Chem. Ber. 113, 471 – 488 (1980)

Sugar Enolones, XI[1]

2-Halopentopyranosyl Halides: Preparation, Configurational Elucidation, and Conversion into Enantiomeric Dihydropyranones

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Received April 23, 1979

Addition of chlorine or bromine to the enediol grouping of tribenzoyl-pentenitol **2** exclusively yields *cis*-adducts, i.e. 1,2-dihalides of α-D-*lyxo* (**4, 6**) and β-D-*xylo* configuration (**5, 7**). Configurational assignments were based on the titanium tetrahalide-induced anomerization to the corresponding β-D-*lyxo* (**8, 10**) and α-D-*xylo* isomers (**9, 11**), on ^{1}H NMR spectroscopic determination of their conformations, and on an *X*-ray crystal structure analysis of the α-D-*xylo* dichloride **9**. — The 1,2-dibromides are partially hydrolyzed in contact with silica gel, clean hydrolysis being effected by silver carbonate in aqueous acetone, with the stereospecific formation of α-D-*threo*-pentosulose **15** from D-*xylo* dibromides (**7, 11**) and of the β-D-*threo* anomer **25** from either of the *lyxo* derivatives (**6, 10**). The dichlorides are more stable requiring heating with sodium hydrogen carbonate in moist benzene, to give the enantiomeric dihydropyranones **16** (from D-*xylo* dichlorides) and **26** (from D-*lyxo* compounds). — Reactions at the anomeric center of **16** and **26**, such as replacement of the benzoyloxy group by halogen, hydroxy, or alkoxy substituents (**20 – 23**), lead to racemization or to elaboration of the γ-pyrone system (**24**). Additions to the enolone grouping, however, proceed with high stereoselectivity as evidenced by the nearly exclusive formation of 4-deoxy-D-*erythro*-pentose (**17**) from α-enolone **16** on hydrogenation and debenzoylation, whilst the β-enolone affords the L-enantiomer **27**.

Zucker-enolone, XI[1]
Darstellung und Konfigurationsermittlung von 2-Halogenpentopyranosyl-halogeniden und ihre Überführung in enantiomere Dihydropyranone

Addition von Chlor oder Brom an die Endiol-Gruppierung des Tribenzoyl-pentenitols **2** liefert ausschließlich *cis*-Addukte, d.h. 1,2-Dihalogenide mit α-D-*lyxo*- (**4, 6**) und β-D-*xylo*-Konfiguration (**5, 7**). Die Konfigurationszuordnung erfolgte anhand der titantetrahalogenid-induzierten Anomerisierung in die entsprechenden β-D-*lyxo*- (**8, 10**) bzw. α-D-*xylo*-Isomeren (**9, 11**), aufgrund ^{1}H-NMR-spektroskopischer Konformationsbestimmungen sowie durch Röntgenstrukturanalyse des α-D-*xylo*-Dichlorids **9**. — Die 1,2-Dibromide werden bereits durch Kontakt mit Silicagel partiell, durch Silbercarbonat in wäßrigem Aceton vollständig hydrolysiert unter stereospezifischer Bildung der α-D-*threo*-Pentosulose **15** aus den D-*xylo*-Dibromiden (**7, 11**) bzw. des β-D-*threo*-Anomeren **25** aus den D-*lyxo*-Derivaten (**6, 10**). Die stabileren Dichloride überführt erst Erhitzen mit Hydrogencarbonat in feuchtem Benzol, ebenso wie die Pentosulosen, in die enantiomeren Dihydropyranone **16** (aus D-*xylo*-Dichloriden) und **26** (aus D-*lyxo*-Verbindungen).

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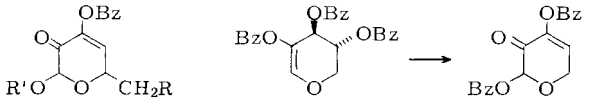
— Eingriffe am anomeren Zentrum von **16** bzw. **26**, wie Ersatz der Benzoyloxy-Gruppe durch Halogen, Hydroxy- oder Alkoxy-Gruppen (**20** – **23**), führen zur Racemisierung oder zur Ausbildung des γ-Pyron-Systems (**24**). Additionen an die Enolon-Gruppierung verlaufen jedoch hoch stereoselektiv: Perhydrierung des α-Enolons **16** liefert nach Entbenzoylierung die 4-Desoxy-D-*erythro*-pentose (**17**), während das β-Enolon **26** analog in das L-Enantiomere **27** übergeführt wird.

In pyranoid hexose-3,2-enolones of type **1** (R = H, OBz) the 3-enol-2-one structural element is flanked on each side by chiral centers, which exert a strong directing influence on addition reactions to the carbonyl and the enolic double bonds[2]. Accordingly, they are not only useful intermediates for the stereospecific preparation of 4-deoxyhexulosides that may be further functionalized via their carbonyl group[3] but they show a high potential as a prochiral six-carbon synthon for the stereo-controlled preparation of a variety of natural products[2].



1 **2** **3**

R = H, OBz
R' = acyl, alkyl Bz = C_6H_5CO

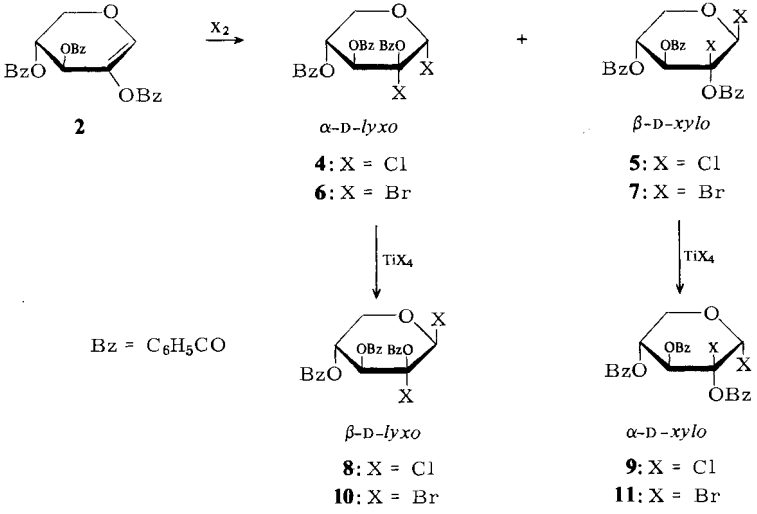
Since a pentose-derived enolone, e. g. **3**, would have a similar potential as a prochiral five-carbon fragment, we have evaluated their conceivable[4] preparation from 2-hydroxylglycal esters, as e. g. from the readily accessible[5] **2**, via the three-step sequence halogenation → hydrolysis → β-elimination. In this communication we describe the preparation and configurational elucidation of the 1,2-dihalides obtained on chlorination and bromination of **2**, which via hydrolysis and subsequent β-elimination provided a facile, expedient access to each of the enantiomers of **3**.

Preparation of 2,3,4-Tri-*O*-benzoyl-1,2-dihalopentoses

As was to be anticipated from the halogen addition onto hexose derived 2-hydroxylglycal esters[6-8], chlorination and bromination of the D-xylose derived D-*threo*-pentenitol **2** exclusively gave the corresponding *cis*-adducts, i. e. a mixture each of the 2,3,4-tri-*O*-benzoyl-2-*C*-halopentopyranosyl halides with α-D-*lyxo* (**4** and **6**, resp.) and β-D-*xylo* configuration (**5**, **7**), proof thereof being provided in the sequel. Although the proportions of *cis*-adducts varied somewhat with the solvents used — in tetrachloromethane **4** and **5** were formed in an approximate 2:1 ratio as compared to benzene or toluene where it is 4:1 to 3:1 — the major product in either case proved to be the α-D-*lyxo* isomer **4** and **6**, respectively, indicating a preference for halogen addition from the α-side.

The 1,2-dichlorides **4** and **5** could readily be separated due to the nearly quantitative crystallization of the β-D-*xylo* isomer **5** from the reaction mixture; the α-D-*lyxo* compound **4**, however, could not be induced to crystallize and, hence, was characterized as a syrup upon purification on silica gel. The hydrolytically more reactive 1,2-dibromides **6** and **7** were separated by chromatography on silica gel, fast elution, however, being

imparative to prevent extensive hydrolysis of either isomer to the respective uloses **15** and **25** (*vide infra*) during contact with silica gel.



