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A ^{13}C NMR study on the interactions of calcium chloride/potassium chloride with pyranosides in D_2O

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ABSTRACT

The ^{13}C NMR spectra of methyl β-D-glucopyranoside, methyl β-D-galactopyranoside, methyl β-D-xylopyranoside, and methyl β-L-arabinopyranoside were recorded in $CaCl_2$/KCl + D_2O mixtures and in D_2O. The chemical shifts of C-1, C-3, and C-5 in the methyl β-D-glucopyranoside and methyl β-D-galactopyranoside decrease rapidly as molalities of $CaCl_2$/KCl increase, while those of C-1, C-2, and C-3 in the methyl β-D-xylopyranoside and methyl β-L-arabinopyranoside decrease rapidly as molalities of $CaCl_2$/KCl increase. Cations (Ca^{2+}/K^+) can weakly complex with O in OMe of the pyranosides studied. Results are discussed in terms of the stereochemistry of the pyranoside molecules and the structural properties of the ions.

1. Introduction

Aqueous saccharide solutions play an important role in nature. Electrolytes and saccharides coexist in biological fluids. Thus, studies on the weak interactions of electrolytes with saccharides are related to a number of biological processes such as the action of metal-containing pharmaceuticals, toxic-metal metabolism,[1,2] Ca^{2+}-mediated carbohydrate–protein binding,[3,4] and specificity of many cell–cell and carbohydrate–carbohydrate recognitions.[5–7]

The interactions of electrolytes with saccharides have been researched using various methods. As early as the 1970s, Angyal et al.[8] studied complexations of Ca^{2+} with some mono- and di-saccharides and their derivatives using paper electrophoresis and ^1H NMR spectroscopy. The association of Ca^{2+} with saccharides at different pH values was investigated by ^1H NMR spectroscopy,[9,10] together with site-specificities in the interactions of Cu^{2+} with aldopentopyranoses in DMSO.[11] The complexations of aluminum(III) with glucose-6-phosphate in aqueous solutions were studied by multinuclear (^{31}P, ^{27}Al, ^{13}C) NMR spectroscopy.[12] Recently, Hernández-Luis et al.[13,14] and Jiang et al.[15,16] reported thermodynamic properties for some electrolyte + saccharide + water systems. In our previous work,[17–20] thermodynamic and transport properties of some saccharides in electrolytic solutions were investigated.

Saccharides exist as an equilibrium mixture of their various isomers in aqueous solution. In this paper, the ^{13}C NMR chemical shifts of four pyranosides (methyl β-D-glucopyranoside, methyl β-D-galactopyranoside, methyl β-D-xylopyranoside, and methyl β-L-arabinopyranoside, each of which has essentially only anomer in aqueous solution) are recorded in D_2O and in $CaCl_2$/KCl + D_2O mixtures. The roles of both cations and anions in the weak interactions with the four glycosides are studied.

2. Results and discussion

Figure 1 shows the structures of the four pyranosides. The ^{13}C NMR chemical shifts for the four glycosides in D_2O and in $CaCl_2$/KCl + D_2O mixtures are listed in Tables 1–4. The ^{13}C NMR chemical shift differences $\Delta\delta$ were calculated from the relation: $\Delta\delta = \delta_{obs} - \delta_0$, where δ_{obs} and δ_0 are the measured chemical shifts of the pyranosides in $CaCl_2$/KCl + D_2O mixtures and in D_2O, respectively. Variations in the $\Delta\delta$ of C with molalities of $CaCl_2$/KCl at 298.15 K are shown in Figures 2 and 3.

