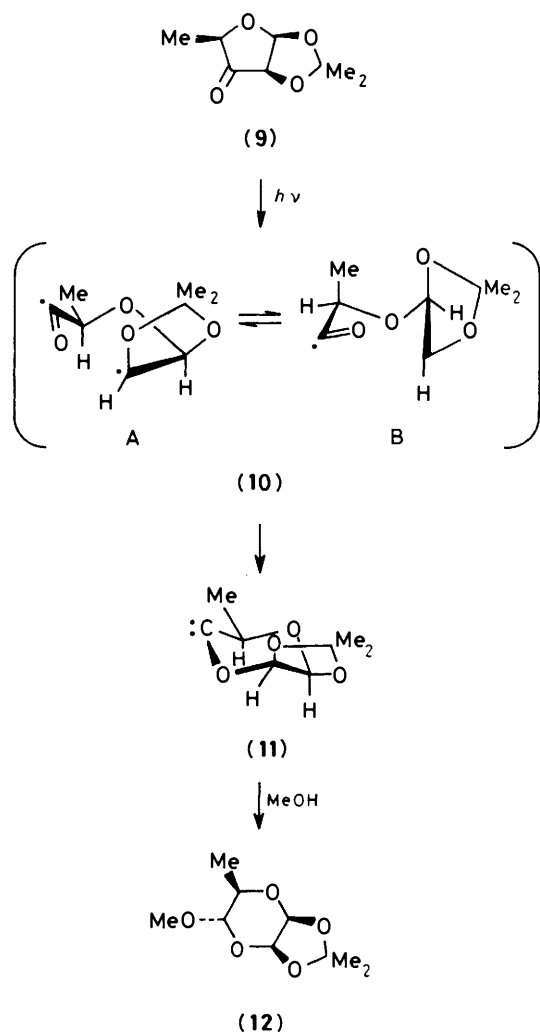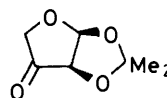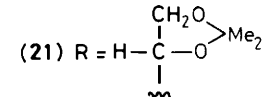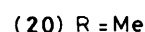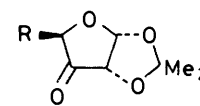
Irradiation of the *erythro*- and *threo*-ketones (20) and (9) in benzene both gave the lactones (13) and (14) as the only identified products. ^{1}H N.m.r. spectroscopic analysis of these reactions in hexadeuteriobenzene revealed that the *E*-lactone (14) was initially formed and subsequently isomerized to (13) during the irradiation.

The conversion of the *threo*-ulose (9) into the 1,4-dioxane (12) may be accounted for as shown in the Scheme. Norrish Type 1 cleavage of the C-2 and C-3 bond in the direction of the dioxolane ring is common with hexosuloses protected with cyclic acetal groups.[11,12] The biradical (10) so formed could rearrange into the oxacarbene (11) and finally be trapped by methanol.[6]

Numerals for n.m.r. assignments

(13) R^1 = H, R^2 = Me
(14) R^1 = Me, R^2 = H

(15) R^1 = [CH$_2$O / H–C–O] >Me$_2$, R^2 = H

(16) R^1 = R^2 = H

(17) R^1 = OH, R^2 = CH(Me)OEt
(18) R^1 = OH, R^2 = OMe
(19) R^1 = OH, R^2 = H

(20) R = Me
(21) R = H–C–O [CH$_2$O >Me$_2$]

(22)

(23) R^1 = OMe, R^2 = OH, R^3 = Me
(24) R^1 = OH, R^2 = OMe, R^3 = Me
(25) R^1 = OH, R^2 = H, R^3 = Me
(26) R^1 = OH, R^2 = R^3 = H
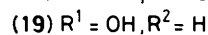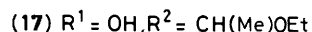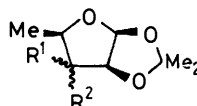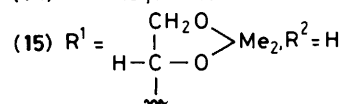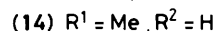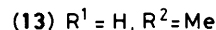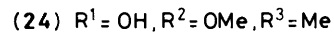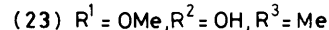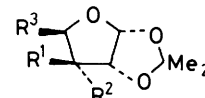
One structural feature, which appears to dictate that a significant proportion of the biradicals (10) ring close to oxacarbenes rather than undergo one of the other transformations available to them, is the 1,3-positional relationship between the carbonyl group and the ring oxygen atom.[9] This structural feature is also present in the six-membered ring ketones (5) and (6) which undergo this reaction.[4,5] The failure of the *erythro*-ulose (20) to ring expand however indicates th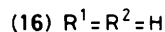at a detailed understanding of the structural requirements for photochemical ring expansion of these heterocyclic ketone

(9)

↓ *hν*

(10)

A   B

↓

(11)

↓ MeOH

(12)

Scheme.

* Detection is most readily achieved by g.l.c. analysis of a photolysate.

