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Complexation of trivalent lanthanide cations by sugars and alditols in water: chromatography–calorimetry comparison

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Abstract

A systematic study of the relative stabilities of the complexes formed between polyhydroxy compounds (sugars and alditols) and the trivalent lanthanide cations in water has been performed by thin-layer ligand-exchange chromatography. The TLC results have been compared with the thermodynamic complexation constants determined previously by calorimetry. Good linear correlations have been observed indicating that the variations of both equilibrium constant and distribution coefficient are governed by the same factors. The efficiencies of plates in Ca^{2+}, La^{3+}, and Sm^{3+} forms for the separation of alditols or sugars are compared.

Keywords: Lanthanide cations, complexation of; Sugars; Alditols

1. Introduction

Polyhydroxy compounds such as small sugars and alditols can specifically interact with divalent and trivalent metal cations in water [1], if they bear a particular sequence of three hydroxyl groups on adjacent carbon atoms. The complexes formed by the sugar isomers having, or being able to assume, an *axial–equatorial–axial* triol on a six-membered ring or a *cis–cis* triol on a five-membered ring, and by the alditols having a *threo–threo* triol on their linear chain are weak ($K < 10$) but selective. Weak interactions of that type can be of importance for biological systems, in particular because of the noteworthy role played by trace elements in the pathogenesis and treatment of some diseases.

Recently, we have determined the Gibbs energies, enthalpies, and entropies of complexation of the trivalent lanthanide cations by ribose [2] and by some alditols [3] in water,

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using a calorimetric method and following a procedure that allows the non-specific interactions to be neglected [4]. It appeared that the trivalent lanthanide cations form more stable complexes than the alkaline-earth metal cations [4], and show an interesting selectivity, the stability constant varying significantly from La^{3+} to Tb^{3+} and passing through a maximum for Sm^{3+}. No significant complexation of the heavier lanthanide cations was detected. It was shown that even if the stability constants are very small, the selectivity towards the lanthanide cations is comparable to that observed with stronger ligands also bearing oxygen atoms as coordinating sites.

This behaviour can be of practical importance for the resolution of mixtures of polyhydroxy compounds by chromatography on a column of cation-exchange resin. For instance, it appears from our calorimetric results that polyhydroxy compounds should be separated better on a column in the samarium form than on a classical column in the calcium or lanthanum form [1,5,6]. Since Goulding's work [7] showing the cation specific selectivity for polyhydroxy compounds separation, studies were performed to improve the chromatographic method by changing the column cationic-form [8,9] but none of these investigations tested the whole series of lanthanide cations. Hence, it appeared of interest to undertake a systematic study of the relative stabilities of the complexes formed between polyhydroxy compounds and the trivalent lanthanide cations in water by thin-layer ligand-exchange chromatography.

In the present work the R_f values of typically complexing (glucitol, xylitol, ribose) and non-complexing (ribitol, arabinose) polyhydroxy compounds on thin layers in La^{3+}, Ce^{3+}, Pr^{3+}, Nd^{3+}, Sm^{3+}, Eu^{3+}, Gd^{3+}, Tb^{3+}, Dy^{3+}, Ho^{3+}, Er^{3+}, Tm^{3+}, and Yb^{3+} forms have been determined. Our purpose is to compare the TLC results for the complexing polyhydroxy compounds with the thermodynamic complexation constants determined previously [2,3]. The behaviour of other alditols and sugars (arabinitol, galactitol, mannitol, altrose, erythrose, fructose, galactose, glucose, mannose, talose, threose, xylose) has also been examined on La^{3+} and Sm^{3+} plates. For comparison, these polyhydroxy compounds were also studied on Ca^{2+} plates. By the time we were completing this work, Angyal and Craig [10] published a paper comparing the R_f values of some alditols on TLC plates prepared with different lanthanide nitrates and, for some ligands, they examined the whole series of rare-earth cations. We shall see below that whenever comparison is possible good agreement is observed between their data and ours.

2. Results and discussion

The measured R_f values for all of the studied systems are listed in Table 1. The values found for the complexing polyhydroxy compounds vary in a peculiar way with the lanthanide cation radius [11], as shown in Fig. 1 for xylitol and ribose. The values found for complexing glucitol have not been plotted since they would superpose on those of xylitol. In this Fig. 1, the behaviour of the complexing polyhydroxy compounds is compared with that of non-complexing references. By analogy with our calorimetric studies [2–4] ribitol and arabinose have been chosen as non-complexing references for xylitol and ribose, respectively.

