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NMR studies of molybdate complexes of D-allose, D-altrose, D-gulose, and D-idose †

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ABSTRACT

Aqueous molybdate complexes of D-allose, D-altrose, D-gulose, and D-idose were studied by ^{1}H and ^{13}C NMR spectroscopy. Different amounts of binuclear tetradentate molybdate complexes, involving the hydrated aldehyde group and the three adjacent hydroxyl groups of the hydrate, i.e., HO-2,3,4, were detected for all the aldoses investigated. In addition, D-altrose and D-idose hydrates preferentially adopt another binuclear tetradentate complex with donor hydroxyl groups HO-2,3,4,5. Both types of binuclear tetradentate molybdate complexes are present in two forms due to a different linkage mode of the asymmetric binuclear molybdate core to the aldose hydrate molecule. Cyclic forms of D-allose and D-gulose predominate in their complexes.

INTRODUCTION

Unsubstituted monosaccharides in acidic aqueous solutions containing a catalytic amount of molybdate ions epimerise to give an equilibrium mixture of C-2 epimeric aldoses. This selective epimerisation reaction, during which C-1/C-2 transposition occurs, is preceded by the formation of active complexes between the aldose and molybdate[1–3]. In order to understand the mechanism of this reaction, the structures and stability of the molybdate complexes have been examined mainly by ^{1}H and ^{13}C NMR spectroscopy.

In previous studies of molybdate complexes[3–6], we found that aldo-pentoses, -hexoses, and -heptoses having *lyxo* or *ribo* configuration participate in the complexation predominantly in their pyranose forms with donor hydroxyl groups having *ax–eq–ax* orientation. Sauvage et al.[7] recently proposed that the aldoses of the *lyxo* series form molybdate complexes in the furanoid form as tetradentate ligands. Aldo-pentoses, -hexoses, and -heptoses of the xylose and arabinose homo-

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morphous series form binuclear tetradentate complexes only in the acyclic hydrated form (hydrate)[3,6]. Regarding the proposed mechanism of the epimerisation reaction[1], the existence of binuclear tetradentate complexes of aldose hydrates, in which the donor hydrated aldehyde group and HO-2,3,4 are involved, could be important. The spatial arrangement of the carbon chain at the complexation site in such a complex depends on the configuration at C-2 and C-3 and can be close to the sickle (*E* type) or the zigzag arrangement (*F* type)[3,8]. Both types of complexes involving the aldose hydrate have been found in two forms E_1,E_2 and F_1,F_2, respectively. For both arrangements (*E* and *F*), the observed *J* values suggest that the ligand conformation is largely identical in the two forms. However, the two forms can clearly be distinguished, as their ^{1}H and ^{13}C NMR chemical shifts differ markedly. These observations have been ascribed to different orientations of the ligand[8] with respect to the asymmetric molybdate core[9].

In this study, the structures of the molybdate complexes of D-allose (**1**), D-altrose (**2**), D-gulose (**3**), and D-idose (**4**) have been elucidated on the basis of various ^{1}H and ^{13}C NMR spectroscopic techniques.

RESULTS AND DISCUSSION

D-*Allose* (**1**).—In aqueous solution, D-allose is predominantly (≥ 90%) in the β-pyranoid form[10]. In the β form, D-allopyranose has the same ring configurational pattern as α-D-ribose. Hence, one can also expect structural similarity of their molybdate complexes. In fact, the ^{1}H and ^{13}C NMR data of the predominant molybdate complex of D-allose (Tables I and II are in good agreement with the NMR data[6] of the D-ribopyranose molybdate complex in the conformation close to $B_{1,4}$ as well as with ^{13}C NMR data published for the molybdate complex of **1** (ref 5). However, due to overlap of the H-4 and H-5 signals of **1** in the complex, it was not possible to assign C-4 and C-5 unambiguously from the heterocorrelation plot. The semiselective INEPT spectrum obtained after irradiation of the H-1 proton of the complex gave the signals C-3 (δ 86.9) and C-2 (δ 80.3) of small intensity and one more intense signal at δ 76.6. This signal could be due to either C-5 of the pyranoid or C-4 of the furanoid aldose form. However, the irradiation of H-2 gave, in addition to signals C-1 (δ 103.1) and C-3, the most intense signal at δ 78.1 which could only be due to C-4. To confirm unambiguously the aldose form in this type of complex, we also performed a semiselective INEPT experiment with D-ribose. The presence of the C-5 signal at δ 66.3 in the semiselective INEPT spectrum after irradiation of H-1 confirmed the pyranoid form of the ligand.