(27) (28)

(29) (30)

(31) R¹ = Me, R² = H
(32) R¹ = R¹ = H
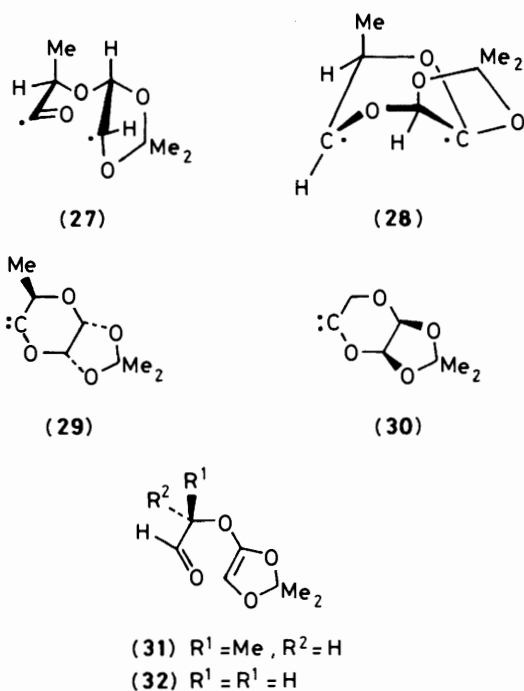
derivatives is not yet complete, but it would appear that the conformation of the biradicals (10) and (27) is important.

In the conversion of the *threo*-ulose (9) into the dioxane (12) the biradical intermediate could adopt conformations (10A) and (10B) for ring closure, but the former is preferred since the methyl group is equator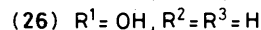ially disposed on the developing six-membered ring. This also leads to bond formation with a favourable anomeric effect at the C-3 position in the oxacarbene (11), which could account for the successful ring closure. On the other hand the equivalent conformation, possessing this advantage, for the biradical intermediate from the *erythro*-ulose (20) is (27). This however places the methyl group in an unfavourable axial position and consequently could cause this biradical to react differently.

The *threo*-ulose (9) in solvents containing methanol also underwent a photochemical rearrangement into the lactones (13) and (14), a process related to the transformation of 1,2:5,6-di-O-isopropylidene-α-D-*ribo*-hexofuranos-3-ulose (21) into (15) observed [13] in irradiated benzene and t-butyl alcohol solutions. Although ring-expanded products were not detected, it was proposed that (15) arose from an oxacarbene intermediate. The observation made in this work with (9) might be taken as support for this proposal, since it could be envisaged that (11) affords both the dioxane (12) and the lactones (13) and (14). For lactones to be formed from this intermediate, the C-5 carbene centre would need to insert into the C-2-hydrogen bond, presumably with (11) in an alternative $B_{2,5}$ conformation. This would yield either a tricyclic compound or the biradical precursor [14] of it [*i.e.* (28)], which could rearrange to (13). However, transannular insertion reactions of carbenes usually occur only with medium-sized rings[15] In our work an insertion has been observed on one occasion[5] with ketone (6), which involved a seven-membered ring carbene and the adjacent C–H bond, and leads to a 1,4-dioxacyclohept-2-ene derivative.

If the *erythro*-ulose (20) failed to afford ring-expanded dioxanes when it was irradiated in methanolic solvents, because the oxacarbene did not form, then the lactones produced from it, and presumably from (9) also, must arise from another intermediate. Enals are common photoproducts from cyclic ketones[16] and compound (31), which is similar to the inter-

mediate required to explain the photorearrangements we observed[17] with some hexopyranos-3-ulose (3-oxacyclohexanone) derivatives, is a possible candidate. It could be transformed in a Patterno–Büchi[18] reaction into the biradical precursor[14] of an oxetane and thence into an unsaturated lactone [formula (28) illustrates the structure, but probably not the correct conformation, of one of the possible C-3 isomers for the biradical intermediate]. An alternative thermal [3,3]-sigmatropic transformation of (31) cannot be excluded because although Claisen rearrangements[19] usually occur at elevated temperatures it has been found that they are accelerated with certain electron-rich systems.[20]

A choice between the enal routes [(9) ⟶ (10) ⟶ (31) ⟶ (13) and (14)] and [(20) ⟶ (27) ⟶ (31) ⟶ (13) and (14)] and the oxacarbene routes [(9) ⟶ (10) ⟶ (11) ⟶ (13) and (14)] and [(20) ⟶ (27) ⟶ (29) ⟶ (13) and (14)] may be made by polarimetric studies. The intermediates (11) and (29) involved in the latter reaction pathway retain the same stereochemistry at C-3 as that possessed at C-2 in (9) and (20) respectively and this will be maintained in the lactones. Thus lactones (13) and (14) from (9) should be the enantiomers of those formed from (20). In the other route both (9) and (20) produce the same enal [*i.e.* (31)] and consequently afford (13) and (14) with the same degree of induced asymmetry.* Since the optical rotations for the lactone mixtures from (9) and (20) were similar, with values of $+28°$ and $+32°$ respectively, the enal appears to be the intermediate in these reactions.