2.1. Interactions of Cl^- with pyranosides

First of all, in order to affim that the variations observed in presence of $CaCl_2$/KCl result from the interactions between the electrolytes and sugars, the dependence of chemical shifts of carbon atoms was investigated on sugar's concentrations. As an example, the ^{13}C NMR chemical shifts of methyl β-D-glucopyranoside in D_2O at different concentrations are given in Table 5. It was shown that the maximum variation is only 0.03 ppm in the concentration range. Thus the concentration effects can be neglected. Symons et al.[9,10] pointed out that ClO_4^- causes a rapid shielding of the Hs of the OHs in saccharide molecules, and Cl^- causes a relatively light

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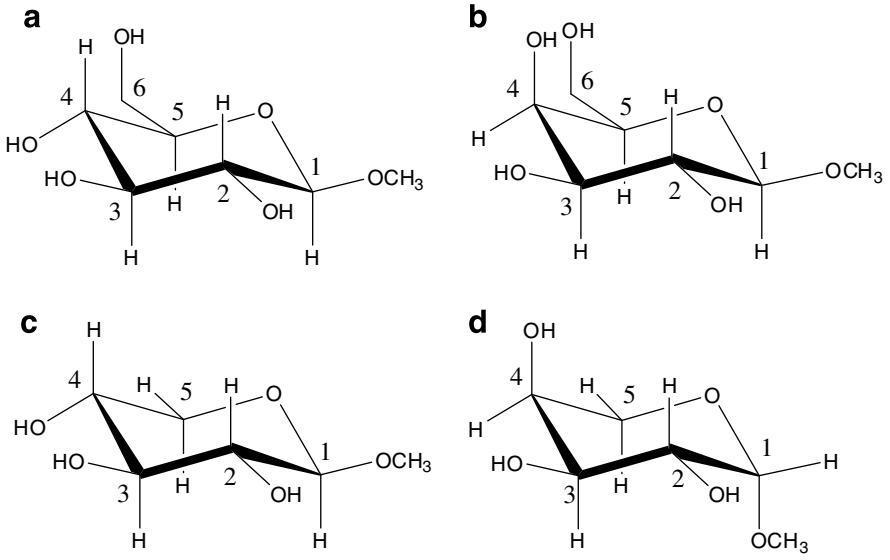

Figure 1. The structures of (a) methyl β-D-glucopyranoside, (b) methyl β-D-galactopyranoside, (c) methyl β-D-xylopyranoside, and (d) methyl β-L-arabinopyranoside.

Table 1
The ^{13}C NMR chemical shifts of methyl β-D-glucopyranoside and methyl β-D-galactopyranoside in D_2O and in D_2O–$CaCl_2$ mixtures at 298.15 K

m_{CaCl_2} (mol kg)	δ (ppm)						
	C-1	C-2	C-3	C-4	C-5	C-6	OMe
Methyl β-D-glucopyranoside							
0	105.90	75.77	78.42	72.30	78.57	63.41	59.87
0.30	105.81	75.73	78.36	72.27	78.49	63.38	59.90
0.60	105.75	75.70	78.31	72.25	78.42	63.36	59.94
0.90	105.66	75.64	78.24	72.20	78.34	63.33	59.96
1.20	105.59	75.60	78.17	72.15	78.27	63.30	60.00
Slope[a]	−0.2611 ± 0.0045	−0.1389 ± 0.0045	−0.2022 ± 0.0042	−0.1144 ± 0.0071	−0.2522 ± 0.0018	−0.0900 ± 0.0017	0.1067 ± 0.0027
Methyl β-D-galactopyranoside							
0	106.48	73.40	75.43	71.33	77.80	63.65	59.84
0.30	106.39	73.36	75.35	71.31	77.71	63.63	59.86
0.60	106.35	73.33	75.27	71.30	77.62	63.63	59.90
0.90	106.23	73.30	75.22	71.29	77.54	63.62	59.95
1.20	106.15	73.27	75.16	71.29	77.46	63.61	59.99
Slope[a]	−0.2689 ± 0.0105	−0.1111 ± 0.0025	−0.2344 ± 0.0074	−0.0400 ± 0.0041	−0.2878 ± 0.0030	−0.0344 ± 0.0030	0.1189 ± 0.0064

[a] The slopes were obtained by linear fits of $\Delta(\delta C\text{-}i)$ to molality of $CaCl_2$ through zero.