Table 1
R_f values of polyols on TLC plates in various cationic forms [a,b]

	Ca^{2+}	La^{3+}	Ce^{3+}	Pr^{3+}	Nd^{3+}	Sm^{3+}	Eu^{3+}	Gd^{3+}	Tb^{3+}	Dy^{3+}	Ho^{3+}	Er^{3+}	Tm^{3+}	Yb^{3+}
Arabinitol	0.72	0.65				0.50								
Galactitol	0.62	0.56				0.27								
Mannitol	0.72	0.72				0.56								
Ribitol	0.80	0.80	0.77	0.74	0.71	0.69	0.76	0.77	0.77	0.82	0.80	0.81	0.80	0.79
[c]			0.77	0.75	0.73	0.73								
Glucitol	0.65	0.51	0.39	0.32	0.29	0.28	0.38	0.37	0.48	0.58	0.62	0.66	0.71	0.68
Xylitol	0.66	0.50	0.40	0.35	0.30	0.29	0.38	0.37	0.48	0.57	0.60	0.65	0.68	0.66
[c]			0.43	0.35	0.30	0.28								
Altrose	0.80	0.84				0.83								
Arabinose	0.77	0.81	0.81	0.81	0.79	0.82	0.79	0.82	0.82	0.80	0.80	0.81	0.80	0.83
[c]				0.82	0.83	0.83								
Erythrose	0.59	0.55				0.31								
Fructose	0.77	0.82				0.82								
Galactose	0.81	0.83				0.85								
Glucose	0.87	0.87				0.84								
Mannose	0.84	0.84				0.83								
Ribose	0.63	0.56	0.48	0.39	0.36	0.33	0.41	0.41	0.50	0.58	0.64	0.66	0.68	0.65
[c]				0.39	0.34	0.31								
Talose	0.61	0.61				0.38								
Threose	0.82	0.79				0.77								
Xylose	0.82	0.83				0.83								

[a] ±0.02.
[b] Unless otherwise indicated, each plate was treated with a chloride solution.
[c] Plate treated with a nitrate solution.

The behaviours of the three complexing polyhydroxy compounds are very similar. In each case, the R_f value varies significantly within the lanthanide cation series and shows a minimum for Sm^{3+}. Similar trends were observed by Angyal and Craig [10]. The curves are smooth except for a small kink at Eu^{3+}. Obviously, the interaction between the complexing polyhydroxy compound and the lanthanide cation gets stronger when going from La^{3+} to Sm^{3+}, then weakens almost linearly when going from Gd^{3+} to Tm^{3+} and, finally, increases very slightly from Tm^{3+} to Yb^{3+}. This is not unusual behaviour since it was noticed previously [2] that the selectivity of various polyoxygenated ligands towards the lanthanide cations, determined by comparison of the stability constants, exhibits a similar trend [2,12–14] regardless of the strength of the ligand (see Fig. 5 of Ref [2]). It is interesting to note that TLC shows weak complexation of the heavier lanthanide cations which was not possible to observe by calorimetry [2], possibly because of very low enthalpic effects.

Arabinose appears to be a satisfactory non-complexing reference since its R_f value is high and independent of the cation radius. Ribitol is not as good since its R_f value varies slightly with the cation size and shows a weak minimum for Sm^{3+}. In fact, even if ribitol does not bear the *threo–threo* complexing site but only *erythro* hydroxyl groups [15], it seems that it exhibits a slight specificity towards the first members of the lanthanide cation series (La^{3+}