In order to investigate further the nature of the intermediate involved in lactone formation we synthesized 1,2-O-isopropylidene-α-L-*glycero*-tetrofuranos-3-ulose (22), irradiated it in benzene, and isolated an unsaturated lactone (16) uncomplicated by Z, E-forms. This could have been formed *via* enal (32), which being symmetric would yield racemic unsaturated lactones. Alternatively the oxacarbene (30) could have been involved and this would possess the same stereochemistry at C-3 as that at C-2 in the ulose (22) and consequently would yield one enantiomer of (16). Examination of the photoproduct by polarimetry and c.d. revealed that it was optically inactive. Thus it is concluded that the lactone is formed as a racemate *via* the enal (32) rather than from the oxacarbene (30).

The assignment of structure to the products formed in these reactions was made as follows. The material with R_F 0.85 obtained from uloses (9) and (20) after a full period of irradiation in benzene or methanol was shown to be an equilibrated mixture of the Z- and E-unsaturated lactones (13) and (14) in which the latter predominated. Elemental analysis, the $v_{max.}$ band at 1 805 cm⁻¹, and n.m.r. spectroscopy were used to make the assignment. The eight carbon resonances exhibited by the major isomer are recorded in Table 1. The signals at δ_C 142.8, 94.7, and 12.3 p.p.m. for C-3, -4, and CH_3 are very similar to the related nuclei in E-1-methoxypropene.[21] The resonance at 167.1 p.p.m. indicates a lactone and those at 27.2, 28.2, and 113.1 p.p.m. suggest an isopropylidene acetal in a five-membered ring, since the $\Delta\delta_C$ of the gem-dimethyl groups is 1.0 p.p.m.[22] When all this evidence is taken in conjunction with the additional acetal carbon signal at δ_C 106.6 p.p.m., a 2,2-dimethyl-5-alkoxy-1,3-dioxolan-4-one is indicated. Dioxolan-4-one ring systems have been prepared by other routes[23] and the limited ¹³C n.m.r. data available[24] indicate that the carbonyl carbon in (14) is shielded by 6.9 p.p.m. compared with this resonance in 2,2,5-trimethyl-1,3-dioxolan-4-one. This shielding must be due to the β-effect of the alkoxy group at C-5 since the chemical shift of the carbonyl carbon in (15), which was also

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* The asymmetric induction is caused by the methyl group at the chiral centre of (31) exerting an influence on the conformation of the six-membered ring transition state[19] involved in the conversion of the enal (31) into the lactones (13) and (14).

Table 1. N.m.r. parameters for 5-alkenoxy-1,3-dioxolan-4-one derivatives in $CDCl_3$,[a],[b] δ_H and J (Hz) measured at 200 MHz, and δ_C (p.p.m.) measured at 15 MHz (values given in brackets)

				Nucleus		
Compd	1	2	3	4	4'	5
(13)		5.44	6.20	4.79		1.63
		s	dq	quin.		dd
			$J_{3,4}$ 6.5	$J_{4,5}$ 6.5		$J_{5,3}$ 2.5
		(4.92)	(5.88)	(4.51)		(1.55)
(14)		5.45	6.30	5.16		1.59
		s	dq	dq		dd
			$J_{3,4}$ 12.5	$J_{4,5}$ 6.5		$J_{5,3}$ 2.0
		(5.01)	(5.98)	(5.10)		(1.24)
	[167.1]	[106.6]	[142.8]	[94.7]		[12.3]
(15)[c]		5.49	6.54	5.17		
		s	d	dd		
			$J_{3,4}$ 13.0	$J_{4,5}$ 8.0		
	[166.0]	[108.8]	[146.3]	[94.4]		
(16)		(4.98)	(6.03)	(4.50)	(4.03)	
		s	dd	dd	dd	
			$J_{3,4}$ 14.0	$J_{4,4'}$ 2.0	$J_{4',3}$ 6.5	

[a] δ_H Values in parentheses are measured in C_6D_6; the J values are unchanged. [b] Isopropylidene groups give rise to two singlets in the region δ_H 1.08—1.41 and for (14) three signals at δ_C 113.1, 28.2, and 27.1. [c] Values taken from ref. 13.

Table 2. ¹³C N.m.r. data (δ_C/p.p.m.) relative to TMS for furanose and 1,4-dioxane derivatives measured at 50.1 MHz in $CDCl_3$

				Nucleus					
Compd	1	2	3	4	5	6	7	Me₂C	OMe
(9)	102.6	77.3[a]	211.2	77.0[a]	18.4			27.0, 27.4 114.6	
(12)		96.2[a]	95.1[a]		100.2	69.9	17.5	27.5, 27.9 110.9	56.4
(20)	102.5	75.8[a]	210.1	73.8[a]	15.4			27.07, 27.09 114.1	
(22)	104.5	69.1[a]	209.6	75.9[a]				27.1, 27.4 114.1	

[a] Signals for each compound are interchangeable.

prepared[13] by ulose photolysis, is similar to that in (14) (see Table 1).

The ¹H n.m.r. spectrum of this product (see Table 1) also indicates structure (14). The vinylic protons are clearly *trans*-disposed because $J_{3,4}$ is 12.5 Hz. The methyl group is attached to C-4 since the three hydrogens are vicinally coupled to 4-H by 6.5 Hz and allylically coupled to 3-H by 2.0 Hz. The low-field singlet (δ_H 5.45) for 2-H is as expected for a proton in this environment.