2

α-D-*lyxo*
4: X = Cl
6: X = Br

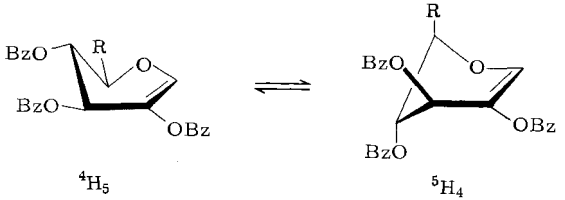
β-D-*xylo*
5: X = Cl
7: X = Br

β-D-*lyxo*
8: X = Cl
10: X = Br

α-D-*xylo*
9: X = Cl
11: X = Br

Expectedly, chlorination of the L-xylose derived L-*threo*-pentenitol — i.e. the L-enantiomer of **2** — proceeded in an analogous fashion affording in yields of 17 and 65 % the crystalline β-L-*xylo*-dichloride and its syrupy α-L-*lyxo* isomer, as evidenced by their physical data that differed from **4** and **5** only by their sign of optical rotation. These results complement and clarify previous findings of *Major* and *Cook*[9] in such that their „1-xyloseen-(1,2) tribenzoate dichloride" is, in fact, 2,3,4-tri-*O*-benzoyl-2-*C*-chloro-β-L-xylopyranosyl chloride, i.e. the L-enantiomer of **5.**

Whereas the exclusive formation of *cis*-adducts is readily understood on the basis of 2-halo-1,2-benzoxonium halide intermediates in which halide attack at the anomeric carbon can only occur from the side opposite to the 1,2-dioxolane ring, the factors governing the ratios of the *cis*-adducts are less easily rationalized. The experimental observations, for example, that **2** shows a clear preference for halogen addition from below the plane of the pyranose ring (α-side) whilst its hexose analog **12** (R = CH_2OBz) is as preferentially attacked from the β-side[8], are not entirely due to different conformational arrangements in the educts. In the pentenitol **2,** the interconversion equilibrium between the two half-chair conformations $^4H_5$ and $^5H_4$ lies nearly entirely on the $^5H_4$ side as evidenced by $J_{3,4}$, $J_{4,5e}$ and $J_{4,5a}$ -values which in chloroform or benzene are all within 2.0 – 2.2 Hz. In the hexose analog **12** (R = CH_2OBz), however, the $J_{3,4}$ and $J_{4,5}$ values of 3.8 and 5.0 Hz in chloroform[10] and 3.9 and 4.7 Hz in benzene are such as to indicate the presence of substantial amounts of the $^4H_5$ form in the equilibrium. This would be anticipated from the unfavorable axial disposition of the 5-CH_2OBz group in the alternate conformation ($^5H_4$), which obviously outweighs the allylic effect[11] operating towards a *quasi*-axial orientation of the 3-OBz moiety.



$^4H_5$ $^5H_4$

2: R = H
12: R = CH_2OBz

Thus, whilst the conformational preferences of the glycal esters **2** and **12** can readily be assessed, a conspicuous relation to the preference for halogen addition is not clearly apparent. On the contrary, **12**, whose $^4H_5 \rightleftharpoons {}^5H_4$ equilibrium is relatively balanced as compared to the $^5H_4$ half-chair for **2**, would be expected to add halogen predominantly from the α-side in its $^4H_5$ form, yet experimentally the opposite is observed. Obviously electronic factors that as yet are less assessable, e.g. those resulting from the operation of the anomeric effect as well as those arising from dipole-dipole interactions in the intermediates, appear to exert a major influence on the steric course.

In contrast to the halogenation products of hydroxyglucal tetrabenzoate, where only one of the two dihalides formed, namely the β-D-*gluco*-dihalide, could be anomerized, here, both halogen adducts responded to the titanium tetrahalide-induced anomerization, yet with somewhat varying ease and uniformity. Thus, when refluxed for 2 h with titanium tetrachloride in 1,2-dichloroethane, the β-D-*xylo*-dichloride **5** was converted into the respective α-anomer **9** nearly quantitatively, whilst the α-D-*lyxo* isomer **4** had anomerized under these conditions to the extent of about 60% only. Similar results were obtained with the respective 1,2-dibromides, of which the β-D-*xylo* compound **7** was uniformly converted into the α-D-*xylo* anomer **11** on refluxing with titanium tetrabromide in 1,2-dichloroethane for 2 h. The α-D-*lyxo*-dibromide **6**, however, responded more sluggishly to these conditions: after refluxing for 6 h, only about half of the educt had reacted on the expense of two products formed in an approximate 2:1 ratio, the major being the expected β-D-*lyxo* anomer **10**, isolated by column chromatography in comparatively low yield (15%), whilst the minor component proved to be the α-D-*xylo* epimer **11**. Thus, in addition to the α → β-anomerization **6** → **10** an epimerization at the tertiary carbon atom (C-2) had occured, presumably via removal of bromide from C-2 and subsequent readdition from the less hindered β-side, the driving force being the elaboration of the isomer (**11**) which in terms of dipole-dipole interactions between halogen atoms as well as between them and the ring oxygen is the thermodynamically most stable.

Configurational Assignments

Some evidence about the configurational relationships between the halogen adducts **4**–**7** could already be derived from their titanium tetrahalide-induced anomerizations, in such that the anomerized products should be the thermodynamically more stable isomers. Rationalizing this in terms of dipole-dipole interactions between the two halo substituents, which are at a minimum in a 1,2-diaxial arrangement, the anomerized products should have β-D-*lyxo* ($^1C_4$) and α-D-*xylo* ($^4C_1$) configuration with those for the educts following correspondingly. Although these conclusions, in fact, proved to be correct, they could, of course, not be the basis for rigid configurational assignments.

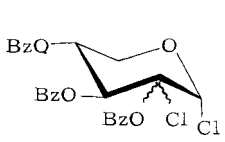
More specific information was provided by ^{1}H NMR data (table 1). The major adduct resulting from the chlorination of **2** had a low field anomeric proton, indicative of an equatorially disposed 1-H, and large values of 9.5 Hz each for $J_{3,4}$ and $J_{4,5a}$, compatible only with a pyranosyl α-chloride in the $^4C_1$ conformation. This established the product to have either α-D-*lyxo* (**4**) or α-D-*xylo* configuration (**9**). For the crystalline minor dichloride, as conclusively, β-D-*xylo* (**5**) or β-D-*lyxo* configuration (**8**) could be delineated from the chemical shift of the anomeric proton (δ = 6.82 for an axial 1-H)

Table 1. ^{1}H NMR data[a] for the isomeric 2,3,4-tri-*O*-benzoyl-2-*C*-halopentopyranosyl halides **4** – **11**, and the anomeric pentosulose tribenzoates **15** and **25**

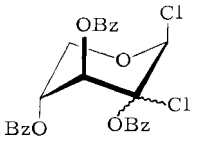
Comp.	Config.	Conform.	1-H	3-H	4-H	5-H	5'-H	$J_{3,4}$	$J_{4,5}$	$J_{4,5'}$	$J_{5,5'}$	$J_{1,3}$	$J_{3,5'}$
4	α-D-*lyxo*	$^4C_1$	>7.3[b]	6.43	5.74	−4.28[c]	–	9.5	9.5	7.0	?	–	–
6	α-D-*lyxo*	$^4C_1$	>7.3[b]	6.65	5.87	4.22	4.48	9.7	10.0	6.5	11.5	–	–
8	β-D-*lyxo*	$^1C_4$	7.18	6.31	5.35	4.78	4.15	1.5	2.0	1.5	13.5	1.5	1.0
10	β-D-*lyxo*	$^1C_4$	>7.3[b]	6.49	5.34	4.73	4.21	2.5	2.0	1.0	13.0	1.0	1.0
5	β-D-*xylo*	$^1C_4$	6.82	6.58	5.38	4.75	4.02	3.8	3.0	2.5	13.0	1.5	1.0
7	β-D-*xylo*	$^1C_4$	>7.3[b]	6.60	5.44	4.78	4.10	3.8	2.8	2.5	13.5	1.0	1.0
9	α-D-*xylo*	$^4C_1$	>7.3[b]	6.46	5.76	4.18	4.42	10.0	10.5	6.3	11.0	–	–
11	α-D-*xylo*	$^4C_1$	>7.3[b]	6.27	5.83	4.10	4.46	10.0	10.0	6.0	11.0	–	–
15	α-D-*threo*		6.44	6.33	5.82	−4.37[c]	–	10.0	7.0	9.0	?	–	–
25	β-D-*threo*		6.55	6.18	5.73	4.66	4.14	7.0	5.0	4.0	13.0	–	–

[a] 100 MHz in $CDCl_3$; δ scale. — [b] The signal is covered by the signals of the aromatic protons. — [c] Due to very close chemical shifts, 5-H and 5'-H give the AB part of an ABX set of signals.

and the coupling patterns (cf. Tab. 1), the most salient features being long-range interproton couplings of $J_{1,3}$ = 1.5 and $J_{3,5}$ = 1.0 Hz, which can only originate from a W-arrangement of the respective protons, i. e. a pyranose ring in the $^1C_4$ conformation.