In the ^{1}H and ^{13}C NMR spectra of **1** in the presence of molybdate ions, there were weak (5%) signals for H-1 at δ 5.53 ($J_{1,2} \leq 1$ Hz) and C-1 at δ 95.4, providing evidence for the presence of a binuclear tetradentate molybdate complex in the E_1 form (Scheme 1), with the hydrated aldehyde group and three vicinal hydroxyl groups at HO-2,3,4 as donors. In such a complex, **1** adopts a sickle arrangement of the carbon chain at the site of complexation.

TABLE I

^{13}C NMR data for molybdate complexes of investigated aldoses

Compound	C-1	C-2	C-3	C-4	C-5	C-6	Type of complex [d]	Content (%)
1	95.2	94.0	81.6	na	na	na	E_1	5
	103.1	80.3	87.0	78.1	76.6	64.0	$B_{1,4}$	60
2	99.8	86.4	81.3	83.9	na	na	F_1	7
	98.3	na [b]	na	na	na	na	F_2	3
	92.4	81.8	89.5	82.7	82.2	na	A_1	10
3	95.3	92.9	82.1	82.0	na	63.9	E_1	5
	112.7	84.3	88.7	81.3	76.2	64.4	furanoid	90
4 [a]	99.1	na	na	na	na	na	F_1	20
	97.7	na	na	na	na	na	F_2	5
	89.8	87.0	85.2 [c]	82.5 [c]	83.0 [c]	62.8	D	65

[a] Chemical shifts estimated at 275 K. [b] na, Not assigned. [c] Signals can be interchanged. [d] E_1,E_2, acyclic (binuclear tetradentate) with donor HO-1,2,3,4 sickle; $B_{1,4}$, pyranoid structure with donor HO-2,3,4; F_1,F_2, acyclic with donor HO-1,2,3,4 zigzag; A_1, acyclic with donor HO-2,3,4,5 sickle; donor hydroxyl groups in the furanoid form are HO-1,2,3; D, acyclic with donor HO-2,3,4,5 zigzag.

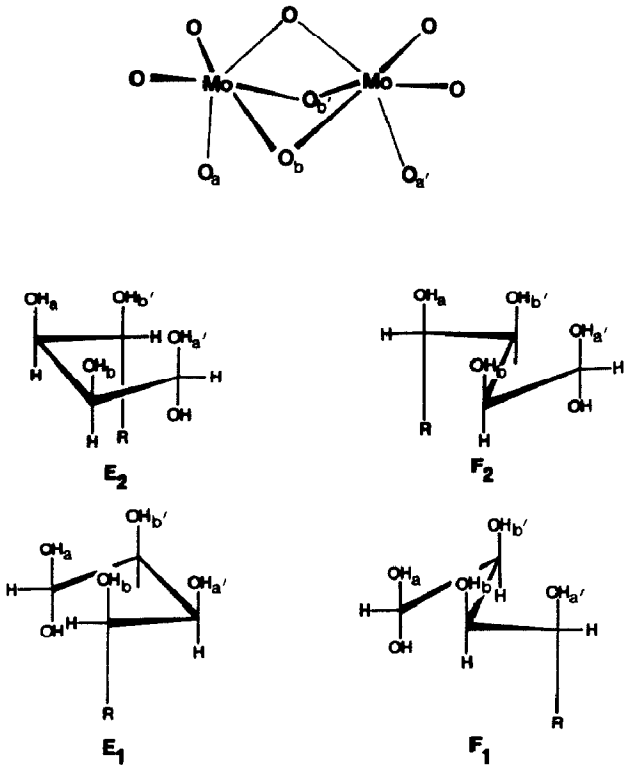
D-*Altrose* (**2**).—D-Altrose (**2**) in aqueous solution represents a mixture of pyranose and furanose forms (αp 30%, βp 41%, αf 18%, and βf 11%)[10]. In the anomeric region of the ^{1}H NMR spectrum of **2** in the presence of molybdate ions, the signals of all uncomplexed forms as well as the signals of complexes were present. As a consequence of this fact, it was only possible to estimate that ca. 20% of hydrated **2** is present in two different types of binuclear tetradentate complexes. In addition, nearly 5% of **2** was present in at least three types of complex not

TABLE II

^{1}H NMR data for molybdate complexes of investigated aldoses

	H-1	H-2	H-3	H-4	H-5	H-6a	H-6b	Complex type [b]
1	5.52	na [a]	na	na	na	na	na	E_1
	6.14	4.79	4.84	4.33	4.33	na	na	pyranoid
2	5.44	4.50	na	na	na	na	na	F_1
	5.60	4.39	na	na	na	na	na	F_2
	5.07	4.13	4.90	4.77	4.52	na	na	A_1
3	6.16	4.94	5.38	4.44	4.08	3.99	3.91	furanoid
4	5.19	broad lines						F_1
	5.30	broad lines						F_2
	$J_{1,2}$	$J_{2,3}$	$J_{3,4}$	$J_{4,5}$	$J_{5,6a}$	$J_{5,6b}$	$J_{6a,6b}$	$^4J_{2,4}$
1	5.9	4.7	2.5	1.6	na	na	na	2.2
	≤1.0	na	na	na	na	na	na	
2	0.2	1.0	na	na	na	na	na	
	2.2	≤1.0	na	na	na	na	na	
	7.3	≤1.0	4.1	≤1.0	6.7	10.2	na	
3	4.5	6.7	7.8	2.6	6.7	6.4	10.8	

[a] na, Not assigned or not resolved. [b] E_1, F_1, F_2, and A_1 as in Table I.