The minor isomer possessed the ¹H n.m.r. spectrum recorded in Table 1 which is very similar to that of the *E*-isomer except for the expected smaller value of 6.5 Hz for the $J_{3,4}$ coupling of the *cis*-vinylic protons.

The product with R_F 0.5 obtained by irradiating the L-*glycero*-ulose (22) in benzene was also shown to be an unsaturated lactone by elemental analysis and i.r. and ¹H n.m.r. spectroscopy. The features in the ¹H n.m.r. spectrum, recorded in Table 1, that are most indicative of structure (16) are the three coupled vinylic proton resonances.

The major product formed upon irradiation of the *threo*-ulose (9) in methanolic solvents with R_F 0.69 and R_t 26.2 min. was characterized as the ring-expanded 1,4-dioxane derivative (12) from its elemental composition, its lack of carbonyl and hydroxyl i.r. absorptions, and by n.m.r. spectroscopy. It was shown to have retained the HCCH₃ and the *O*-isopropylidene groups originally present in (9), by the resonances at δ_C 69.9 and 17.5 p.p.m. (see Table 2) and the 3-H doublet at δ_H 1.28 and the 1-H quintet at δ_H 3.47 (see Table 3) for the former group and the three resonances at δ_C 110.9, 27.5, and 27.9 p.p.m. (Table 2) and the two 3-H singlets at δ_H 1.44 and 1.64 (Table 3) for the acetonide group. The incorporation of a methoxy group into the product was indicated by the δ_C 56.34 p.p.m. signal and the 3-H singlet at δ_H 3.54. The signals in Table 2 at δ_C 95.1, 96.2, and 100.2 p.p.m. and those in Table 3 at δ_H 5.46, 5.24, and 4.62 showed the product possessed three acetal methine carbons. All these structural units appear in the proposed compound (12) and the splitting patterns of the coupled protons corroborate this assignment.

The stereochemistry at C-2 and C-6 in (12) is assumed to be the same as at C-1 and C-4 respectively in ulose (9) since bonds to these carbons were not cleaved during the reaction, whereas the configuration at C-3 can be either (*R*) as shown in (12) or (*S*). Ring closure of the biradical (10) to give the latter configuration would produce a *trans*-fused isopropylidene ring. Although strained this arrangement has been produced during the photo-isomerization of a 2,3-*O*-isopropylidenepyranosid-4-ulose.[12] However, vicinal proton coupling at the *trans* junctions of these rings was *ca.* 10 Hz. Since the $J_{2,3}$ value is 3.0 Hz the rings must be *cis*-fused in compound (12). Consequently the conformation of the dioxane ring is not locked. Therefore the $J_{5,6}$ coupling of 6.5 Hz indicates the (5*S*)-structure for (12) in which 5-H and 6-H adopt the ax–ax and eq–eq orientations in the two chair forms of the dioxane ring, rather than the alternative (5*R*)-structure in which these hydrogens would be eq–ax and ax–eq in the two conformers. These conclusions are supported by the observations of Fuchs and co-workers on 2,3- and 2,5-dialkoxy-1,4-dioxane ring systems.[25]

The uloses (9) and (20) readily formed hemiacetals in methanolic solution at + 20 °C, which is not surprising since hydroxylic solvents are known[26] to add to the keto groups of furanos-3-ulose and pyranos-2-ulose derivatives. The adducts from (9) and (20) were identified by spectroscopic analysis of the material obtained upon evaporation of the alcohol. Strong i.r. absorptions indicated that hydroxy groups were present in the products. The ¹H n.m.r. spectrum of the residue from (20) indicated that in addition to 16% unchanged (20) (δ_H 6.11, d, 1-H), 39 and 45% of the isomeric hemiacetals (23)/(24) were present. This was indicated by the two doublets at δ_H 5.85 and 5.77 for the anomeric protons, the two singlets at δ_H 3.46 and 3.48 for the methoxy groups, as well as signals for the other required protons which are recorded in Table 3.

Ulose (9) produced a single hemiacetal (18), which was less stable than (23) and (24). The ¹H n.m.r. spectrum of the material which remained after evaporation of the methanol showed, in addition to weak signals for a trace of unchanged (9), a doublet at δ_H 5.75 and a singlet at δ_H 3.42 for the anomeric proton and the methoxy group respectively. In addition there were signals for the other protons in (18) as recorded in Table 3.

On steric grounds ulose (20), with the upper and lower faces of the furanose ring equally exposed, would be expected to add methanol from either direction, whereas it would be anticipated that (9) with a sterically crowded upper face would yield only one hemiacetal with attack from the methoxy group occurring most probably from the open lower face of the furanose ring.

