J. Chem. Eng. Data **2006,** *51,* 919−927

Volumetric and Viscosity Properties of Monosaccharides in Aqueous Amino Acid Solutions at 298.15 K

Kelei Zhuo,* Qian Liu, Yaping Wang, Qiuhe Ren, and Jianji Wang

School of Chemistry and Environmental Science, Henan Normal University, Xinxiang,
Henan 453007, People's Republic of China

Apparent molar volumes $V_{\Phi,S}$ and viscosity *B*-coefficients for D-(+)-glucose, D-(+)-galactose, D-(+)-xylose, and D-(−)-ribose in aqueous amino acid (glycine or L-alanine) solutions have been determined respectively from density and viscosity measurements at 298.15 K. Infinite-dilution apparent molar volumes for the saccharides $V^0_{\Phi,S}$ in aqueous glycine or L-alanine solutions have been evaluated, together with the standard transfer volumes $\Delta_t V^0_{\Phi,S}$ of the saccharides from water to aqueous amino acid solutions. It is shown that values of transfer volumes and viscosity *B*-coefficients are positive and increase with increasing amino acid contents. Volumetric parameters indicating the interactions of saccharides with amino acids in water have been obtained from the transfer volumes of the saccharides. The interactions between saccharides and amino acids are discussed in terms of the structural interaction model and the stereo structure of monosaccharide molecules.

Introduction

The properties of carbohydrate solutions are of considerable interest in various aspects of basic researches and applications. Saccharides and their derivatives are important chemicals in life process. Many functional features of saccharides in biology are now becoming obvious but are far from being fully understood. Therefore, the increasing interest in biophysical and biochemical research is presently being directed toward the novel subdiscipline termed "glycobiology".[1] Many technological applications of carbohydrates utilize the exotic rheological properties of their aqueous solutions,[2] including the control of gelling processes[3] and the osmoregulation of tissues and organs in cryoprotective provisions.[4,5]

In living organisms, interactions of carbohydrates with proteins play a key role in a wide range of biochemical process. In particular, carbohydrates located at cell surface are receptors with regard to the bioactive structures of hormones, enzymes, viruses, antibodies, etc.[5] Therefore, the studies of carbohydrate−protein interactions are very important for immunology, biosynthesis, pharmacology, and medicine. Analysis of literature data shows that general information about the interaction between carbohydrates and proteins could be obtained from X-ray crystallography,[6−9] NMR spectra,[10] computer calculations,[11−13] and chromatography data.[14,15] There are also investigations devoted to the kinetics of these interactions.[16,17] However, thermodynamic studies of the interactions between carbohydrates and proteins in solutions are rare, especially the viscosity property. Due to complex conformation and configuration of proteins in various solvents, a direct study on proteins is very difficult. As amino acids are model compounds of proteins, it is necessary to study the thermodynamic properties for carbohydrate + amino acids + water systems.

Recently, an attention has been paid, in particular, to the rich conformational variety of carbohydrates.[18,19] As part of glycoproteins, glycolipids, and other biomolecules, carbohydrates, due to their conformational flexibility, offer an additional "alphabet" in many biological processes, such as signaling, cell−cell recognition, and molecular and cellular communication.[20]

In our previous work,[21−27] thermodynamic studies of some ternary electrolyte + saccharide + water systems have been carried out using galvanic cells and densimeter. In this paper, we will explore the interactions between monosaccharides (S) and amino acids (A) in water. Densities ρ and viscosities η of aqueous monosaccharide [D-(+)-glucose, D-(+)-galactose, D-(+)-xylose, and D-(−)-ribose] solutions will be reported with and without amino acids (glycine and L-alanine) at 298.15 K. From these data, the standard partial molar volumes $V^0_{\Phi,S}$ and viscosity *B*-coefficients for the monosaccharides will also be calculated. Results will be discussed in terms of the cosphere overlap model and the stereochemistry of saccharide molecules. It is expected that these should provide additional information on the effect of saccharides on the stability of globular proteins.

Experimental Section

Chemicals. High-purity D-(+)-glucose, D-(+)-galactose, D-(+)-xylose, D-(−)-ribose, and glycine were all obtained from Sigma Chemical Company, but L-alanine was from Fluka. They were used without further purification, dried under vacuum to constant weight, and then stored over P_2O_5 in desiccators. The deionized water was doubly distilled over $KMnO_4$. The water sample with a conductivity of 1.2×10^{-6} s·cm^{-1} was used throughout the experiments.