Table 2
The ^{13}C NMR chemical shifts of methyl β-D-xylopyranoside and methyl β-L-arabinopyranoside in D_2O and in D_2O–$CaCl_2$ mixtures at 298.15 K

m_{CaCl_2} (mol kg)	δ (ppm)					
	C-1	C-2	C-3	C-4	C-5	OMe
Methyl β-D-xylopyranoside						
0	106.61	75.62	78.36	71.83	67.77	59.85
0.30	106.53	75.56	78.30	71.80	67.71	59.88
0.60	106.45	75.52	78.23	71.77	67.67	59.90
0.90	106.36	75.46	78.17	71.73	67.62	59.93
1.20	106.28	75.40	78.08	71.69	67.57	59.96
Slope[a]	−0.2744 ± 0.0018	−0.1800 ± 0.0033	−0.2233 ± 0.0055	−0.1122 ± 0.0030	−0.1678 ± 0.0030	0.0900 ± 0.0017
Methyl β-L-arabinopyranoside						
0	102.52	71.42	71.54	70.75	65.15	57.84
0.30	102.42	71.37	71.51	70.72	65.12	57.87
0.60	102.33	71.33	71.48	70.69	65.10	57.89
0.90	102.25	71.30	71.45	70.67	65.09	57.91
Slope[a]	−0.3071 ± 0.0060	−0.1405 ± 0.0060	−0.1000	−0.0929 ± 0.0031	−0.0738 ± 0.0060	0.0810 ± 0.0034

[a] The slopes were obtained by linear fits of $\Delta(\delta C\text{-}i)$ to molality of $CaCl_2$ through zero.

shielding, while Ca^{2+} causes a deshielding. On the basis of the principles of NMR spectroscopy, it can be expected that cations/anions can make a similar influence on the chemical shift of C linked to OH in saccharide molecules. It is well known that cations (especially for Ca^{2+}, La^{3+}) can complex with monosaccharide molecules that have a ax–eq–ax configuration. In this case, the interactions

Table 3
The ^{13}C NMR chemical shifts of methyl β-D-glucopyranoside and methyl β-D-galactopyranoside in D_2O and in D_2O–KCl mixtures at 298.15 K

m_{KCl} (mol kg)	δ (ppm)						
	C-1	C-2	C-3	C-4	C-5	C-6	OMe
Methyl β-D-glucopyranoside							
0.15	105.87	75.76	78.40	72.29	78.55	63.39	59.88
0.30	105.85	75.75	78.39	72.28	78.53	63.37	59.88
0.60	105.82	75.72	78.36	72.26	78.49	63.35	59.88
0.90	105.79	75.70	78.34	72.24	78.46	63.32	59.89
1.20	105.77	75.69	78.31	72.23	78.44	63.30	59.90
Slope[a]	−0.1185 ± 0.0066	−0.0722 ± 0.0029	−0.0926 ± 0.0023	−0.0623 ± 0.0019	−0.1168 ± 0.0043	−0.0970 ± 0.0038	0.0237 ± 0.0023
Methyl β-D-galactopyranoside							
0.15	106.46	73.36	75.40	71.31	77.77	63.64	59.84
0.30	106.44	73.36	75.37	71.30	77.75	63.63	59.85
0.60	106.42	73.36	75.35	71.30	77.73	63.62	59.86
0.90	106.39	73.36	75.32	71.30	77.71	63.62	59.88
1.20	106.37	73.34	75.29	71.29	77.68	63.60	59.88
Slope[a]	−0.0970 ± 0.0038	−0.0551 ± 0.0113	−0.1240 ± 0.0075	−0.0386 ± 0.0069	−0.1052 ± 0.0069	−0.0413 ± 0.0033	0.0369 ± 0.0026

[a] The slopes were obtained by linear fits of $\Delta(\delta C\text{-}i)$ to molality of KCl through zero.

Table 4
The ^{13}C NMR chemical shifts of methyl β-D-xylopyranoside and methyl β-L-arabinopyranoside in D_2O and in D_2O–KCl mixtures at 298.15 K