Experimental

General Methods.—¹H N.m.r. spectra were usually measured on $CDCl_3$ solutions with tetramethylsilane (TMS) as internal standard, with a Jeol FX 200 FT instrument. Natural-abundance ¹³C n.m.r. spectra were determined usually at 15 MHz with a Jeol FX 60 spectrometer and occasionally at 50

Table 3. ^{1}H N.m.r. parameters (δ_H and J/Hz) for furanose and 1,4-dioxane derivatives measured at 200 MHz in CDCl$_3$

Compd	1	2	3	4	4'	5	6	7	Me$_2$C	OMe
(9)	5.98	4.44		4.22		1.46[b]			1.41[b]	
	d	dd		dq		d			1.48[b]	
	$J_{1,2}$ 4.0	$J_{2,4}$ 1.5		$J_{4,5}$ 6.5		$J_{5,4}$ 6.5			2 s	
(12)		5.46[a]	5.24[a]			4.62	3.47	1.28[b]	1.44[b]	3.54[b]
		d	d			d	quin.	d	1.64[b]	s
		$J_{2,3}$ 3.0	$J_{3,2}$ 3.0			$J_{5,6}$ 6.5	$J_{6,7}$ 6.5	$J_{7,6}$ 6.5	2 s	
(18)	5.75	4.32		4.01		1.13[b]			1.31[b]	3.42[b]
	d	d		q		d			1.52[b]	s
	$J_{1,2}$ 4.5	$J_{2,1}$ 4.5		$J_{4,5}$ 6.5		$J_{5,4}$ 6.5			2 s	
(20)	6.11	4.39		4.49		1.34[b]			1.41[b]	
	d	dd		dq		d			1.52[b]	
	$J_{1,2}$ 4.5	$J_{2,4}$ 1.0		$J_{4,5}$ 6.5		$J_{5,4}$ 6.5			2 s	
(22)[c]	5.50	3.63		3.93	3.48				1.28[b]	
	d	br d		dd	dd				1.12[b]	
	$J_{1,2}$ 4.2	$J_{2,4}$ ca. 1.0		$J_{4,4'}$ 17.0	$J_{4',2}$ ca.0.5				2 s	
(23)	5.83	4.3—4.4		4.00		1.23[b]			1.37[b]	3.37[b]
	d	m		q		d			1.57[b]	
	$J_{1,2}$ 4.0			$J_{4,5}$ 6.0		$J_{5,4}$ 6.0			2 s	
(24)	5.77	4.3—4.4		4.12		1.18[b]			1.35[b]	3.48[b]
	d	m		q		d			1.56[b]	
	$J_{1,2}$ 4.0			$J_{4,5}$ 6.0		$J_{5,4}$ 6.0			2 s	

[a] Could be interchanged. [b] The signals have integrals equivalent to three protons, the others have integrals equivalent to one proton. [c] Measured in C$_6$D$_6$. Parameters for compounds (9) and (20) in this solvent are recorded in the Experimental section.

MHz with a Jeol FX 200 instrument using TMS as internal standard in CDCl$_3$ solution.

Optical rotations were measured on ca. 0.5% chloroform solutions at 21 ± 2 °C with an Optical Activity polarimeter model A100. C.d. measurements were made in the range 300—230 nm on solutions in methanol containing 0.5% chloroform using a Cary 61 instrument. I.r. spectra were recorded for solids dispersed in KBr discs and for gums smeared on KBr discs with a Perkin-Elmer model 597 spectrophotometer.

T.l.c. was carried out on silica gel GF$_{254}$ (Merck) and materials were located either visually under u.v. light, with a sulphuric acid–ethanol spray reagent, or in iodine vapour. Column chromatography was carried out on silica gel 230—400 mesh (Merck 9835 under slight pressure). G.l.c. was carried out on Chromosorb W impregnated with 5% OV25 in a 20 ft × 0.125 in column maintained at 100 °C with a Varian-Aerograph instrument model 2700 equipped with an f.i.d. detector. Non-alcoholic organic solvents were dried with molecular sieves 4A.

5-*Deoxy*-1,2-*O*-*isopropylidene*-β-D-threo-*pentofuranos*-3-*ulose* **(9)**.—5-Deoxy-1,2-*O*-isopropylidene-β-D-arabinofuranose **(19)** (2.8 g) was oxidized in CCl$_4$ with ruthenium tetraoxide (from 2.4 g of the dioxide) to give, after the usual work-up and chromatography on silica gel, the furanosulose **(9)** (1.5 g, 55%), [α]$_D$ −30° {lit.,[10] [α]$_D$ −26.3° (CHCl$_3$); for the enantiomer **(3)**, lit.,[3] [α]$_D$ +76° (CHCl$_3$)}; δ_H and δ_C parameters are recorded in Table 3 and 2 respectively.

The ulose **(9)** (10 mg) was dissolved in methanol (0.1 ml) and after 1 h at 22 °C g.l.c. analysis showed two peaks, one at R_t 19.6 min and the other at R_t 24 min for the ulose **(9)**. The first peak was present in most solutions of **(9)** which contain methanol. It was probably not the hemiacetal **(18)** but possibly a thermal degradation product formed from it. The solution was cooled to below −10 °C and its volume rapidly reduced at 0.1 mmHg, deuteriochloroform (0.3 ml) was added, and the ^{1}H n.m.r. spectrum was measured. In addition to weak signals for ulose **(9)** there were resonances that could be assigned to a hemiacetal **(18)** as recorded in Table 3.