Scheme 1. The ligands are shown in two forms E_1,E_2 for the sickle arrangement and F_1,F_2 for the zigzag arrangement, respectively, for the binuclear tetradentate molybdate complexes with the donor hydrated aldehyde group and HO-2,3,4. They are formed due to a different mode of binding of the asymmetric binuclear molybdate core to the aldose hydrate molecule. The formation of A_1,A_2 forms of the D-arabinose complex is the same as that of E_1,E_2 and F_2,F_2. The only difference is the participation of the hydrated aldehyde group in the complex.

observed previously. However, their structures could not be identified because of their low concentration.

Since **2** and D-arabinose have the same configurational pattern, structural similarities in their molybdate complexes were expected. D-Arabinose hydrate was found to form a binuclear molybdate complex with the three secondary and one primary hydroxyl groups HO-2,3,4,5 as donors with a sickle arrangement of the carbon chain. For the two observed forms A_1,A_2 (Scheme 1) of this complex, the ^{13}C chemical shift of C-5 at $\delta \sim 70.1$ and ~ 72.8, respectively, were diagnostic. For **2**, analogous complexes could in principle form with HO-3,4,5,6. However, C-6 signals suggesting the presence of such types of complex were not observed in the ^{13}C NMR spectrum of **2** in the presence of molybdate ions.

One of the observed binuclear tetradentate complex types was quite easy to identify on the basis of the chemical shifts and coupling constants of C-1 and H-1, which are characteristic of the complex with the donor hydrated aldehyde group and the three adjacent hydroxyl groups (HO-2,3,4) with a zigzag arrangement. The

two forms F_1 and F_2 (Tables I and II, Scheme 1) were found to be present in the ratio 7:3 to the extent of 10%. The same $F_1 : F_2$ ratio was found for D-threose and 5-deoxy-L-arabinose[8]. This type of complex was not found in a detectable amount for D-arabinose, even though its formation could be expected on the basis of its presence for D-galactose[6].

The second type of binuclear tetradentate molybdate complex of **2** involved four secondary hydroxyl groups HO-2,3,4,5 with a sickle arrangement of the carbon chain at the site of complexation. Analogous complexes have been found for D-galactose and D-*glycero-galacto*-heptoses in two forms A_1 and A_2 in the ratio 6:4 (ref 6). 1D COSY and multistep 1D relayed coherence transfer COSY experiments allowed the chemical shifts and coupling constants of all proton signals to be determined (Table II). These values, as well as the ^{13}C NMR chemical shifts obtained from a heterocorrelation plot, are in full agreement with the data for the A_1 form of D-galactose[6]. The H-1 signals due to complexes of the form A_2 typically appear around δ 5.21 (ref 6). For **2**, no signal was found at this value, whereas a number of small overlapping signals were present at δ 5.16. However, they could not be assigned unambigously. In the ^{13}C NMR spectrum, a number of signals were also present in the region close to δ 90.5, at which the C-1 resonance of A_2 was expected. In the ^{13}C NMR spectrum, the carbon signals of nonhydrated aldehyde groups not involved in the complex were observed at δ 209.8 and 198.5. In the ^1H NMR spectrum, only one signal could be resolved at δ 9.75. These values are in good agreement with those reported for D-galactose[6]. Hence, it is probable that this form of the complex is also present in the solution.

D-*Gulose* (**3**).—The pyranoid form is predominant in an aqueous solution of D-gulose[10]. In the presence of aqueous ammonium molybdate, more than 90% of D-gulose was complexed in the cyclic form. NMR data for this complex are in full agreement with those of the predominant type of complex found for D-lyxose and D-mannose. This type of complex involved the pyranoid form of the aldoses with donor hydroxyl groups at HO-1,2,3 (ref 3). In contrast, Sauvage et al.[7] recently proposed that D-lyxose, D-mannose, and L-rhamnose undergo this complexation in the furanoid form with donor hydroxyl groups at HO-1,2,3,5.