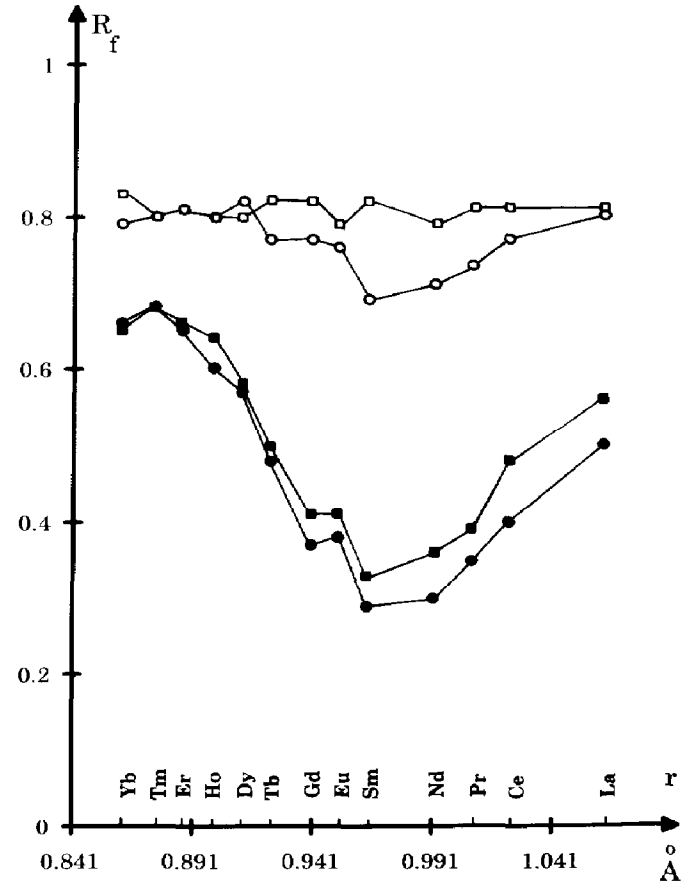

Fig. 1. R_f values of xylitol (●), ribitol (○), ribose (■), and arabinose (□) versus lanthanide cation radius.

to Sm^{3+}), possibly by achieving a complexing arrangement through C–C bond rotations. In fact, any alditol can take up a conformation containing a complexing arrangement and it is not possible to find a better reference.

The true migration rates R_f' can be obtained by correcting the measured R_f values as follows

$$R_f' = \xi R_f \tag{1}$$

where ξ is a parameter that takes into account the different disturbing factors (frontal volume gradient, pre-loading effect, etc.). ξ was estimated from the R_f values measured on layers in the H^+ form, this cation being not complexed by sugars or alditols. The R_f values found for ribose, arabinose, xylitol, and ribitol were equal to 0.86 ± 0.01, leading to an average ξ value of 1.16.

The migration rate R_f' is related to the distribution coefficient K_d as follows [16]

$$R_f' = \frac{1}{1 + K_d(W_a/V_m)} \tag{2}$$

where W_a is the weight of stationary phase and V_m the volume of mobile phase. The term $K_d(W_a/V_m)$ corresponds to the capacity factor k which represents the ratio of the amount of solute in the stationary phase to that in the mobile phase. It follows that

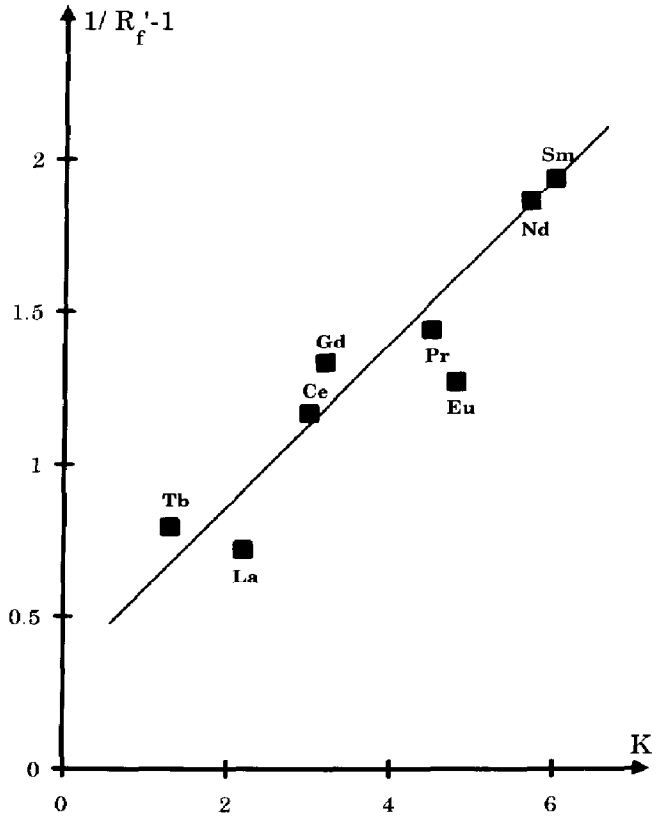

Fig. 2. Correlation between the capacity factors of xylitol and the stability constants determined by calorimetry [3].