Preparative-scale U.v.-irradiation of 5-Deoxy-1,2-*O*-*isopropylidene*-β-D-threo-*pentofuranos*-3-*ulose* **(9)**.—(a) *In benzene.* The 3-ulose **(9)** (1.1 g) was dissolved in deoxygenated benzene (80 ml) and the solution was agitated by a flow of nitrogen and irradiated with light from a 450-W medium-pressure lamp in the annular cavity formed between a water-cooled immersion quartz probe (o.d. 52 mm) and an outer vessel, the diameter of which was such that the benzene solution was exposed to the full length of the mercury arc. After 45 min, t.l.c. [light petroleum (40—60 °C)–diethyl ether (5:1)] indicated that most of the ulose **(9)** R_F 0.18 had reacted to produce some polar degraded material and a non-polar product, R_F 0.5, which could be visualized under u.v. light or by absorption of iodine vapour but not with ethanolic sulphuric acid spray reagent.

The ^{1}H n.m.r. spectrum of the gum obtained after solvent evaporation was measured, and the gum was then subjected to flash chromatography which afforded 2,2-*dimethyl*-5-[(Z)-*prop*-1-*enyloxy*]-1,3-*dioxolan*-4-*one* **(13)** and its *E*-isomer **(14)** (74 mg; it is estimated that 60% of these products were lost on the column), [α]$_D$ +28°; ν$_{max.}$ 1 805 cm^{-1} (Found: C, 58.7; H, 7.4. C$_8$H$_{12}$O$_4$ requires C, 58.7; H, 7.5%). The ^{1}H n.m.r. spectrum showed two sets of signals in the ratio 2:3 for the *Z*- and *E*-isomer **(13)** and **(14)** which are recorded in Table 1. The ^{13}C n.m.r. spectrum for the *E*-isomer **(14)**, measured on a specimen in which there was little *Z*-compound, is recorded in Table 1.

(b) *In diethyl ether–methanol at* −60 °C. The 3-ulose **(9)** (500 mg) was dissolved in diethyl ether and methanol (4:1) (125 ml) in a 18 mm diameter quartz tube and the solution was maintained at ca. −60 °C in a transparent quartz Dewar flask and irradiated with a 450-W medium-pressure lamp situated in a water-cooled well 8 cm from the ulose solution. After 4 h the solvent was evaporated off to give a gum (585 mg), g.l.c. analysis of which showed six peaks at R_t 15 min (with relative intensity 1.1), 18 min (2.3), 19.6 min (1.1), 24 min (1.0) [ulose **(9)**], 26.2 min (9.5), and 33 min (0.8); and t.l.c. [benzene–diethyl ether (5:1)] showed materials with R_F 0.86, 0.69, 0.54 [ulose **(9)**], 0.40, 0.23, and 0.14. The ^{1}H n.m.r. (CDCl$_3$) spectrum showed that the lactones **(13)** and **(14)** and the dioxane **(12)** (see below for isolation and characterization) were present in a 5:14 ratio.

The crude product was then fractionated by flash chromatography [light petroleum (40—60 °C)–ethyl acetate (10:1)]. The first fraction (25 mg), R_F 0.86, R_t 15 and 18 min, was a mixture of 35% Z- and 65% E-lactone (13) and (14) characterized by [1]H n.m.r. spectroscopy.

The second fraction (154 mg), R_F 0.69, R_t 26.2 min, was (2S,3R,5S,6R)-2,3-isopropylidenedioxy-5-methoxy-6-methyl-1,4-dioxane (12) (Found: C, 53.0; H, 7.9. $C_9H_{16}O_5$ requires C, 52.9; H, 7.9%); δ_H (C_6D_6) 5.22 (1 H, d, J 3.0 Hz, 2- or 3-H), 4.89 (1 H, d, J 3.0 Hz, 3- or 2-H), 4.54 (1 H, d, $J_{5,6}$ 6.5 Hz, 5-H), 3.35 (1 H, quin, $J_{6,5}$ 6.5, $J_{6,Me}$ 6.5 Hz, 6-H), 1.17 (3 H, d, [3]J 6.5 Hz, 6-Me), 3.19 (3 H, s, OMe), and 1.28 and 1.64 (each 3 H, together 2 s, CMe_2); δ_H (CDCl₃) see Table 3, and in addition there were several very weak sharp signals in this spectrum, two in the region δ 1.1—1.3, four between 1.4—1.5, and four between 5.2—5.3.

The third fraction (25 mg), R_F 0.54, was not pure; it contained 40% unchanged ulose (9), R_F 0.40, in addition to another substance of unassigned structure which exhibited [1]H n.m.r. signals at δ_H 5.86 (d, J 6.5 Hz), 5.64 (d, J 6.5 Hz), 4.87 (s), 4.50 (t, J 7.0 Hz), 1.64 (d, J 7.0 Hz), 1.62 (br s), and 1.68 (br s).

Materials which were even more polar were eluted with ethyl acetate and these were rechromatographed with benzene–diethyl ether (3:1) to give a further two fractions (15 mg and 32 mg), R_F 0.23 and 0.14 [benzene–diethyl ether (5:1)] which gave [1]H n.m.r. spectra which indicated that diethyl ether had added to the ulose.