Measurement of Densities and Viscosities. Solution densities were measured using a vibrating-tube digital densimeter (model DMA 60/602 Anton Paar Austria), which has been described elsewhere.[21−23] The temperature around the density meter cell was controlled by circulating water from a constant-temperature bath (Schott, Germany). A CT-1450 temperature controller and a CK-100 ultracryostat were employed to maintain the bath temperature at (298.15 ± 0.005) K. The density meter was calibrated with pure water (the value of density was taken to be 0.997047 g·cm^{-3} at 298.15 K from Kell's data[28]) and dry air. The uncertainty of molalities of monosaccharides and amino acids is evaluated to be less than ± 0.0001 mol·kg^{-1}. The uncertainty in density was estimated to be $\pm 3 \times 10^{-6}$ g·cm^{-3}. Solution viscosities were measured by a suspended level Ub-

---

* Corresponding author. E-mail: klzhuo@263.net.

10.1021/je050412t CCC: $33.50

Table 1. Solution Densities ρ and Apparent Molar Volumes $V_{\Phi,S}$ for Monosaccharides in Water and in Aqueous Glycine Solutions at 298.15 K[a]

$\frac{m_S}{\mathrm{mol\cdot kg^{-1}}}$	$\frac{\rho}{\mathrm{g\cdot cm^{-3}}}$	$\frac{V_{\Phi,S}}{\mathrm{cm^3\cdot mol^{-1}}}$	$\frac{m_S}{\mathrm{mol\cdot kg^{-1}}}$	$\frac{\rho}{\mathrm{g\cdot cm^{-3}}}$	$\frac{V_{\Phi,S}}{\mathrm{cm^3\cdot mol^{-1}}}$	$\frac{m_S}{\mathrm{mol\cdot kg^{-1}}}$	$\frac{\rho}{\mathrm{g\cdot cm^{-3}}}$	$\frac{V_{\Phi,S}}{\mathrm{cm^3\cdot mol^{-1}}}$
Glucose in Water								
0.2000	1.010418	111.94	0.6000	1.035322	112.22	1.0000	1.057986	112.51
0.4000	1.023160	112.09	0.8000	1.046917	112.37	1.2000	1.068590	112.64
Galactose in Water								
0.2000	1.010729	110.36	0.6000	1.036283	110.56	1.0000	1.059604	110.81
0.4000	1.023810	110.43	0.8000	1.048233	110.65	1.2000	1.070559	110.89
Xylose in Water								
0.2000	1.007782	95.55	0.6000	1.027997	95.71	1.0000	1.046668	95.89
0.4000	1.018090	95.64	0.8000	1.037513	95.80	1.2000	1.055493	95.96
Ribose in Water								
0.2000	1.007829	95.31	0.6000	1.028154	95.44	1.0000	1.046944	95.60
0.4000	1.018185	95.39	0.8000	1.037724	95.53	1.2000	1.055805	95.68
Glucose in Glycine Solutions								
m_{Gly}/mol·kg^{-1} = 0.1000			m_{Gly}/mol·kg^{-1} = 0.2000			m_{Gly}/mol·kg^{-1} = 0.3000		
0	1.000217		0	1.003340		0	1.006417	
0.2000	1.013415	112.18	0.2000	1.016378	112.37	0.2000	1.019309	112.50
0.4000	1.026006	112.30	0.4000	1.028814	112.49	0.4000	1.031615	112.60
0.6000	1.038016	112.43	0.6000	1.040704	112.58	0.6000	1.043372	112.69
0.7991	1.049449	112.54	0.8000	1.052057	112.69	0.8000	1.054610	112.80
1.0000	1.060457	112.67	1.0000	1.062914	112.80	1.0000	1.065365	112.89
1.2000	1.070976	112.76	1.2000	1.073307	112.90	1.2000	1.075655	112.99
m_{Gly}/mol·kg^{-1} = 0.1500			m_{Gly}/mol·kg^{-1} = 0.2500			m_{Gly}/mol·kg^{-1} = 0.3500		
0	1.001783		0	1.004883		0	1.007940	
0.1999	1.014890	112.30	0.2000	1.017846	112.44	0.2000	1.020754	112.59
0.4000	1.027409	112.41	0.4000	1.030217	112.55	0.4000	1.032986	112.69
0.6000	1.039349	112.53	0.6000	1.042034	112.65	0.6000	1.044669	112.79
0.8000	1.050761	112.64	0.7992	1.053294	112.74	0.7995	1.055813	112.89
0.9928	1.061292	112.74	1.0000	1.064124	112.86	0.9982	1.066430	112.99