$^4C_1$
α-D-*lyxo*
α-D-*xylo*



$^1C_4$
β-D-*lyxo*
β-D-*xylo*

In the case of the bromine addition products to **2** — later proved to be **6** and **7**, respectively — the ^1H NMR spectra are very similar to those of the chlorine adducts (cf. table 1) establishing the major product to be a α-D-*xylo* or α-D-*lyxo* isomer in the $^4C_1$ conformation, and the minor adduct to be either one of the two β-anomers in the alternate $^1C_4$ form.

Relevant information as to the configuration at the tertiary carbon atom (C-2) could thus not be derived from the ^1H NMR data of the adducts, and the same applies to the products formed therefrom via titanium tetrahalide catalyzed anomerization. In each case, the anomerized products not only had the opposite configuration at C-1, but also the alternate conformation. By consequence, either α-D-*lyxo* ($^4C_1$) → β-D-*xylo* ($^1C_4$) and β-D-*xylo* ($^1C_4$) → α-D-*xylo* ($^4C_1$) anomerizations had taken place — as proved to be correct (*vide infra*) — or the respective reverse reactions.

Similarly deficient of clues concerning the configuration at C-2 were the ^{13}C NMR data (table 2), despite of the fact that all four isomeric dichlorides were available. The signal differences were considerably smaller than in the hexose-1,2-chlorides[6], as exemplified by nearly identical resonances in the chlorine adducts **4** and **5** for the anomeric carbon (91.1 and 91.2) and C-2 (96.3 and 95.5). Although these differences proved to be more pronounced in the anomerized products **8** and **9** (table 1), they do not appear to allow unequivocal conclusions as to their stereochemistry at C-2.

Table 2. ^{13}C NMR data[a] for the isomeric 2,3,4-tri-*O*-benzoyl-2-*C*-chloropentopyranosyl chlorides

Compound	Config.	Conform.	C-1	C-2	C-3[b]	C-4	C-5
4	α-D-*lyxo*	$^4C_1$	91.1	96.3	72.6	68.7	61.4
5	β-D-*xylo*	$^1C_4$	91.2	95.5	68.9	68.5	61.0
8	β-D-*lyxo*	$^1C_4$	90.6	92.7	69.8	68.1	60.1
9	α-D-*xylo*	$^4C_1$	92.9	97.3	70.8	67.9	61.7

a) In $CDCl_3$ (p.p.m. relative to tetramethylsilane).
b) Assignments for C-3 and C-4 may be reversed.

Ultimately, absolute proof of the configurations implemented so far was provided by an *X*-ray structure analysis of the α-D-*xylo*-dichloride **9**, its three-dimensional features

(fig. 1) clearly revealing the *trans*-arrangement of the chlorine substituents together with an equatorially disposed 2-benzoyloxy group. The pyranose ring is in a chair conformation that deviates somewhat from the ideal $^4C_1$ geometry at C-1 and C-2 as shown by the comparatively small torsional angles (table 3) between C-1 – C-2 / C-3 – C-4 (47.8°) and O-5 – C-1 / C-2 – C-3 (50.1°). This flattening of the ring around C-1 and C-2 is also evident from the torsional angle between the chlorine atoms which with 166.6° diverges from a perfect antiparallel arrangement. Torsional angles between vicinal, axially disposed halogen substituents are not unusual though, but are similarly observed for *trans*-2,3-dichloro-1,4-dioxane (**13**)[12] and for *trans*-2,3-dichloro-5-α-cholestane (**14**)[13] (fig. 2) as the only examples available for direct comparison. Whilst the low value for the latter (157°) is a result of *syn*-1,3-diaxial interactions between the 2-Cl and the angular methyl group, the value of 162° for the dioxane derivative **13** is inherent yet, characteristically, smaller than that observed for the α-D-*xylo*-dichloride **9**.

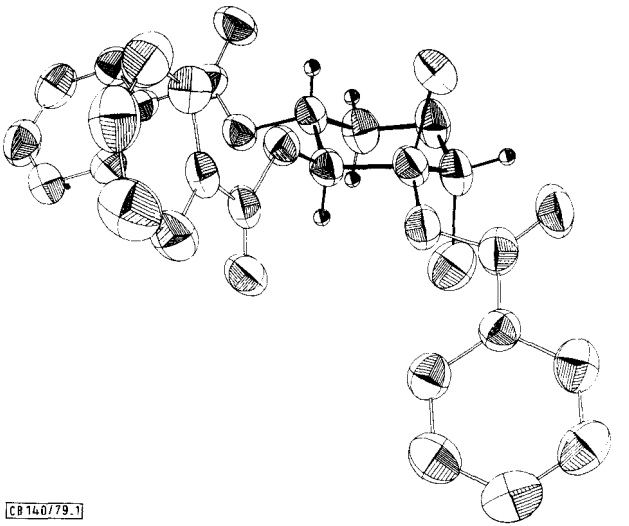
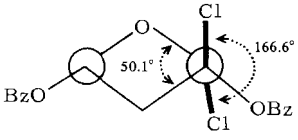


Fig. 1. ORTEP drawing of 2,3,4-tri-*O*-benzoyl-2-*C*-chloro-α-D-xylopyranosyl chloride (**9**), showing thermal ellipsoids (for numbering, see fig. 3). Hydrogen atoms of benzene rings have been omitted

The bond distances (cf. fig. 3) are within the expected limits, i.e. the O-5 – C-1 bond was shortened to 1.38 Å as anticipated[8] for α-anomers and both C – Cl bonds exhibited distances of 1.80 Å, practically identical with the mean value for the paraffinic C – Cl bond[14] (1.79 Å). Inspection of the ester group conformations indicated the expected[8,15] antiparallel arrangements for the bonds R – O and C – C_6H_5 within the R – O – CO – C_6H_5 fragment only for the benzoyloxy groups at C-3 and C-4, where deviations from 180° are 3.6 and 3.3°, respectively (cf. table 3). For the benzoyloxy group linked to the tertiary carbon, however, a considerably higher deviation of 11.1° is observed, conceivably caused by unfavorable steric interactions with the vicinal 1-chlorine atom.

Table 3. Selected torsional angles (degr.) in 2,3,4-tri-*O*-benzoyl-2-*C*-chloro-α-D-xylopyranosyl chloride (**9**)

Pyranose ring		Ring substituents	
C-1 – C-2 / C-3 – C-4	– 47.8	Cl-1 – C-1 / C-2 – Cl-2	+166.6
C-2 – C-3 / C-4 – C-5	+ 52.1	Cl-1 – C-1 / C-2 – O-21	+ 43.5
C-3 – C-4 / C-5 – O-5	– 57.4	H-1 – C-1 / C-2 – O-21	– 77.2
C-4 – C-5 / O-5 – C-1	+ 61.6	H-1 – C-1 / C-2 – Cl-2	+ 45.9
C-5 – O-5 / C-1 – C-2	– 58.2	Cl-2 – C-2 / C-3 – H-3	–177.9
O-5 – C-1 / C-2 – C-3	+ 50.1	Cl-2 – C-2 / C-3 – O-31	– 52.5
Benzoyl substituents		O-21 – C-2 / C-3 – O-31	+ 66.1
C-2 – O-21 / C-21 – C-22	–168.9	H-3 – C-3 / C-4 – H-4	+176.2
C-2 – O-21 / C-21 – O-22	+ 11.8	O-31 – C-3 / C-4 – O-41	– 70.1
O-22 – C-21 / C-22 – C-23	–177.7	H-4 – C-4 / C-5 – H-51	–172.3
C-3 – O-31 / C-31 – C-32	+173.0	H-4 – C-4 / C-5 – H-52	– 55.0
C-3 – O-31 / C-31 – O-32	– 3.6		
O-32 – C-31 / C-32 – C-33	–168.9		
C-4 – O-41 / C-41 – C-42	+176.0		
C-4 – O-41 / C-41 – O-42	– 3.3		
O-42 – C-41 / C-42 – C-43	+ 10.1		