The agreement between NMR data obtained for the molybdate complex of **3** (Tables I and II) with those obtained for aldoses of the *lyxo* series in this type of complex prompted us to reinvestigate the aldose form involved. The furanoid structure of the aldose in this complex was confirmed by a ^{13}C semiselective INEPT experiment. In the ^{13}C NMR spectrum acquired with selective irradiation of H-1 (δ 6.16), the population transfer allowed observation of the signal for C-4 (δ 81.3) across the ring oxygen, together with the signals C-2 (δ 84.3) and C-3 (δ 88.7), thus confirming the furanoid form of the aldose in the complex. It has been suggested[7] that this type of complex with a furanoid ligand form is stabilised by participation of HO-5 in the complex. However, one-bond coupling constants $^1J_{C,H}$ of the carbon atoms whose attached hydroxyl groups are involved in the complex have higher values after complexation than those found for uncomplexed aldoses.

The $^1J_{C\text{-}5,H\text{-}5}$ values reported for D-lyxose, D-mannose, and L-rhamnose[11] and the values of the constants for D-gulose ($^1J_{C\text{-}1,H\text{-}1}$ to $^1J_{C\text{-}6,H\text{-}6}$: 177.4, 156.0, 153.4, 151.0, 141.2, and 139.9) confirm that the donor hydroxyl groups are HO-1,2,3 in this type of complex.

A singlet signal at δ 5.44 ($J_{1,2} \leq 1$ Hz) provided evidence for the presence of a small amount (5%) of D-gulose hydrate in a binuclear tetradentate molybdate complex in which the hydrated aldehyde group and the three adjacent hydroxyl groups (HO-2,3,4) are involved. The spatial arrangement of the carbon chain at the site of complexation is close to the sickle (form E_1).

D-*Idose* (**4**).—A mixture of pyranoid and furanoid forms of D-idose is present in aqueous solution together with a relatively high content of acyclic aldehyde and hydrate forms[12]. In the presence of molybdate ions, ca. 90% of the D-idose hydrate was bound in a binuclear tetradentate complex with the secondary HO-2,3,4,5 as donors. An analogous complex has been found for 6-deoxy-L-glucitol and it has been denoted *D*. Broad lines are characteristic of this type of complex in both the ^{1}H and ^{13}C NMR spectra[13]. At room temperature, the ^{1}H and ^{13}C NMR signals due to the predominant type of complex of D-idose were also broad and the anomeric signals of the two forms F_1,F_2 of another expected binuclear tetradentate complex involving the hydrated aldehyde group and HO-2,3,4 could not be identified. After decreasing the temperature to 275 K, the lines became narrower and the presence of the two forms F_1 and F_2 of the latter type of complex was evident. However, the lines were still too broad for the elucidation of the coupling constants in the ^{1}H NMR spectrum. The content of the former predominant complex at this temperature decreased to 65% and the total amount of F_1 and F_2 forms was 25%, with the ratio $F_1 : F_2 = 4 : 1$ (estimated from the ^{13}C NMR spectrum).

CONCLUSIONS

The amount of binuclear tetradentate molybdate complexes involving the hydrated aldehyde group and three adjacent vicinal hydroxyl groups (HO-2,3,4) of the aldose hydrated form was found to be different for all the aldoses investigated. In addition, D-idose and D-altrose as hydrates enter another binuclear tetradentate complex with HO-2,3,4,5 as the donors. As a consequence of a different mode of linkage of the asymmetric binuclear molybdate core to the aldose hydrate molecule, both of these complexes are present in two forms.

D-Allose and D-gulose preferentially enter the molybdate complex in the cyclic form. The ^{13}C semiselective INEPT experiment proved that in the complex with the *B* conformation, which is characteristic of the ribose homomorphous series, the aldose is present in the pyranoid form. In the complex characteristic of the *lyxo* series, the aldose enters as a furanose with HO-1,2,3 as the donors.

EXPERIMENTAL

Deuterium oxide solutions containing the saccharide and ammonium molybdate $[(NH_4)_6Mo_7O_{24} \cdot 4H_2O]$ in the ratio of 1 mol of aldose to 2 mol of molybdenum were subjected to NMR spectroscopy in a Bruker AM-300 spectrometer at 298 K, unless stated otherwise. Internal references for ^{13}C (75 MHz) and ^1H NMR (300 MHz) spectra were methanol (δ 50.15) and sodium 3-(trimethylsilyl)propionate (δ 0.00), respectively. The digital resolution was 1.9 and 0.12 Hz per point, respectively.

The following techniques were employed for assignment of the signals: ^{13}C NMR, H,C COSY with decoupling in the F_1 domain, DEPT, gated decoupling ^{13}C NMR spectra with NOE suppression, and ^{13}C semiselective INEPT; ^1H NMR, 2D COSY, 1D COSY, and 1D-relayed coherence transfer COSY. Fixed delays in 1D COSY and 1D-relayed COSY experiments for selective coherence transfer were optimised for known values of the coupling constants. For the selective excitation in ^1H and ^{13}C 1D experiments, the soft rectangular pulse was used with duration between 40–100 ms (depending on the desired selectivity) and 10 ms, respectively.

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