m_{KCl} (mol kg)	δ (ppm)					
	C-1	C-2	C-3	C-4	C-5	OMe
Methyl β-D-xylopyranoside						
0.30	106.58	75.60	78.32	71.82	67.75	59.85
0.60	106.55	75.58	78.30	71.81	67.74	59.86
0.90	106.51	75.55	78.27	71.81	67.72	59.86
1.20	106.48	75.54	78.25	71.79	67.71	59.87
Slope[a]	−0.1078 ± 0.0018	−0.0700 ± 0.0026	−0.0967 ± 0.0040	−0.0300 ± 0.0026	−0.0522 ± 0.0018	0.0144 ± 0.0018
Methyl β-L-arabinopyranoside						
0.30	102.48	71.39	71.52	70.73	65.14	57.84
0.60	102.45	71.36	71.50	70.71	65.13	57.84
0.90	102.42	71.34	71.48	70.70	65.13	57.85
Slope[a]	−0.1143 ± 0.0034	−0.0929 ± 0.0031	−0.0667 ± 0.0001	−0.0595 ± 0.0031	−0.0262 ± 0.0031	0.0071 ± 0.0031

[a] The slopes were obtained by linear fits of $\Delta(\delta C\text{-}i)$ to molality of KCl through zero.

between the anions and saccharides can be disregarded. However, the four pyranosides studied do not have that configuration, and the interactions of the four pyranosides with $CaCl_2$/KCl are weak. Consequently, both cation and anion effects should be considered.

As seen from Figures 2 and 3, all the $\Delta\delta$ values of C for methyl β-D-glucopyranoside and methyl β-D-galactopyranoside decrease with increasing molalities of $CaCl_2$/KCl except for C in OMe, and those of C-1, C-5, and C-3 decrease rapidly. Similar trends were also observed in our previous work.[20] This can be interpreted using the saccharide–salt interaction model suggested by Ortiz et al.[21] Each of the methyl β-D-glucopyranoside and methyl β-D-galactopyranoside molecules presents an outer positive ring formed by H atoms of OH groups (C-2, C-3, C-4, and C-6), and presents an inner negative ring formed by O atoms of OMe (C-1) and OH groups (C-2, C-3, C-4, and C-6) around the five C atoms. The CH protons have little charge. In the two glycosides, both C-1 and C-5 are linked to the –O– bridge, their electrons are induced by the ring oxygen, and the zones around them are the most positive. This can also be observed from the chemical shifts of C-1 and C-5, which are the largest (δ_{C-1} = 105.90 ppm, and δ_{C-5} = 78.57 ppm for methyl β-D-glucopyranoside; δ_{C-1} = 106.48 ppm, δ_{C-5} = 77.80 ppm for methyl β-D-galactopyranoside) in all the C atoms. The C-1, C-3, and C-5 atoms are on the same plane, and charge-density of C-3 is similar to C-1 and C-5. In addition, the chemical shift of C-3 is larger than that of C-2, C-4, C-6, and the C of OMe. Therefore, these zones are prone to interacting with Cl^-, causing a shielding of C-1, C-5, and C-3.

Figure 2 shows that the $\Delta\delta$ values of C for methyl β-D-galactopyranoside decrease with increasing molality of $CaCl_2$ except for the $\Delta\delta$ value of C in the OMe group. The Δ (δ_{C-4}) values for methyl β-D-galactopyranoside increase most rapidly with increasing molality of $Ca(NO_3)_2$, and the $\Delta\delta$ values of the C-2, C-3, and C-6 atoms vary slightly, together with the $\Delta\delta$ values of C in the OMe group.[20] These confirm that Cl^-–O interactions are stronger than NO_3^-–O interactions for the two pyranosides. This can be interpreted by structural properties of Cl^- and NO_3^-. The volume of NO_3^- is larger than Cl^-. Moreover, the four-center, six-electron π-bonding of NO_3^- makes the negative charges around it more dispersive than Cl^-. Thus, steric hindrance and a low charge-density affect the repulsions between NO_3^- and the O of the OH groups and the attractions between NO_3^- and H.

The Gibbs energy interaction parameters (g_{ES}) for the pair of complexes, $Ca(NO_3)_2$–galactose (-174.8 J kg mol^{-2}), and $CaCl_2$–galactose (32.5 J kg mol^{-2}) in water, have been determined in our previous work.[18,22] The g_{ES} values are mainly controlled by electrostatic interactions. The anion–O interactions are mainly electrostatic (repulsive) and contribute positive values to g_{ES}, whereas the interactions of cation with O are mainly electrostatic (attractive) and contribute negative values to g_{ES}. It was concluded from the g_{ES} values that the Ca^{2+}–O interactions are stronger for $Ca(NO_3)_2$–galactose, while Cl^-–O interactions are stronger for $CaCl_2$–galactose. Methyl β-D-galactopyranoside can be considered as a derivative of β-D-galactose (dominant conformation of galactose) via replacing the H of OH-1 by a methyl group. This conclusion can be confirmed further by NMR spectra in this work.