$$k = K_d(W_a/V_m) = \frac{1-R_f'}{R_f'} = \frac{1}{R_f'} - 1. \quad (3)$$

The capacity factors of xylitol and ribose have been plotted versus the stability constants determined previously by calorimetry but not corrected for the non-specific interactions [2,3] (Figs. 2 and 3, respectively). The values found for glucitol have not been plotted since they give a correlation very similar to that observed with xylitol. Only the complexes of the first members of the lanthanide cation series (La^{3+} to Tb^{3+}) appear in these figures since no significant complexation of the heavier lanthanide cations could be detected by the calorimetric method. It should be noted that the stability constants used in Fig. 3 are relative to the whole of ribose isomers present in solution whereas the mean stability constants given in Ref [2] characterize solely the 43% of ribose isomers that bear a complexing site. Figs. 2 and 3 show that a good linear correlation is observed between k and K regardless of the ligand (xylitol and ribose). Moreover, the slope is almost the same in the two cases. The slightly positive intercept observed reflects the fact that weakly complexed species behave differently in homogeneous and heterogeneous systems. For instance, a species such as Yb^{3+}–xylitol has an equilibrium constant in the homogeneous phase assumed to be equal to zero whereas, upon heterogeneous distribution (see R_f values of Table 1), xylitol is slightly retained on the stationary phase in the Yb^{3+} form.

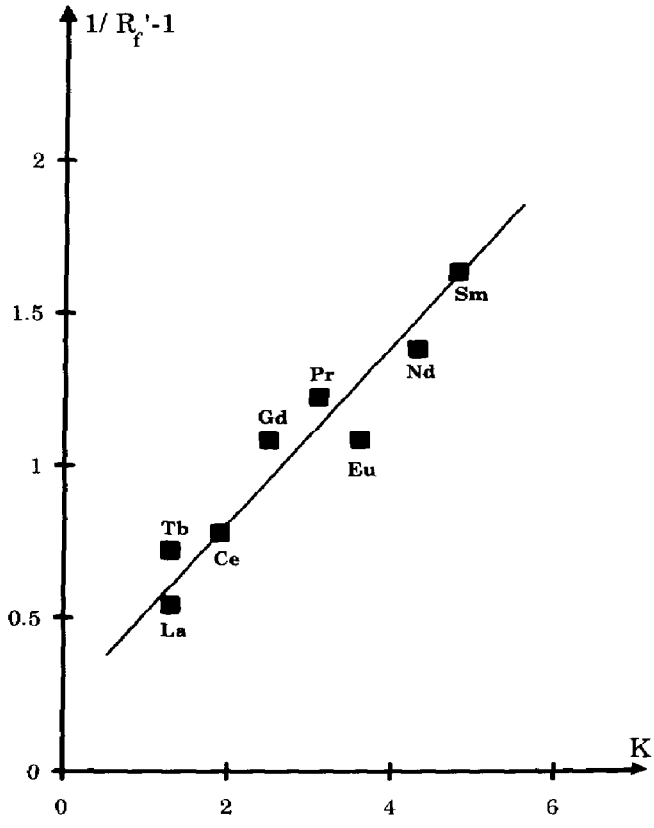

Fig. 3. Correlation between the capacity factors of ribose and the stability constants determined by calorimetry [2].

The good linear relationship between k and K reflects the fact that both constants show similar trends across the lanthanide cation series. This seems to indicate that the variations of both constants are governed by the same factors. Among these are the importance of the desolvation of the cation, and the fact that an inner-sphere hydration number change occurs within the rare-earth metal ion series [17,18]. This change in coordination number is considered to be the main factor explaining the irregularity in the stability constants, at or very near Sm^{3+}, observed with nearly every ligand studied [11]. This phenomenon appears to be also of prime importance for the cations fixed on the sorbing stationary phase.

Figs. 4 and 5 show the efficiency of columns in Ca^{2+}, La^{3+}, and Sm^{3+} forms for the separation of alditols and sugars, respectively. Our results clearly indicate that the industrially interesting separation of mannitol and glucitol would significantly be improved on a column in Sm^{3+} (relative to Ca^{2+}) form whereas the separation of glucose and fructose (which has the same R_f as arabinose on the three studied plates) is better on a column in the Ca^{2+} form. Angyal and Craig [10] recommended less expensive neodymium rather than samarium for chromatographic columns. Whatever the form of the plate, the sugars are split into two groups, one (group A) involving the strongly retained talose, ribose, and erythrose, and one (group B) gathering the other studied compounds. The use of lanthanide cations improves the separation of both groups but does not improve the separation within group B. The situation is slightly different with the alditols. All of them are more or less