1.2000	1.072115	112.86	1.1999	1.074458	112.96	1.2000	1.076763	113.08
Galactose in Glycine Solutions								
m_{Gly}/mol·kg^{-1} = 0.1000			m_{Gly}/mol·kg^{-1} = 0.2000			m_{Gly}/mol·kg^{-1} = 0.3000		
0.2000	1.013758	110.44	0.2000	1.016729	110.59	0.2000	1.019649	110.76
0.4000	1.026679	110.57	0.4000	1.029501	110.73	0.4000	1.032287	110.87
0.5996	1.038990	110.71	0.6000	1.041704	110.85	0.6000	1.044358	110.99
0.7945	1.050492	110.82	0.8000	1.053374	110.97	0.8000	1.055894	111.11
1.0000	1.062093	110.94	0.9988	1.064477	111.08	1.0000	1.066952	111.21
1.2000	1.072885	111.07	1.2000	1.075225	111.19	1.2000	1.077532	111.32
m_{Gly}/mol·kg^{-1} = 0.1500			m_{Gly}/mol·kg^{-1} = 0.2500			m_{Gly}/mol·kg^{-1} = 0.3500		
0.2000	1.015250	110.50	0.1965	1.017960	110.70	0.2000	1.021094	110.86
0.3999	1.028073	110.69	0.4000	1.030896	110.81	0.4000	1.033663	110.95
0.6000	1.040347	110.81	0.6000	1.043039	110.91	0.6000	1.045668	111.06
0.7999	1.052078	110.91	0.8000	1.054642	111.03	0.8000	1.057150	111.17
0.9998	1.063289	111.03	1.0000	1.065742	111.15	1.0000	1.068151	111.27
1.2000	1.074029	111.16	1.2000	1.076385	111.25	1.2000	1.078675	111.38
Xylose in Glycine Solutions								
m_{Gly}/mol·kg^{-1} = 0.1000			m_{Gly}/mol·kg^{-1} = 0.2000			m_{Gly}/mol·kg^{-1} = 0.3000		
0.2000	1.010817	95.71	0.2000	1.013822	95.79	0.2000	1.016774	95.91
0.4000	1.020998	95.79	0.4000	1.023892	95.86	0.4000	1.026729	95.97
0.6000	1.030792	95.85	0.5996	1.033549	95.94	0.6000	1.036291	96.06
0.8000	1.040200	95.93	0.8000	1.042879	96.01	0.8000	1.045492	96.13
1.0000	1.049261	96.00	1.0000	1.051835	96.09	1.0000	1.054355	96.20
1.2000	1.057980	96.07	1.2000	1.060458	96.16	1.2000	1.062891	96.26
m_{Gly}/mol·kg^{-1} = 0.1500			m_{Gly}/mol·kg^{-1} = 0.2500			m_{Gly}/mol·kg^{-1} = 0.3500		
0.1998	1.012311	95.76	0.2000	1.015300	95.86	0.2000	1.018231	95.99
0.3998	1.022440	95.82	0.4000	1.025315	95.92	0.4000	1.028124	96.05
0.5989	1.032139	95.88	0.6000	1.034950	95.97	0.6000	1.037640	96.11
0.8000	1.041555	95.96	0.8000	1.044196	96.06	0.8000	1.046789	96.19
1.0000	1.050557	96.04	0.9999	1.053108	96.13	0.9881	1.055090	96.24
1.2000	1.059247	96.10	1.2000	1.061686	96.21	1.2000	1.064090	96.31
Ribose in Glycine Solutions								
m_{Gly}/mol·kg^{-1} = 0.1000			m_{Gly}/mol·kg^{-1} = 0.2000			m_{Gly}/mol·kg^{-1} = 0.3000		
0.2000	1.010887	95.35	0.1978	1.013765	95.50	0.2000	1.016845	95.55
0.4000	1.021128	95.45	0.4000	1.024008	95.56	0.4000	1.026854	95.65
0.6000	1.030972	95.54	0.5987	1.033690	95.63	0.6000	1.036487	95.72
0.8000	1.040442	95.62	0.8000	1.043112	95.71	0.8000	1.045751	95.79
0.9776	1.048549	95.68	1.0000	1.052141	95.77	0.9987	1.054612	95.86
1.1950	1.058119	95.76	1.2000	1.060839	95.83	1.2000	1.063279	95.92
m_{Gly}/mol·kg^{-1} = 0.1500			m_{Gly}/mol·kg^{-1} = 0.2500			m_{Gly}/mol·kg^{-1} = 0.3500		
0.2000	1.012384	95.44	0.2000	1.015361	95.55	0.1998	1.018283	95.67
0.4000	1.022561	95.54	0.4000	1.025433	95.61	0.3982	1.028168	95.71
0.6000	1.032345	95.62	0.6000	1.035120	95.68	0.6000	1.037832	95.78
0.8000	1.041752	95.70	0.8000	1.044445	95.74	0.7999	1.047043	95.85
1.0000	1.050820	95.76	1.0000	1.053418	95.81	1.0000	1.055902	95.93
1.1978	1.059455	95.83	1.2000	1.062055	95.88	1.2000	1.064450	95.99