Figures 2 and 3 also show that all the $\Delta\delta$ values of C for methyl β-D-xylopyranoside and methyl β-L-arabinopyranoside decrease

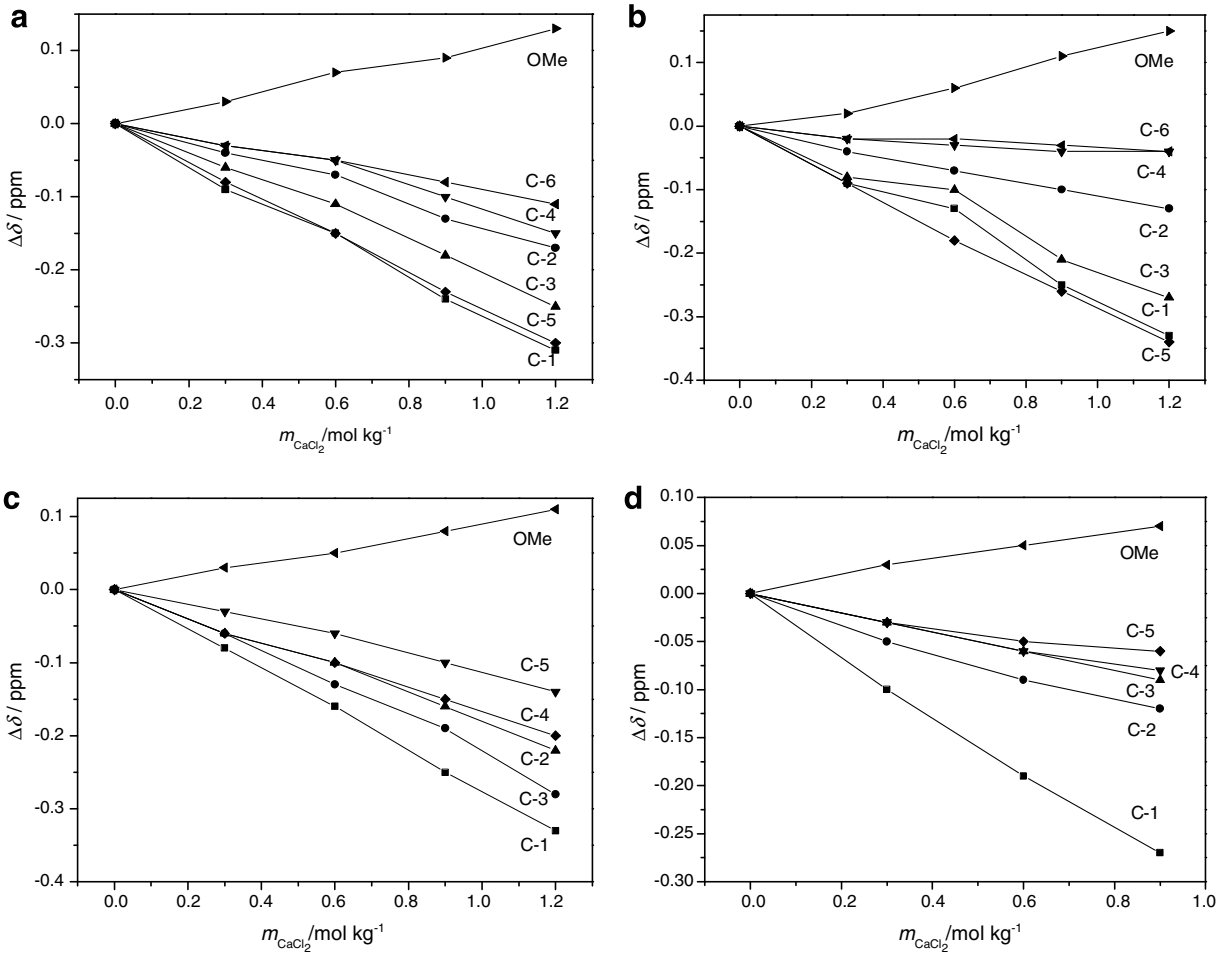

Figure 2. Variation in the $\Delta\delta$ of C atoms for (a) methyl β-D-glucopyranoside, (b) methyl β-D-galactopyranoside, (c) methyl β-D-xylopyranoside, and (d) methyl β-L-arabinopyranoside with molality of $CaCl_2$ at 298.15 K.