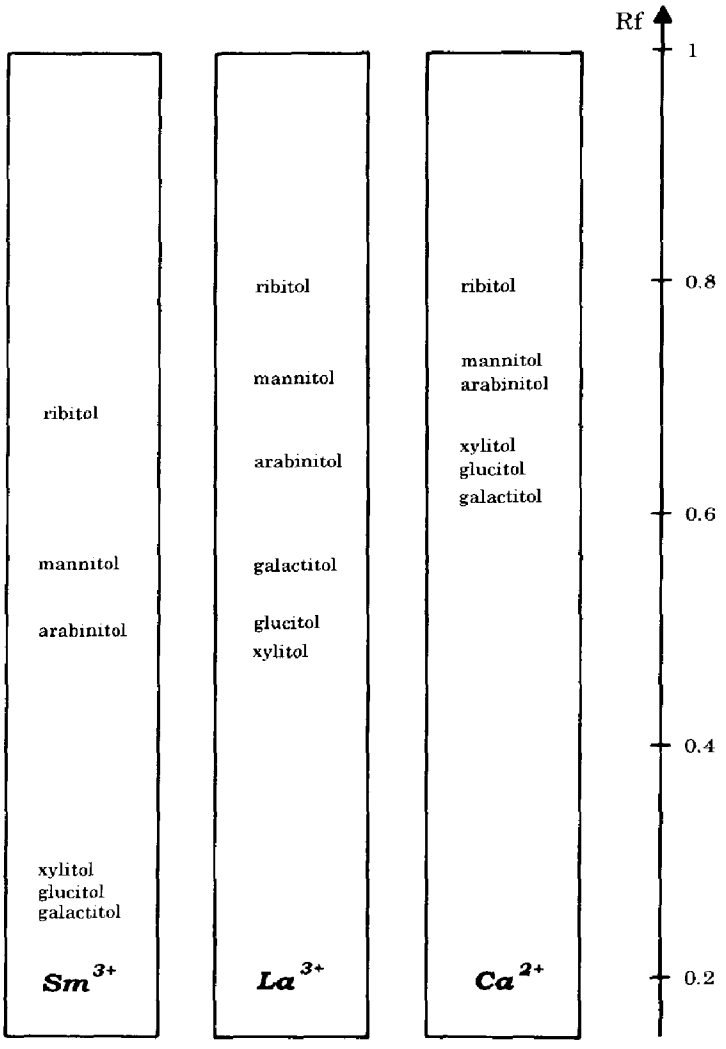

Fig. 4. Efficiency of columns in the Ca^{2+}, La^{3+}, and Sm^{3+} forms for the separation of alditols.

grouped together on a Ca^{2+} plate and, on the whole, their separation is improved by the use of lanthanide cations. However, Sm^{3+} and La^{3+} are more or less efficient depending on the alditols to be separated.

Whatever the cation used, xylitol and glucitol remain together. In Fig. 4, xylitol appears above glucitol with Ca^{2+} and Sm^{3+} and under glucitol with La^{3+} but this cannot be considered as significant since the R_f values differ by only ± 0.01 (Table 1). Angyal and Mills [19] observed more important differences with Ca^{2+} (0.04) and La^{3+} (0.06) plates.

Galactitol appears to form a particularly strong complex with Sm^{3+}. Fig. 4 shows that its R_f value decreases tremendously when going from La^{3+} to Sm^{3+}. Angyal and Craig [10] suggested that galactitol forms a 1:2 complex with the lanthanide cations, the primary hydroxyl groups being involved in complex formation. Furthermore, they have isolated a crystal of a 1:2 complex of galactitol with Pr^{3+}. They observed that the complexing ability of galactitol increased more in the Nd–Eu region than that of the other hexitols and this is