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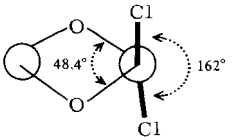

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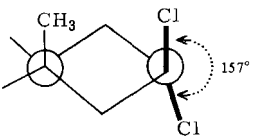

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Fig. 2. Torsional angles between vicinal axial chlorine atoms in **9**, *trans*-2,3-dichloro-1,4-dioxane[12] (**13**) and *trans*-2,3-dichloro-5-α-cholestane[13] (**14**, ring A), as exemplified by Newman projections along the chloride carrying C – C bond

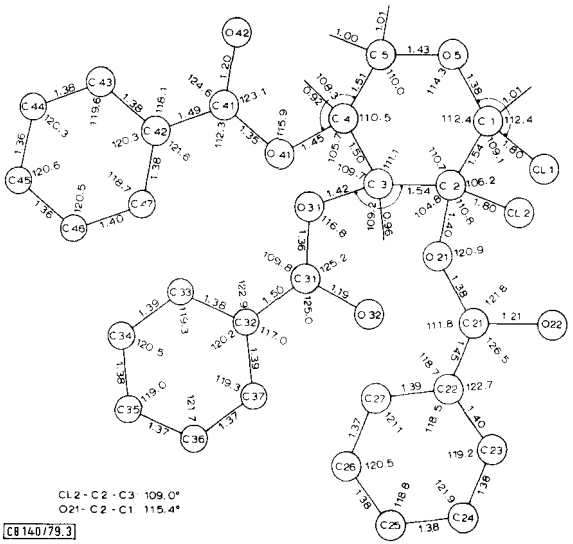
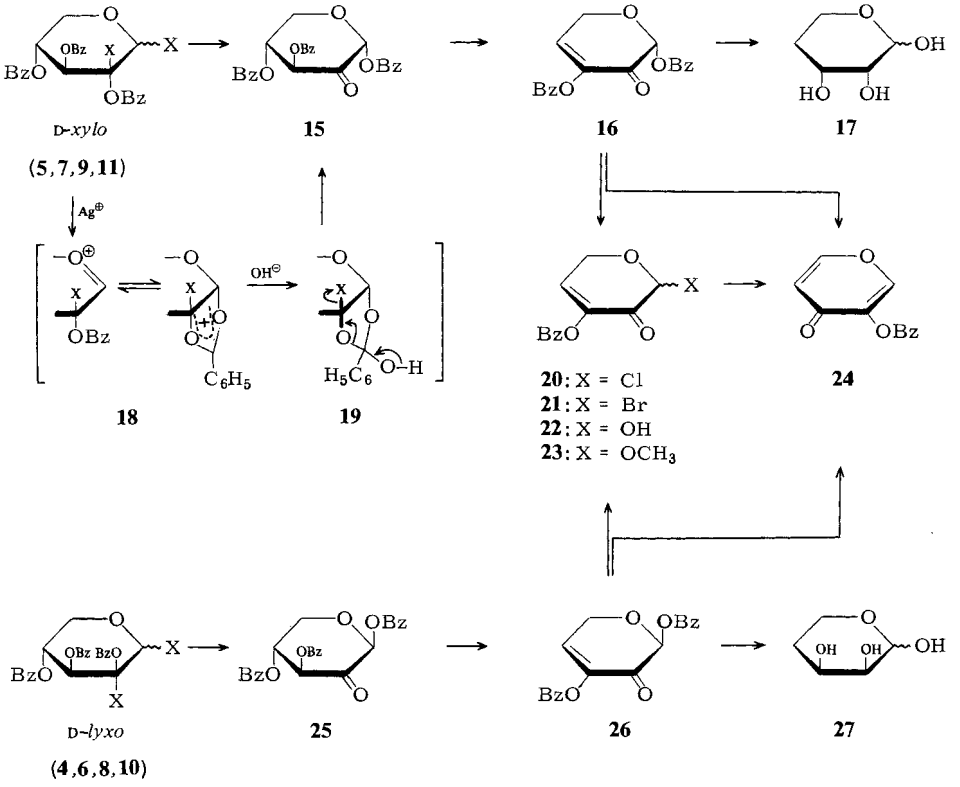


Fig. 3. Bond distances (Å) and bond angles (deg.) in **9**. Standard deviations are within 0.01 Å and 0.8°, respectively

Hydrolysis to Uloses and Enolones

In either of the eight dihalides **4** – **11** described, the halogen can be removed by silver ion induced hydrolysis. Hereby, the α-pentosulose **15** is obtained from each of the D-*xylo* isomers **5**, **7**, **9**, and **11**, as expected for a mechanism, which involves initial removal of the anomeric 1-halogen and — via carboxonium and 1,2-benzoxonium ion intermediates of type **18** — the elaboration of an ortho-acid structure **19**, wherefrom the elements of HX are eliminated. Accordingly, the hydrolysis of the D-*lyxo*-dihalides **4**, **6**, **8**, and **10** is sterically determined by the alternate configuration of the 2-benzoyloxy group yielding the β-pentosulose **25** or the β-enolone **26**, exclusively.



Clear reactivity differences were observed between the comparatively stable dichlorides and the readily hydrolyzable 1,2-dibromo compounds. In the case of the former, no reaction occurred on exposure to silver carbonate in aqueous acetone at room temperature, and on refluxing (56 °C) hydrolysis was extremely slow (TLC). Treatment with silver perchlorate/silver carbonate in moist acetone at room temperature resulted in gradual conversion to the respective pentosuloses **15** (from D-*xylo* derivatives) and **25** (from **4** and **8**, respectively), whereby in the latter case substantial amounts of the β-enolone **26** were also formed due to accompanying β-elimination (**25** → **26**).

The higher reactivity of the dibromides is already reflected by their partial hydrolysis during separation on silica gel columns, and is similarly borne out by the smooth formation of pentosuloses **15** and **25**, respectively, upon brief exposure (30 min) to silver carbonate in aqueous acetone. This, in fact, proved to be a most satisfactory procedure for their preparation, the β-D-*xylo*-dibromide **7** affording **15** in the form of its monohydrate in 68% yield, the α-D-*lyxo*-dibromide giving the corresponding β-anomer **25** in a yield of 72%.

Conversion of the anomeric pentosuloses to the corresponding enantiomeric enolones, i.e. **15** → **16** and **25** → **26**, was readily effected by gentle heating in benzene with moist sodium hydrogen carbonate. However, a preparatively more satisfactory approach to these target compounds proved to be the subjection of the chlorination products **4** and **5** to these conditions (refluxing with $NaHCO_3$ in moist benzene). In this way, the α-enolone **16** was obtainable from the glycal ester **2** in two simple operations readily adaptable for large scale preparation, in an overall yield of 25%; for the β-enolone **26**, correspondingly arising from the α-D-*lyxo* portion (**4**) of the chlorination products of **2**, the overall yield was even more favorable (40%).

That the two enolones **16** and **26** are enantiomers was derived from the identity of their physical data such as melting point, TLC behaviour, IR, and ^{1}HNMR-data on one hand, and from the same magnitude yet opposite sign of their specific rotations (+141.7° for **16** versus −142.3° for **26**) on the other. Further evidence was provided by the circular dichroic curves that proved to be mirror images, with an exciton-split Cotton effect at short wavelengths of $\Delta\varepsilon = +7.98$ at 228 and −3.56 at 248 nm for the α-anomer **16** as compared to the same magnitudes yet of opposite sign in the case of the β-compound **26**. The absolute configuration, hereby, was most readily derived from the sign of the longwave, less intense ($\Delta\varepsilon = 1.2$) Cotton effect, i.e. the enone R band in the 335 nm region, which expectedly[7] is positive for the β-anomer and negative for the α-compound.

As in the hexose[7] series the enolone system in **16** and **26** is remarkably insensitive towards acid, thus allowing the replacement of the anomeric benzoyloxy group by halogen. Treatment with hydrogen chloride/acetyl chloride or hydrogen bromide/acetic acid smoothly gave the haloenolones **20** and **21** as well crystallized products, yet their small optical rotation ($[\alpha]_D \approx 1-7°$) clearly indicated that the chiral integrity at the anomeric carbon was essentially lost. The same applied to the 2-hydroxy- (**22**) and 2-methoxyenolone derivatives (**23**) readily obtained from either of the haloenolones on hydrolysis and methanolysis.