with increasing molalities of $CaCl_2$/KCl except for C in OMe; those of C-1, C-2, and C-3 vary more rapidly. This demonstrates that the interactions of Cl^- with these zones are stronger, leading to shielding of C-1, C-2, and C-3. There are no CH_2OH groups linked to C-5 of methyl β-D-xylopyranoside and methyl β-L-arabinopyranoside in comparison with methyl β-D-glucopyranoside and methyl β-D-galactopyranoside. Thus, each of the two pyranosides cannot present an inner negative ring; however, each presents only an inner negative zone around C-1 to C-4. Similarly, each of them presents an outer positive zone around C-1 to C-4. This is a main reason why the sites of methyl β-D-xylopyranoside and methyl β-L-arabinopyranoside interacting with Cl^- (C-1, C-2, and C-3) are not the same as those of methyl β-D-glucopyranoside and methyl β-D-galactopyranoside (C-1, C-3, and C-5).

2.2. Interactions of Ca^{2+}/K^+ with pyranosides

Since methyl is an electron-donating group, the zone around O of OMe group is more negative, and consequently the O atom is prone to interacting with a cation. The $\Delta\delta$ values of C in the OMe groups for the four pyranosides increase more rapidly with increasing molality of $CaCl_2$ than those of KCl. This means that the interaction of Ca^{2+} with O is stronger than that of K^+.[23] The Ca^{2+} attraction to O of the OMe group leads to a larger deshielding of the C of the OMe group than is observed with K^+. The shielding of C-1 from the interactions of Cl^- with the zones around C-1 is larger than the deshielding from the interactions of Ca^{2+}/K^+ with O of OMe, so the $\Delta\delta$ values of C-1 for the pyranosides decrease with increasing molalities of $CaCl_2$/KCl.

3. Experimental

Methyl β-D-glucopyranoside, methyl β-D-galactopyranoside, methyl β-D-xylopyranoside (>99.0%, Sigma), and methyl β-L-arabinopyranoside (>97.0%, Sigma) were dried under vacuum at room temperature to constant weight. Calcium chloride (AR, >96.0%, Beijing Chem. Co.) was recrystallized from a water–ethanol mixture, and then was dried under vacuum at 413 K to constant weight. Potassium chloride (reference reagent, Tianjing Kermel Chem. Co.), deuterated water (99.9% deuteration, Cambridge Isotope Laboratories), and sodium 4,4-dimethyl-4-silapentanesulfonate (DSS, Beijing Chem. Co.) were used without further purification.

The ^{13}C NMR spectra were recorded using a Bruker AV-400 MHz NMR spectrometer equipped with a 5-mm tube at (298.15 ± 0.1) K at 100.62 MHz. DSS was used as the external reference. D_2O was used for the deuterium lock. The concentrations of the four pyranosides in all solutions are 0.6 mol kg^{-1} (defined as the number of moles of solutes per kilogram of pure water).

4. Conclusions

^{13}C NMR data show that the zones around C-1, C-3, and C-5 of methyl β-D-glucopyranoside and methyl β-D-galactopyranoside are prone to interacting with Cl^-. However, the interactions of