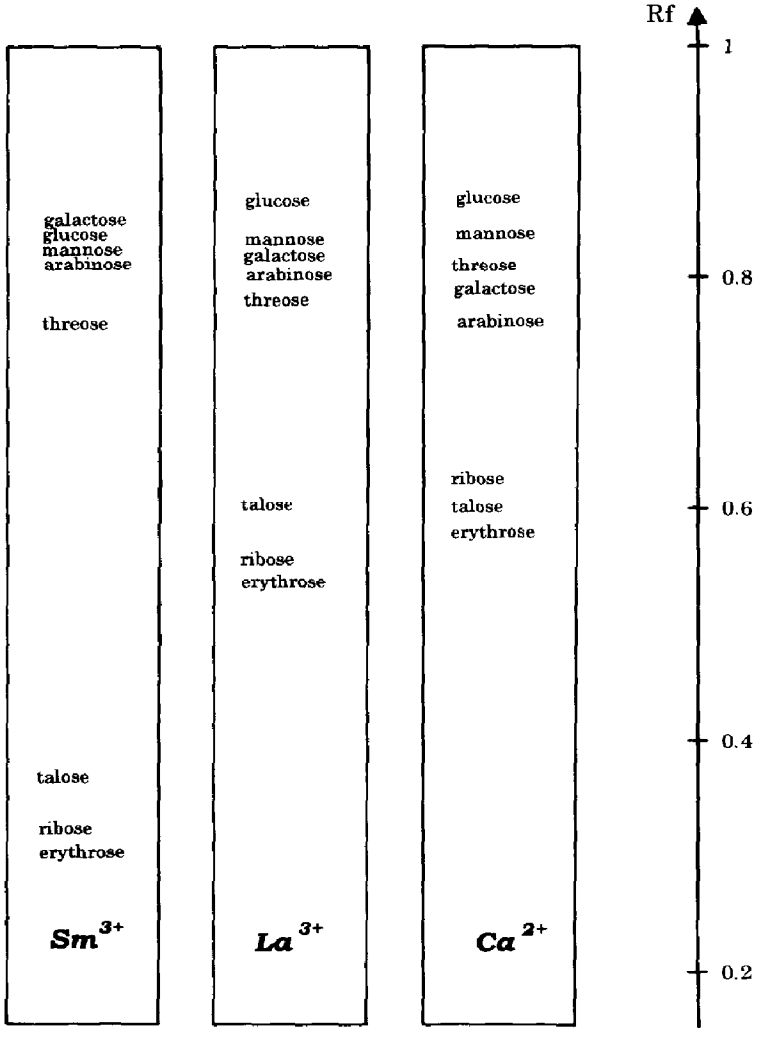

Fig. 5. Efficiency of columns in the Ca^{2+}, La^{3+}, and Sm^{3+} forms for the separation of sugars.

confirmed by the present results. On the other hand, our calorimetric studies [3] have shown that no 1:2 complex was formed between galactitol and Sm^{3+} in aqueous solutions containing up to 0.25 M samarium chloride. The chromatographic results seem to indicate that at least part of the galactitol is retained on the stationary phase by both chain ends. Fig. 4 shows also that galactitol is not separated from glucitol on the Sm^{3+} plate, in agreement with Angyal and Craig's observation with Nd^{3+} [10], whereas Caruel et al. [9] separated them by HPLC at 50°C on Pr^{3+} ion-exchange resin. It appears from Fig. 4 that this particular separation is much better on the La^{3+} plate, in agreement with the HPLC studies [9].

3. Experimental

General reagents.—The alditols and sugars were commercial products from Fluka (arabinitol, galactitol [dulcitol], mannitol, ribitol, xylitol, arabinose, fructose, galactose, glu-

cose, mannose, and xylose), Sigma (altrose, erythrose, and threose), Merck (glucitol [sorbitol]), and Senn Chemicals (talose). Their purity was ca. 99–99.5% except for altrose (mixture of anomers), erythrose (> 50%), and threose (> 70%). The hydrated lanthanide chlorides and nitrates (99.9%) were purchased from Strem Chemicals. HCl was from Merck (1 M Titrisol).

Methods.—Complexing of the polyhydroxy compounds with the lanthanide cations and with Ca^{2+} was observed by thin-layer chromatography (TLC). Resin-coated chromatosheets in the sodium form (Macherey-Nagel Polygram Ionex-25 SA Na sheets) were converted into the various lanthanide cation forms as follows [19–21]. The sheets were immersed in triply-distilled water until the thin layers were completely wet. Each sheet was dipped for 1 h into a 0.1 M aqueous solution of a given lanthanide chloride. In 1 M HCl, 4–5 h were required. The sheets were washed several times with triply-distilled water and then dried in air at room temperature for ca. 24 h. The polyhydroxy compounds were spotted individually (1 μL of a 0.1 M aqueous solution) and the chromatograms developed for 1–1.75 h with triply-distilled water as the eluent. The products were detected by using a saturated solution of potassium permanganate in acetone.

Chlorides were used for the whole series of lanthanide cations. No anionic effect was noticed when $Ce(NO_3)_3$, $Pr(NO_3)_3$, $Nd(NO_3)_3$, and $Sm(NO_3)_3$ were used, contrary to what was indicated by Angyal and Craig [10]. The R_f values measured for ribose, arabinose, xylitol, and ribitol on plates treated either with a nitrate or a chloride solution were identical, within experimental uncertainty, as shown in Table 1.

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