Basic conditions such as sodium methoxide/methanol cause de-*O*-benzoylation and give intractable product mixtures from either of the enolones. On brief heating with sodium acetate/acetic anhydride, however, or more smoothly on standing in pyridine at ambient temperature the γ-pyrone system is elaborated, affording *O*-benzoylpyromeconic acid (**24**) as the exclusive product from any of the enolones **16**, **20** – **23**, and **26**.

Addition reactions at the enolone system of **16** and **26**, however, preserve the chiral integrity at the anomeric carbon. Platinum-catalyzed perhydrogenation of the α-enolone **16** followed by acid de-*O*-benzoylation gave 4-deoxy-D-*erythro*-pentose (**17**) nearly exclusively, only traces of other products being detectable by TLC in the

hydrogenation mixture. Similarly, the β-enolone **26** afforded 4-deoxy-L-*erythro*-pentose (**27**) as a homogeneous reducing syrup with a rotational value close to those observed for **27** prepared by other routes[16,17]. Thus, the benzoyloxy group at the chiral center not only dominates the steric course of addition to the vicinal carbonyl function, but also exerts sufficient steric control at the more distant enolic double bond, such that addition occures predominantly if not exclusively from the unhindered side, remote from the prochiral substituent.

This highly stereoselective response to perhydrogenation is similarly to be expected for nucleophilic addition reactions to the carbonyl function as well as to the enolic double bond, thus rendering possible the stereo-controlled synthesis of a variety of five carbon fragments with two and/or three chirality centers. Work in progress is focused on these aspects.

We express our appreciation with thanks to the *Deutsche Forschungsgemeinschaft* and the *Fonds der Chemischen Industrie* for generous support of these investigations.

Experimental Part

Melting points: Bock Monoskop, uncorrected. — Spectral measurements: Perkin-Elmer 125 (IR), Perkin-Elmer 141 (rotations), Jasco J-20 (CD), Varian A-60A/XL-100 (^{1}H NMR), Varian XL-100/15 (^{13}C NMR), and Varian MAT 311 A (MS) instruments. — TLC: Kieselgel F_{254} plastic sheets (Merck), used to monitor the reactions and to ascertain the purity of the products. Developers employed: A tetrachloromethane/ethyl acetate (10:1), B benzene, C ethyl acetate/ethanol/water (15:2:1). The spots were visualized by UV light or by charring with sulfuric acid. — Column chromatography: Kieselgel 60 (70–230 mesh, Merck). — Preparative layer chromatography (PLC): 1.5 mm layers of Kieselgel PF_{254} (Merck) on 20 × 40 cm glass plates.

1. Dichlorides

2,3,4-Tri-O-benzoyl-2-C-chloro-β-D-xylopyranosyl chloride (**5**): Chlorine was passed through a cooled (0°C) solution of 1,5-anhydro-2,3,4-tri-*O*-benzoyl-D-*threo*-pent-1-enitol[5] (**2**, 4.45 g, 10 mmol) in tetrachloromethane (20 ml). After standing for 15 min at 0°C and another 15 min at room temperature, the solvent was evaporated *in vacuo* followed by several additions of tetrachloromethane and reevaporation. The sirupy residue, consisting of an approximate 2:1 mixture of the *lyxo*-isomer **4** (R_F 0.41 in benzene) und **5** (R_F 0.25), crystallized on trituration with ethanol (900 mg; filtrate cf. below). Recrystallization from ethanol afforded 1.85 g (36%) of **5** as colorless needles; m.p. 183–184°C, $[\alpha]_D^{25} = -109.3°$ (c = 1, chloroform). — ^{1}H and ^{13}C NMR data cf. tables. — MS (70eV) above m/e = 350:408/410 (1%, M – C_6H_5CO), 391/393 (13, M – $C_6H_5CO_2H$), 373/375 (1, M – C_6H_5CO and HCl), 356/358 (13, M – $C_6H_5CO_2H$ and HCl), base peak at 105 (C_6H_5CO).

$C_{26}H_{20}Cl_2O_7$ (515.3) Calc. C 60.59 H 3.91 Cl 13.76 **5:** Found C 60.49 H 3.95 Cl 13.83
4: Found C 60.06 H 4.00 Cl 13.66
8: Found C 60.67 H 4.04 Cl 13.90
9: Found C 60.62 H 4.00 Cl 13.70

2,3,4-Tri-O-benzoyl-2-C-chloro-α-D-lyxopyranosyl chloride (**4**): The ethanolic filtrate remaining after isolation of crystalline **5** was evaporated *in vacuo* to a syrup consisting mainly of **4** with approximately 5% of **5** and traces of slower moving products. Elution from a silica gel column (3 × 25 cm) with n-hexane/ethyl acetate (10:1) afforded another 110 mg of **5** from the first fraction, whilst evaporation of the fraction containing **4**, eluted next, gave 2.32 g (45%) of a chroma-

tographically (TLC in A and B) uniform syrup of $[\alpha]_D^{25} = -92°$ ($c = 1$, chloroform); ^1H and ^{13}C NMR data cf. tables 1 and 2. M.S. data corresponded with those of **5** except for minor intensity differences.

For large scale preparations of **4**, e.g. when required for subsequent conversion into the β-enolone **24** (*vide infra*), the chlorination of **2** was performed in dry toluene (5 min, 0°C) and processed after standing for 1 h at room temperature by evaporation to dryness. From the resulting

Table 4. Atom positions and thermal parameters for 2,3,4-tri-*O*-benzoyl-2-*C*-chloro-α-D-xylopyranosyl chloride[a] (**9**)

Atom	x/a	y/b	z/c	u_{11}	u_{22}	u_{33}	u_{23}	u_{13}	u_{12}
Cl1	-215	898	9089	603	1040	952	-36	165	31
Cl2	2714	788	9669	705	719	489	-56	-123	-2
C1	920	1345	9475	719	664	412	-58	104	59
C2	1656	526	9059	612	497	396	-72	-15	-6
C3	1815	848	8070	455	490	401	-43	22	18
C4	1942	2163	7955	605	458	354	-47	1	14
C5	1152	2834	8391	754	467	556	-72	41	147
O5	1097	2529	9315	951	500	463	-101	123	118
O21	1434	-688	9053	722	499	405	-18	78	-31
C21	1137	-1255	9821	607	688	488	58	24	13
O22	1195	-789	542	1175	779	415	-99	110	-133
C22	774	-2438	9635	494	514	512	44	-9	-22
C23	701	-2897	8768	554	547	563	13	49	29
C24	303	-3999	8644	673	618	684	-105	-91	75
C25	-13	-4674	9347	478	554	1016	45	13	71
C26	64	-4222	199	604	563	843	218	55	41
C27	454	-3127	342	599	659	578	127	-11	116
O31	2617	239	7754	561	426	440	-108	60	-8
C31	2467	-745	7241	663	441	296	-10	24	-12
O32	1725	-1096	7008	590	681	538	-188	-39	-33
C32	3372	-1360	7062	603	517	277	-2	2	42
C33	4223	-829	7212	585	553	549	15	22	33
C34	5032	-1463	7033	649	847	723	100	46	-2
C35	4987	-2613	6703	763	795	719	-26	116	261
C36	4135	-3120	6565	928	615	1023	-257	-18	203
C37	3327	-2515	6733	767	537	620	-167	12	24
O41	1901	2374	7002	666	429	411	-14	-12	-95
C41	2274	3414	6718	518	476	581	-51	51	-46
O42	2656	4107	7208	1063	687	627	-89	-123	-322
C42	2143	3597	5744	414	426	482	-29	41	-45
C43	2348	4704	5394	686	483	727	-37	112	-57
C44	2231	4905	4492	852	659	780	257	144	-79
C45	1933	4015	3948	816	915	582	160	91	-29
C46	1731	2926	4285	792	908	468	-74	16	-162
C47	1829	2698	5199	573	568	515	28	37	-113
Largest values of standard deviations:									
Cl	1	2	1	9	13	16	16	9	10
C	4	6	5	44	43	55	40	36	36
O	3	4	3	35	29	24	25	22	29

CB 140/79 Tab. 4

[a] All data are to be multiplied with 10^{-4}. The form of the anisotropic factor is $T = \exp[-2\pi^2(U_{11}a^{*2}h + U_{22}b^{*2}k^2 + U_{33}c^{*2}l^2 + 2U_{12}a^*b^*hk + 2U_{13}a^*c^*hl + 2U_{23}b^*c^*kl)]$.