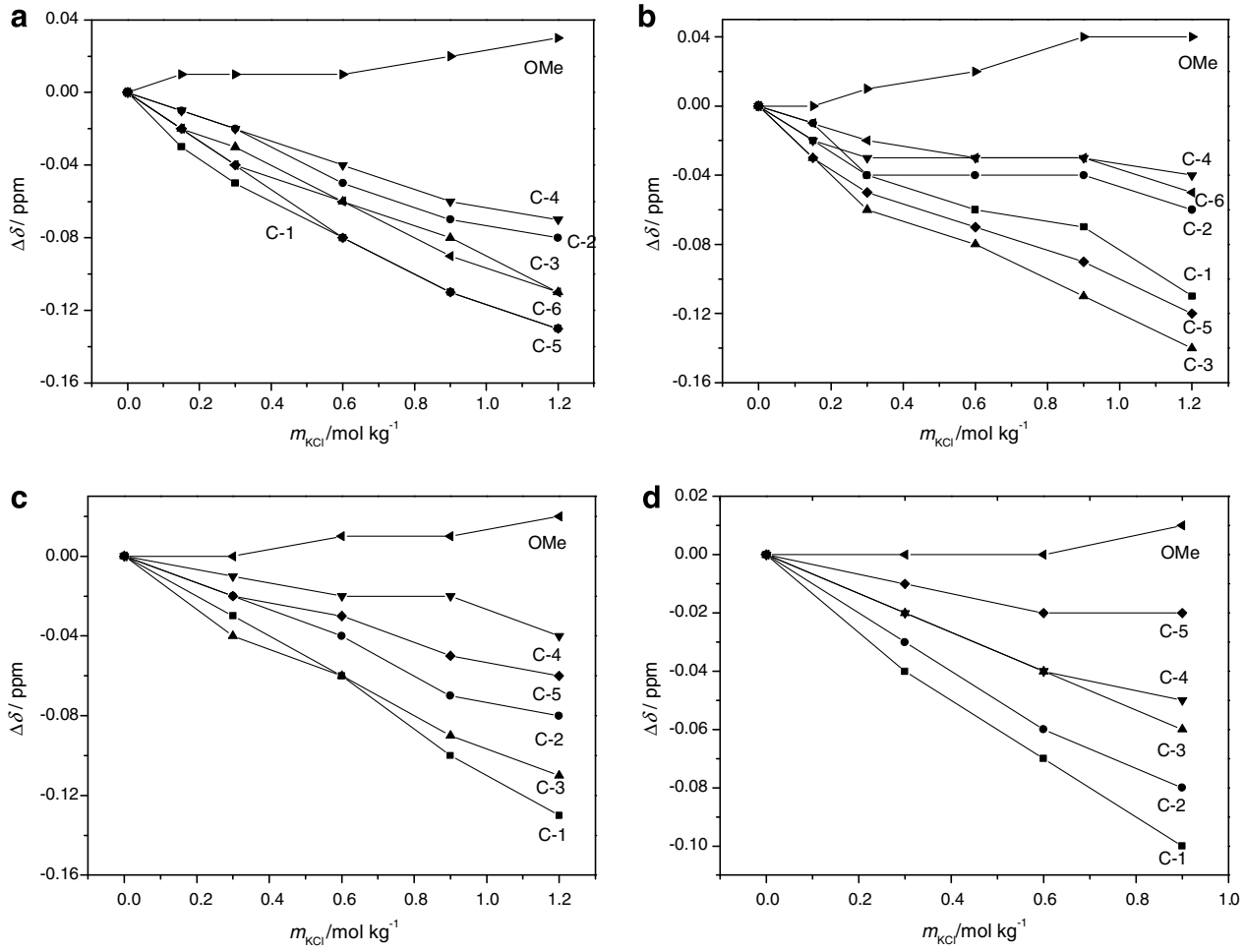

Figure 3. Variation in the $\Delta\delta$ of C atoms for (a) methyl β-D-glucopyranoside, (b) methyl β-D-galactopyranoside, (c) methyl β-D-xylopyranoside, and (d) methyl β-L-arabinopyranoside with molality of KCl at 298.15 K.