(c) In methanol at 20 °C. In a typical experiment the ulose (9) (500 mg) was dissolved in methanol (25 ml) and the solution was irradiated for 3 h in a 8 mm diameter quartz tube situated 5 cm from a water-cooled medium-pressure lamp. Evaporation of the solvent gave a gum (505 mg) which g.l.c. showed contained unchanged (9), R_t 24 min, and two products, R_t 19.6 and 26.2 min. This material was subjected to flash chromatography which gave three fractions, R_F 0.80 (80 mg), 0.25 (230 mg), and 0.06 (180 mg), and unchanged (9) R_F 0.45 (20 mg) [light petroleum (40—60 °C)–diethyl ether (5:2)]. The [1]H n.m.r. spectrum of the first fraction showed it to be mainly the 1,4-dioxane (12) and further chromatography of this material [methylene dichloride–diethyl ether (9:1)] gave pure (12) (24 mg). This product could also be isolated directly by preparative g.l.c. by collection of the peak with R_t 26.2 min.

The L-enantiomer of compound (9), compound (3), was photolysed in the same fashion and gave similar results.[4]

(d) In methanol at −60 °C. The ulose (9) (500 mg) was dissolved in deoxygenated methanol at −60 °C and the solution was irradiated as described in (b) for 3.5 h and then evaporated to give a syrup (600 mg), the [1]H n.m.r. spectrum of which clearly showed signals for 1-, 2-, and 4-H for the unchanged ulose (9) at δ_H 5.98 (d), 4.44 (dd), and 4.22 (dq) and for 2-, 3-, and 5-H for the 1,4-dioxane derivative (12) at δ_H 5.46 (d), 5.24 (d), and 4.62 (d). The relative intensities for these sets of signals were each 6:7.5. It further indicated only traces of hemiacetal (18) and lactones (13) and (14). The g.l.c. of this material showed only two peaks of significant intensity and three weak ones. The major two arose from unchanged ulose (9), R_t 24 min, and the dioxane derivative (12), R_t 26.2 min, present in the ratio 6:5.8, and the others were at R_t 15, 18, and 19.6 min, each with a relative intensity of 0.1. The crude gum was chromatographed [light petroleum (40—60 °C)–ethyl acetate (5:1)] to give the dioxane (12) (70 mg), unchanged ulose (9) (112 mg), and a third fraction which was highly polar and possessed an uninformative [1]H n.m.r. spectrum, and was not investigated further.

5-Deoxy-1,2-O-isopropylidene-α-D-erythro-pentofuranos-3-ulose (20).—5-Deoxy-1,2-O-isopropylidene-α-D-xylofuranose (25) (14 g) was oxidized as described for the arabinose isomer.

Work-up and chromatography gave a syrup which crystallized to give the 3-ulose (20) (9.6 g, 69%), R_F 0.22 [light petroleum (40—60 °C)–ethyl acetate (3:1)], m.p. 40—41 °C; $[\alpha]_D$ + 175° (c 0.5) {lit.,[10] m.p. 39—41 °C; $[\alpha]_D^{23}$ +181.4° (CHCl₃)}; δ_H (CDCl₃) values are recorded in Table 3; δ_H (C_6D_6) 5.55 (1 H, d, $J_{1,2}$ 4.5 Hz, 1-H), 3.71 (1 H, dd, $J_{2,4}$ 0.5 Hz, 2-H), 4.15 (1 H, dq, $J_{4,2}$ 0.5, $J_{4,5}$ 6.5 Hz, 4-H), 1.06 (3 H, d, $J_{5,4}$ 6.5 Hz, 5-H₃), and 1.08 and 1.31 (each 3 H, together 2 s, CMe_2); δ_C values are recorded in Table 2.

The 3-ulose (20) (100 mg) was dissolved in methanol (4 ml) and after 2 h at 20 °C the solvent was evaporated whilst the solution was maintained below −15 °C. The residual gum was left under vacuum (0.1 mmHg) for 15 min at −5 °C and then the [1]H n.m.r. spectrum was measured in CDCl₃. The spectrum showed signals for 16% unchanged ulose (20) and for two isomeric hemiacetals (39 and 45%) (23)/(24); δ_H values are recorded in Table 3.

U.v.-irradiation of 5-Deoxy-1,2-O-isopropylidene-α-D-erythro-pentofuranos-3-ulose (20).—(a) In benzene. A solution of the 3-ulose (20) (3.1 g) in deoxygenated benzene (310 ml) was irradiated as described above in (a) for the threo-isomer. Evaporation gave a syrup, which g.l.c. showed contained Z and E lactones, R_t 15 and 18 min, and unchanged ulose, R_t 17 min, which was confirmed by the [1]H n.m.r. spectrum. The material was purified by column chromatography [light petroleum (40—60 °C)–diethyl ether (5:1)]. The first fraction (380 mg), $[\alpha]_D$ + 32°, was a 33% Z and 67% E mixture of lactones (13) and (14) and the second fraction (220 mg) was a 41% Z and 59% E mixture of lactones as indicated by [1]H n.m.r. spectroscopy. The third fraction (40 mg) contained lactones mixed with an equal quantity of other unidentified materials.