4:1 mixture of **4** and **5** the major portion of the latter was removed by trituration with ethanol and filtration (yields 14 – 17 %). Concentration of the filtrate to a small volume and standing in the refrigerator overnight gave a small second crop of **5**. The mother liquor resulting therefrom was nearly devoid of **5** and gave chromatographically uniform, sirupy **4** by fast elution from a silica gel column with benzene and subsequent evaporation of the eluate, in yields of 65 – 70 %.

2,3,4-Tri-O-benzoyl-2-C-chloro-β-D-lyxopyranosyl chloride (**8**): A solution of **4** (1.0 g, 2 mmol) and titanium tetrachloride (0.6 ml) in 1,2-dichloroethane (40 ml) was heated under reflux for 2 h. Processing of the mixture by pouring into ice-water, successively followed by washing with water, aqueous sodium hydrogen carbonate, water, drying over sodium sulfate, and evaporation to dryness left a syrup, comprising an approximate 2:1 mixture of **8** (R_F 0.31 in B) and educt (0.41). Purification by PLC (benzene, three 40 cm plates), extraction of the appropriate zone with benzene and evaporation to dryness afforded 440 mg (44 %) of **8** as a syrup; $[\alpha]_D^{25} = -115°$ (c = 1, chloroform).

2,3,4-Tri-O-benzoyl-2-C-chloro-α-D-xylopyranosyl chloride (**9**): Titanium tetrachloride (0.8 ml) was added to a solution of 1.55 g (3 mmol) of **5** in dry 1,2-dichloroethane and the mixture was refluxed for 2 h. The darkbrown solution, comprising an approximate 9:1 mixture of α-D-*xylo*-dichloride **9** (R_F 0.42 in B) and educt **5** (R_F = 0.25)[18], was poured onto ice and after filtration of the precipitate formed, was extracted with dichloroethane. The combined organic phases were washed with aqueous sodium hydrogen carbonate and water, followed by drying over sodium sulfate, and evaporation to dryness. The residue was subjected to PLC (benzene) for removal of **5** and other, slower moving impurities, to give on elution of the appropriate zone and evaporation to dryness a residue that crystallized on trituration with methanol (0.79 g, 51 %). The analytical sample was recrystallized from methanol: prisms of m.p. 138 – 139°C, $[\alpha]_D^{25} = -14.8°$ (c = 1, chloroform). – NMR data cf. tables.

Table 5. Positional and thermal parameters for hydrogen atoms of **9**[a]

Atom	$x/a \times 10^4$	$y/b \times 10^4$	$z/c \times 10^4$	$U \times 10^4$ (Å^2)[b]
H1	961	1252	71	581
H3	1278	634	7796	581
H4	2536	2349	8170	581
H51	540	2720	8109	581
H52	1259	3730	8354	581
H23	943	−2490	8281	733
H24	260	−4368	8082	733
H25	− 86	−5658	9261	733
H26	−167	−4792	722	733
H27	528	−2758	925	733
H33	4310	31	7442	719
H34	5549	−1025	7092	719
H35	5624	−3011	6535	719
H36	4138	−3928	6415	719
H37	2647	−2811	6600	719
H43	2588	5313	5726	936
H44	2439	5606	4299	936
H45	1918	4160	3322	936
H46	1589	2267	3979	396
H47	1707	1816	5465	936

[a] Largest value for standard deviations ($\times 10^4$): x/a 37; y/b 51; z/v 40; U 92.
[b] Common isotropic temperature factors were used for refinement of structurally similar hydrogen atoms.

The crystals of **9** were orthorhombic, space group $P2_12_12_1$, with 4 molecules per unit cell of dimensions $a = 14.38 \pm 0.01$, $b = 11.23 \pm 0.01$, and $c = 15.00 \pm 0.01$ Å. An automatic 4-circle diffractometer (STADI-4) was used with Cu-K_α radiation to measure 7050 reflexes (*h*0l-*h*7l). After data reductions, including averaging of symmetry-related reflexions, 3400 reflexes remained and were used for structure determination by direct methods, i.e., the SHEL-X programme[19] which also allowed full-matrix least-squares refinement of the provisional parameters, and by difference Fourier maps. Structure refinement (all but the hydrogen atoms were treated anisotropically) converged at $R = 0.046$. The final positional and thermal parameters are listed in tables 4 and 5. The bond distances and bond angles are given in fig. 3 and torsional angles in table 3. The thermal motions of the atoms were calculated and plotted by the ORTEP[20] programme to yield fig. 1.

Chlorination of 1,5-anhydro-2,3,4-tri-O-benzoyl-L-threo-pent-1-enitol (L-enantiomer of **2***):* Following the procedure of *Major* and *Cook*[9], a crystalline product of m.p. 183 – 184 °C and $[\alpha]_D^{25} = +110°$ ($c = 1$, chloroform) was obtained in 21% yield (lit.[9] m.p. 178 – 180 °C, $[\alpha]_D^{20} = +110°$, $c = 1.5$, chloroform, 17%). – NMR ($CDCl_3$) and IR data were identical with those observed for **5**, as expected for its L-enantiomer, i.e. *2,3,4-tri-O-benzoyl-2-C-chloro-β-L-xylopyranosyl chloride*[21].

Processing of the ethanolic mother liquor as described for the isolation of **4** afforded syrupy *2,3,4,-tri-O-benzoyl-2-C-chloro-α-L-lyxopyranosyl chloride* (L-enantiomer of **4**) of $[\alpha]_D^{25} = +91.6°$ ($c = 1$, chloroform) in a yield of 65%. ^{1}H NMR data corresponded to those of **4**.

2. Dibromides

Bromination of 1,5-anhydro-2,3,4-tri-O-benzoyl-D-threo-pent-1-enitol (**2**): To a solution of **2** (890 mg, 2 mmol) in anhydrous benzene (40 ml) was added an excess of bromine at room temperature. The solution was kept for 30 min at the same temperature. The solvent was evaporated *in vacuo* followed by addition of benzene and reevaporation. This procedure was repeated thrice to give a nearly colorless syrup, comprising an approximate 3 : 1 mixture of the α-D-*lyxo*- **6** (R_F 0.46 in A, δ for 4-H in $CDCl_3$ 5.87) and the β-D-*xylo*-dibromide **7** (R_F 0.38, δ = 5.44). Separation was effected by fast elution from a short silica gel column (2 × 15 cm) with cyclohexane/ethyl acetate (10 : 1)[22].

The first fractions, containing *2,3,4-tri-O-benzoyl-2-C-bromo-α-D-lyxopyranosyl bromide* (**6**) exclusively (TLC in A), were pooled and evaporated to dryness to afford 560 mg (46%) as a syrup of $[\alpha]_D^{23} = +4.6°$ ($c = 1$, chloroform). Another crop (80 mg, 12%) was obtained on rechromatography of the second fraction which consisted of a mixture of **6** and **7**.

$C_{26}H_{20}Br_2O_7$ (604.3) Calc. C 51.66 H 3.31 **6**: Found C 51.64 H 3.40
7: Found C 51.55 H 3.37

The third fraction contained *2,3,4-tri-O-benzoyl-2-C-bromo-β-D-xylopyranosyl bromide* (**7**) as prismatic needles; m.p. 117 – 118 °C, $[\alpha]_D^{23} = -140°$ ($c = 1$, chloroform).

On elution of the column with a more polar eluant, i.e. cyclohexane/ethyl acetate (4 : 1), fractions containing the β-enolone **26** (40 mg, 6%) and the α-ulose **15** are obtained.

2,3,4-Tri-O-benzoyl-2-C-bromo-α-D-xylopyranosyl bromide (**11**): To a solution of **7** (300 mg, 2 mmol) in tetrachloromethane (20 ml) was added titanium tetrabromide (180 mg) and the mixture was refluxed for 3 h, followed by pouring onto ice-water and filtration of the precipitate formed. The filtrate was washed successively with water, aqueous sodium hydrogen carbonate, and water. After drying over sodium sulfate, evaporation *in vacuo* gave a syrup (230 mg), which was purified by elution from a silica gel column with n-hexane/ethyl acetate (10 : 1). The chromato-

graphically uniform syrup obtained (185 mg, 58%) sluggishly crystallized from ethyl acetate/n-hexane; m.p. 164–165 °C, $[\alpha]_D^{23} = -7.7°$ (c = 1, chloroform).