Table 5
The ^{13}C NMR chemical shifts of methyl β-D-glucopyranoside in D_2O at different molalities (m)

m (mol kg)	δ (ppm)						
	C-1	C-2	C-3	C-4	C-5	C-6	OMe
0.35	105.87	75.74	78.41	72.30	78.55	63.40	59.84
0.40	105.87	75.74	78.41	72.30	78.55	63.40	59.84
0.50	105.88	75.75	78.42	72.30	78.57	63.41	59.85
0.60	105.90	75.77	78.42	72.30	78.57	63.41	59.87

Cl^- with methyl β-D-xylopyranoside and methyl β-L-arabinopyranoside lead to an enhancing shield effect for C-1, C-2, and C-3 of the two pyranosides. The interactions of Ca^{2+}/K^+ with O in OMe are stronger than those of O in OH groups of the four pyranosides, and the interactions of Ca^{2+} with O are stronger than those of K^+.

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References

1. *Carbohydrates in Chemistry and Biology*; Ernst, B., Hart, G. W., Sinaÿ, P., Eds.; Wiley: Weinheim, 2000; Vols. 1–4,.
2. Lindhorst, T. K. *Essentials of Carbohydrate Chemistry and Biochemistry*; Wiley: Weinheim, 2000.
3. Sauchelli, V. *Trace Elements in Agriculture*; VanNostrand: New York, 1969.
4. Holm, R. P.; Berg, J. M. *Pure Appl. Chem.* **1984**, *56*, 1645–1657.
5. Predki, P. F.; Whitfield, D. M.; Sarkar, B. *Biochem. J.* **1992**, *281*, 835–841.
6. Weis, W. I.; Drickamer, K.; Hendrickson, W. A. *Nature* **1992**, *360*, 127–134.
7. Gege, C.; Geyer, A.; Schmidt, R. R. *Eur. J. Org. Chem.* **2002**, 2475–2485.
8. Angyal, S. J.; Mills, J. A. *Aust. J. Chem.* **1979**, *32*, 1993–2001.
9. Symons, M. C.; Benbow, J. A.; Pelmore, H. *J. Chem. Soc., Faraday Trans. I* **1982**, *78*, 3671–3677.
10. Symons, M. C.; Benbow, J. A.; Pelmore, H. *J. Chem. Soc., Faraday Trans. I* **1984**, *89*, 1999–2016.
11. Araki, K.; Tajima, H. *J. Inorg. Biochem.* **1993**, *52*, 89–98.
12. Champmartin, D.; Rubini, P.; Lakatos, A.; Kiss, T. *J. Inorg. Biochem.* **2001**, *84*, 13–21.
13. Hernández-Luis, F.; Amado-González, E.; Esteso, M. A. *Carbohydr. Res.* **2003**, *338*, 1415–1424.
14. Hernández-Luis, F.; Galleguillos, H. R.; Vázquez, M. V. *J. Chem. Thermodyn.* **2004**, *36*, 957–964.
15. Jiang, Y. C.; Gao, S. Y.; Xia, S. P.; Wang, J. J.; Zhuo, K. L.; Hu, M. C. *J. Chem. Thermodyn.* **2002**, *34*, 1959–1973.
16. Jiang, Y. C.; Gao, S. Y.; Xia, S. P.; Hu, M. C.; Wang, J. J.; Zhuo, K. L. *J. Chem. Thermodyn.* **2003**, *35*, 493–501.
17. Zhuo, K. L.; Wang, J. J.; Wang, H. Q. *Carbohydr. Res.* **2000**, *325*, 46–55.
18. Zhuo, K. L.; Liu, G. J.; Wang, Y. P.; Ren, Q. H.; Wang, J. J. *Fluid Phase Equilib.* **2007**, *258*, 78–82.
19. Zhuo, K. L.; Liu, H. X.; Zhang, H. H.; Liu, Y. H.; Wang, J. J. *J. Chem. Eng. Data* **2008**, *53*, 57–62.
20. Zhuo, K. L.; Wang, Y. P.; Zhao, Y.; Liu, Q.; Wang, J. J. *Spectrochim. Acta A*, in press.
21. Ortiz, P.; Fernandez-Bertran, J.; Reguera, E. *Spectrochim. Acta A* **2005**, *61*, 1977–1983.
22. Zhuo, K. L. Ph.D. Thesis, Lanzhou Institute of Chemical Physics, The Chinese Academy of Sciences, 2000, pp 40–62.
23. Angyal, S. J. *Adv. Carbohydr. Chem. Biochem.* **1989**, *47*, 1–43.