(b) In diethyl ether–methanol at −60 °C. A solution of 3-ulose (20) (500 mg) in diethyl ether–methanol (4:1; 125 ml) maintained at ca. −60 °C was irradiated for 2.5 h as described under (b) for the threo-compound (9). The crude gum (580 mg) obtained on work-up gave an [1]H n.m.r. spectrum which showed some clearly resolved signals for unchanged ulose (20), δ_H 6.04 (d) [signal intensity 4], for Z and E lactones (13) and (14), δ_H 6.20 and 6.30 (2 dq) and 5.44 and 5.45 (2 s) [5], and for the two hemiacetals (23)/(24), δ_H 5.82 (d) [1] and 5.78 (d) [3].

Chromatography [benzene–diethyl ether (5:1)] gave a sample containing only the Z and E lactones (13) and (14) (15 mg), with an [1]H n.m.r. spectrum identical with that obtained previously. The second fraction was a mixture, the components of which could not be identified, and the third fraction (64 mg), δ_H 6.04 (d, J 4.5 Hz), was mainly unchanged ulose (20).

1,2-O-Isopropylidene-β-D-threofuranose [enantiomer of (26)].—D-Arabinitol (100 g) was treated with benzaldehyde as described by Hudson and co-workers[27] to give 1,3-O-benzylidene-D-arabinitol (120 g, 75%). The material was then oxidatively cleaved between the 4-OH and 5-OH groups with sodium metaperiodate as described by Perlin[28] to give 2,4-O-benzylidene-D-threose as a dimer.[29]

The benzylidenated dimer (28 g) was heated under reflux for 4 h in acetone (1.6 l) containing toluene-p-sulphonic acid 5.5 g). The solution was cooled and then stirred with solid sodium hydrogen carbonate (100 g) until neutral. After filtration and evaporation of solvent the product was purified by chromatography to give the title compound (4.6 g, 22%), m.p. 80—83 °C; $[\alpha]_D^{24}$ −13.8° {lit.,[28,30] m.p. 84 °C; $[\alpha]_D$ −15°}; δ_H 5.94 (1 H, d, $J_{1,2}$ 4.0 Hz, 1-H), 4.47 (1 H, br d, $J_{2,1}$ 4.0, $J_{2,3}$ 0.5 Hz, 2-H), 4.23 (br s, $w_{\frac{1}{2}}$ 7.0 Hz, 3-H), 4.06 (1 H, dd, $J_{4,4'}$ 10.0, $J_{4,3}$ 2.8 Hz, 4-H), 3.86 (1 H, dd, $J_{4',4}$ 10.0, $J_{4',3}$ 1.2 Hz, 4'-H), 3.05 (br s, $w_{\frac{1}{2}}$ 8.0 Hz, HO), and 1.31 and 1.47 (each 3 H, together 2 s, CMe_2); δ_C 105.5 (C-1), 85.2 (C-2), 75.1 and 73.1 (C-3 and -4), and 112.0, 26.8, and 26.2 (CMe_2).

1,2-O-*Isopropylidene*-α-L-glycero-*tetrofuranos-3-ulose* (**22**).—
1,2-O-Isopropylidene-α-D-threofuranose [enantiomer of (**26**)]
(4 g) was oxidized with ruthenium tetraoxide as described for
the preparation of (**9**) to give, after chromatography, the pure 3-
ulose derivative (**22**) (1.0 g, 25%), m.p. 44—45 °C; $[\alpha]_D$ −96.8°
{lit.,[31] m.p. 56—58 °C; $[\alpha]_D^{18}$ −157° (CHCl$_3$); hydrated
form, m.p. 60—63 °C; $[\alpha]_D^{18}$ −73.4° (CHCl$_3$)}; lit.[32,33] values:
the D-enantiomer, m.p. 60—61.5 °C and 50—60 °C, $[\alpha]_D$
+140° (CCl$_4$) and +151° (CHCl$_3$); hydrated form, m.p. 65—
80 °C; $[\alpha]_D$ +79.5° (CHCl$_3$); δ_H (C$_6$D$_6$) values are recorded in
Table 3, and δ_C values in Table 2.

U.v.-irradiation of 1,2-O-*Isopropylidene*-α-L-glycero-*tetro-
furanos-3-ulose* (**22**) *in Benzene*.—The 3-ulose (**22**) (200 mg) was
irradiated for 1.5 h in deoxygenated benzene (50 ml) in a 1.2 cm
diameter quartz tube as described above until t.l.c. indicated
that most of the ulose had reacted. Only one non-polar product
was observed (in iodine vapour), with R_F 0.5 [light petroleum
(40—60 °C)–diethyl ether (5:1)], and this was isolated in low
yield by chromatography and shown to be the lactone (**16**) (15
mg), $\nu_{max.}$ 1 805 cm^{-1}; $[\alpha]_D$ 0°; c.d. measurement in methanol
also indicated that the material is optically inactive over the
range 230—300 nm; δ_H (C$_6$D$_6$) values are recorded in Table 1
(Found: C, 52.7; H, 6.8. C$_7$H$_{10}$O$_4$ requires C, 53.2; H, 6.4%).

The ^{1}H n.m.r. spectrum of the gum prior to chromatography
indicated that considerably more lactone had been produced
than was isolated. It was concluded therefore that the lactone
was unstable.

Acknowledgements

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