$C_{26}H_{20}Br_2O_7$ (604.3) Calc. C 51.66 H 3.31 **11**: Found C 51.59 H 3.27
10: Found C 51.80 H 3.40

2,3,4-Tri-O-benzoyl-2-C-bromo-β-D-lyxopyranosyl bromide (**10**): A solution of **6** (440 mg, 0.73 mmol) and titanium tetrabromide (550 mg, 2 molar equiv). in tetrachloromethane (15 ml) was heated under reflux for 6 h. Similar work-up as described above (**7** → **11**) gave a syrup (310 mg), comprising an approximate 3:2:1 mixture (TLC in A, ^{1}H NMR) of educt **6** (R_F 0.48), its β-anomer **10** (R_F 0.41) and the α-D-*xylo* isomer **11** (R_F 0.37). The mixture was fractionated on a silica gel column with n-hexane/ethyl acetate (10:1) to yield after elution of educt **6** a fraction containing **6** and **11**, from which on evaporation and trituration with n-hexane/ethyl acetate **11** crystallized: 62 mg (12%) of m.p. and mixed m.p. 163–164 °C. The fraction eluted next consisted of the β-D-*lyxo* isomer **10** exclusively; evaporation to dryness afforded 65 mg (15%) as a syrup of $[\alpha]_D^{24} = -99.8°$ (c = 0.5, chloroform).

3. Uloses and Enolones

1,3,4-Tri-O-benzoyl-α-D-threo-pentopyranos-2-ulose (**15**): A solution of silver carbonate (180 mg) and **7** (420 mg, 0.7 mmol) in 25 ml acetone/water (9:1) was stirred for 30 min followed by processing of the mixture as described for the β-ulose (cf. below). The syrup obtained slowly crystallized from chloroform/n-hexane to give, after drying *in vacuo* overnight, 225 mg (68%) of a material, mainly consisting of the monohydrate; m.p. 100–102 °C, $[\alpha]_D^{25} = +26°$ (c = 1, chloroform). – ^{1}H NMR ($CDCl_3$): table 1.

$C_{26}H_{20}O_8 \cdot H_2O$ (478.4) Calc. C 65.27 H 4.64 Found C 65.57 H 4.53

Other preparations had even less acceptable analytical data, obviously due to the presence of hydrate, i.e. the *gem*-diol, and the non-hydrated carbonyl form in the crystalline material, as indicated by IR-absorptions 3400 (OH) and 1750/1720 cm^{-1} (C=O). Repeated evaporation from toluene for azeotropic removal of water, whereby bath temperature was kept at ≈30 °C to prevent formation of the α-enolone **16**, left a glassy material with minimal OH-absorption around 3400 cm^{-1} and analytical data between values for the hydrate and the free ulose (calc. for **15**: C 67.82 H 4.38; Found: C 66.94 H 4.50).

1,3,4-Tri-O-benzoyl-β-D-threo-pentopyranos-2-ulose monohydrate (**25**·H_2O)[23]: Silver carbonate (280 mg, 1 mmol) was added to a solution of sirupy α-D-*lyxo*-dibromide[24] (**6**, 600 mg, 1 mmol) in 30 ml of acetone/water (9:1), followed by stirring of the mixture at ambient temperature for 30 min, filtration and evaporation of the filtrate to dryness. The resulting crude **25** was dissolved in chloroform, the solution washed with water, dried over sodium sulfate, and evaporated to a syrup, which crystallized from chloroform/n-hexane: 345 mg (72%) of **25** monohydrate; m.p. 109–110 °C; $[\alpha]_D^{25} = -90.7°$ (c = 1, chloroform). – ^{1}H NMR ($CDCl_3$): table 1.

$C_{26}H_{20}O_8 \cdot H_2O$ (478.4) Calc. C 65.27 H 4.64 Found C 65.18 H 4.57

(2R)-2,4-Bis(benzoyloxy)-2H-pyran-3(6H)-one (1,3-di-O-benzoyl-4-deoxy-α-D-pent-3-enopyranos-2-ulose) (**16**)

a) *By treatment of β-D-xylo-dichloride* **5** *with $NaHCO_3$ in moist benzene:* To a benzene solution of **5** (2.6 g in 100 ml) was added solid $NaHCO_3$ (4 g) and water (1.5 ml) and the mixture was refluxed for 1.5 h. The salts were subsequently removed by filtration, and the filtrate was washed with water, dried (Na_2SO_4), and evaporated to dryness. The remaining syrup gradually crystallized on trituration with ethanol. Recrystallization from the same solvent gave the α-enolone **16** (1.06 g, 69%); m.p. 116–117 °C, showing depression to 97–98 °C on admixture with β-enolone **26**[25]; $[\alpha]_D^{25} = +141.7°$ (c = 0.5, chloroform).

CD (methanol): 228 nm ($\Delta\varepsilon$ = +7.98), 248 (−3.56), 334 (+1.22). − ^{1}H NMR ($CDCl_3$): δ = 4.56 (q, 1H $J_{5,6}$ = 4.0, $J_{6,6'}$ = 19.0 Hz, 6-H), 4.97 (q, 1H, $J_{5,6'}$ = 2.5 Hz, 6'-H), 6.63 (s, 1H, 2-H), 6.95 (q, 1H, J = 2.5 and 4.0 Hz, 5-H). − ^{13}C NMR ($CDCl_3$, TMS): δ = 181.23 (C-2), 141.38 (C-4), 133.91 (C-3), 91.25 (C-1), 61.6 (C-5).

$C_{19}H_{14}O_6$ (338.3) Calc. C 67.45 H 4.17 **16**: Found C 67.50 H 4.09
26: Found C 67.51 H 4.11

b) *From α-ulose* **15** *by elimination of benzoic acid:* A mixture **15** (160 mg) and $NaHCO_3$ (180 mg) in moist benzene (10 ml, containing 0.3 ml of water) was refluxed for 1.5 h. Filtration and evaporation of the filtrate to dryness left a syrup which crystallized on trituration with ethanol. Recrystallization from ethanol afforded α-enolone **16** (75 mg, 64%), identical in all respects with the product described above.

(2S)-2,4-Bis(benzoyloxy)-2H-pyran-3(6H)-one (1,3-di-O-benzoyl-4-deoxy-β-D-pent-3-enopyranos-2-ulose) (**26**)

a) *By treatment of α-D-lyxo-dichloride* **4** *with moist $NaHCO_3$ in benzene:* To a solution of 2.6 g (10 mmol) of sirupy **4** in benzene (150 ml) was added solid $NaHCO_3$ (6 g) and, dropwise, 2 ml of water, followed by refluxing the mixture for 1.5 h, and removal of the salts by filtration. The filtrate was diluted with benzene (100 ml), washed with water, dried (Na_2SO_4), and evaporated to dryness. The residue readily crystallized on trituration with ethanol, wherefrom it was recrystallized once: 2.1 g (62%) of **26** as needles of m.p. 116−117 °C, $[\alpha]_D^{25}$ = −142.3 ° (c = 1, chloroform). − CD (methanol): 228 nm ($\Delta\varepsilon$ = −7.95), 248 (+3.69), 334 (−1.28). − ^{1}H NMR data ($CDCl_3$) corresponded with those of its enantiomer **16**.

b) *By prolonged treatment of α-D-lyxo-dibromide* **6** *with Ag_2CO_3 in aqueous acetone:* On exposure of **6** (600 mg) to Ag_2CO_3 in 9 : 1 acetone/water (300 mg in 30 ml) for more than 30 min at room temperature, gradual conversion of the initially formed β-ulose **25** into enolone **26** takes place, after 16 h only traces of **25** being detectable. The mixture was then filtered, followed by evaporation to dryness and crystallization of the syrup by trituration with ethanol. Recrystallization from the same solvent afforded 240 mg (71%) of **26**, identical with the product described above in all respects.

c) *From β-ulose* **25** *by elimination of benzoic acid:* Refluxing a solution of **25** and $NaHCO_3$ in moist benzene for 1.5 h and workup as described under a), afforded **26** in 75% yield. The enolone **26** was similarly obtained on treatment of β-D-*lyxo*-dibromide **10** with silver carbonate in acetone/water (9 : 1) at room temperature for 16 h; yield 71%.

4-Benzoyloxy-2-chloro-2H-pyran-3(6H)-one (**20**): A solution of **26** (1.0 g, 3 mmol) in 15 ml of acetyl chloride presaturated with HCl gas was kept at room temperature for 24 h. Evaporation *in vacuo* afforded a colorless syrup which was reevaporated twice from n-pentane and subsequently triturated with ether/n-pentane effecting gradual crystallization. After standing overnight in a refrigerator **20** was collected: 600 mg (80%) of m.p. 113−115 °C. − ^{1}H NMR ($CDCl_3$): δ = 4.57 (q, 1H, $J_{6,6'}$ = 19, $J_{5,6}$ = 4.0 Hz, 6-H), 5.05 (q, 1H, $J_{5,6'}$ = 2.0 Hz, 6'-H), 6.21 (s, 1H, 2-H), 6.92 (q, 1H, J = 4.0 and 2.0 Hz, 5-H), 7.4−8.3 (m, 5H, C_6H_5).

$C_{12}H_9ClO_4$ (252.7) Calc. C 57.05 H 3.59 Found C 57.11 H 3.53

The low rotation of the product ($[\alpha]_D^{20}$ = −1.5 °, chloroform) as compared to the educt **26** ($[\alpha]_D$ = −142 °) indicates nearly complete racemization at the anomeric carbon atom during the conversion.

4-Benzoyloxy-2-bromo-2H-pyran-3(6H)-one (**21**): HBr gas was passed into a stirred suspension of **16** (600 mg, 2 mmol) in ether (10 ml) until a clear solution was obtained. After 2 h the solvent was removed *in vacuo* leaving a syrupy residue which gradually crystallized on trituration with

ether/n-pentane: 370 mg (75%) as colorless crystals of m. p. 108–109°C. — NMR data in $CDCl_3$ duplicated those for the chloroenolone **20** except for the anomeric proton (s at δ = 6.58).

$C_{12}H_9BrO_4$ (278.1) Calc. C 48.51 H 3.05 Found C 48.41 H 2.98

The product exhibited a rotation of −7° (chloroform) indicating nearly complete loss of chirality at C-2 during the conversion **16** → **21.**

4-Benzoyloxy-2-hydroxy-2H-pyran-3(6H)-one (**22**): A solution of **20** (140 mg, 0.5 mmol) in a mixture of acetone (7 ml) and water (0.5 ml) was stirred in the presence of silver carbonate (100 mg) for 8 h at ambient temperature. Filtration and evaporation of the filtrate *in vacuo* (finally 2 Torr) left a syrup that crystallized from ether/n-hexane: 80 mg (62%), m.p. 124–126°C. — ^{1}H NMR ($CDCl_3$): δ = 5.40 (s, 1H; 2-H), other signals duplicated those of methoxy-enolone **23.**

$C_{12}H_{10}O_5$ (234.2) Calc. C 61.54 H 4.30 Found C 61.46 H 4.23

4-Benzoyloxy-2-methoxy-2H-pyran-3(6H)-one (**23**): A solution of **20** in methanol (400 mg in 8 ml) was kept at 30°C. After 2 h crystals started separating which were collected after another 2 h at 30°C and standing in a refrigerator overnight: 250 mg (64%), m.p. 90–91°C. – ^{1}H NMR ($CDCl_3$): δ = 3.59 (s, 3H, OCH_3), 4.42 (q, 1H, $J_{5,6}$ = 4 and $J_{6,6'}$ = 19 Hz, 6-H), 4.84 (q, 1H, $J_{5,6'}$ = 2 Hz, 6'-H), 4.93 (s, 1H, 2-H), 6.83 (q, 1H, J = 2 and 4 Hz, 5-H). – ^{13}C NMR ($CDCl_3$, TMS): δ = 182.74 (C-2), 140.85 (C-4), 133.88 (C-3), 99.53 (C-1), 59.59 (C-5), 56.82 (OCH_3).

$C_{13}H_{12}O_5$ (248.2) Calc. C 62.90 H 4.87 Found C 62.76 H 4.79

3-Benzoyloxy-4H-pyran-4-one (O-benzoylpyromeconic acid) (**24**): A solution of **16** (500 mg, 1.5 mmol) in pyridine (10 ml) was kept at ambient temperature for 24 h, whereafter TLC in A indicated complete absence of educt in favor of **24.** The solvent was removed by evaporation *in vacuo* and the residue was dissolved in chloroform followed by washing of the solution with 1N H_2SO_4, water, drying, and evaporation to dryness. The partially crystalline mass was triturated with diisopropyl ether, collected, and recrystallized from ethanol: 210 mg (63%) needles; m.p. 152–153°C (lit.[26] 152–153°C). – ^{1}H NMR (100 MHz, $CDCl_3$): δ = 6.55 (d, 1H, $J_{5,6}$ = 6.0 Hz, 5-H), 7.55 and 8.20 (3H- and 2H-m, C_6H_5), 7.82 (q, 1H, $J_{2,6}$ = 1.0 Hz, 6-H), 8.06 (1 Hz-d, 1H, 2-H).

$C_{12}H_8O_4$ (216.2) Calc. C 66.67 H 3.73 Found C 66.58 H 3.70

Standing of **26** in pyridine at ambient temperature for several days similarly afforded **24.** Heating with acetic anhydride in the presence of sodium acetate (1–2 h at 80°C) converted either ulose (**15** or **25**) or any of the enolones (**16, 20–23, 26**) into the γ-pyrone **24.**

4-Deoxy-D-erythro-pentose (**17**): To a prehydrogenated suspension of PtO_2 (500 mg) in 20 ml of methanol/ethyl acetate (1:1) was added **16** (340 mg, 1 mmol) and the hydrogenation was continued. After 3–4 h — TLC in A indicated the formation of one compound with only traces of other products — the catalyst was filtered off, the filtrate was evaporated to dryness, and the solution of the residue in 10 ml of 0.3N H_2SO_4 was briefly (5 min) refluxed. Upon neutralization with sodium carbonate and evaporation to dryness the residue was extracted with hot ethyl acetate. Evaporation of the extract and purification of the syrupy residue by elution from a cellulose column (2 × 20 cm) with ethyl acetate gave **17** as a colorless, chromatographically homogeneous syrup (90 mg, 67%), which readily reduced Fehling solution; $[\alpha]_D^{23}$ = −27.6° (*c* = 0.5, water). – ^{1}H NMR (D_2O): δ = 4.88 (5 Hz-d, 1H, 1-H).

$C_5H_{10}O_4$ (134.1) Calc. C 44.77 H 7.52 Found C 44.49 H 7.57

4-Deoxy-L-erythro-pentose (**27**): Perhydrogenation of **26** followed by acid de-*O*-benzoylation and work-up as described for its enantiomer **16** (cf. above) gave a syrup of $[\alpha]_D^{23}$ = +28.9° (*c* = 0.2, water), pure by TLC and combustion analysis [lit.[16,17] $[\alpha]_D^{21}$ = +23.1° and +28.5° (*c* = 0.2, water)].

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[18] After refluxing for 6 – 8 h, educt **5** had essentially disappeared yet on expense of considerable decomposition which drastically affected the yield.

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[22] Slow elution and longer columns result in increasing formation of the pentosuloses **15** and **25** and of the β-enolone **26** (via **25**), the latter being eluted from the column with a more polar eluent (cyclohexane/ethyl acetate 4:1).

[23] Unlike the α-ulose **15,** where hydration does not appear to occur stoichiometrically, the β-ulose **25** clearly accumulates as the monohydrate, i.e. the geminal 2,2-diol.

[24] Hereby, a product containing 3 – 5 % of the alternate β-D-*xylo* isomer **7,** i.e. intermediate fractions originating from the separation of **6** and 7 on silica gel columns, can readily be used; the α-ulose **15,**formed from **7,** has a considerably lower tendency for crystallization than the β-ulose **25,** thus not impairing the isolation of the latter. Even the dibromide mixture resulting from the bromination of **2** may be used for the preparation of **25,** yet yields are affected (30 – 40 %).

[25] In a preliminary report[4] a m.p. of 94 – 95 °C and $[\alpha]_D^{20} = -40°$ in $CHCl_3$ had been forwarded for the α-anomer **16,** which subsequently was proved to be a mixture of α- and β-anomers as formed by hydrolysis of the 1,2-dichloride mixture **4/5.**

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