[a] m_S = molality of monosaccharide in water. m_{Gly} = molality of glycine in water.

Table 2. Solution Densities ρ and Apparent Molar Volumes $V_{\Phi,S}$ for Monosaccharides in Water and in Aqueous Alanine Solutions at 298.15 K[a]

m_S / mol·kg^{-1}	ρ / g·cm^{-3}	$V_{\Phi,S}$ / cm^3·mol^{-1}	m_S / mol·kg^{-1}	ρ / g·cm^{-3}	$V_{\Phi,S}$ / cm^3·mol^{-1}	m_S / mol·kg^{-1}	ρ / g·cm^{-3}	$V_{\Phi,S}$ / cm^3·mol^{-1}
Glucose in Alanine Solutions								
m_{Ala}/mol·kg^{-1} = 0.1001			m_{Ala}/mol·kg^{-1} = 0.2002			m_{Ala}/mol·kg^{-1} = 0.2999		
0	0.999919		0	1.002733		0	1.005483	
0.1966	1.012889	112.14	0.2000	1.015747	112.34	0.2000	1.018332	112.50
0.4000	1.025691	112.26	0.4000	1.028167	112.45	0.4000	1.030606	112.58
0.6000	1.037706	112.37	0.6000	1.040033	112.55	0.5992	1.042287	112.68
0.7996	1.049175	112.47	0.7964	1.051188	112.63	0.8005	1.053583	112.76
1.0000	1.060183	112.58	1.0000	1.062247	112.73	0.9987	1.064216	112.86
1.1987	1.070628	112.68	1.2000	1.072636	112.83	1.2000	1.074575	112.94
m_{Ala}/mol·kg^{-1} = 0.1500			m_{Ala}/mol·kg^{-1} = 0.2500			m_{Ala}/mol·kg^{-1} = 0.3502		
0	1.001328		0	1.004113		0	1.006853	
0.2002	1.014450	112.21	0.2000	1.017037	112.46	0.2000	1.019630	112.52
0.4000	1.026941	112.33	0.4000	1.029387	112.53	0.4000	1.031837	112.60
0.6000	1.038898	112.42	0.6000	1.041186	112.62	0.6000	1.043504	112.70
0.8000	1.050314	112.53	0.8000	1.052475	112.70	0.8000	1.054662	112.79
1.0000	1.061249	112.62	1.0000	1.063256	112.81	1.0000	1.065347	112.88
1.2000	1.071706	112.72	1.2000	1.073624	112.88	1.2000	1.075567	112.98
Galactose in Alanine Solutions								
m_{Ala}/mol·kg^{-1} = 0.1000			m_{Ala}/mol·kg^{-1} = 0.2000			m_{Ala}/mol·kg^{-1} = 0.3000		
0.2000	1.013441	110.44	0.2000	1.016082	110.60	0.2000	1.018695	110.65
0.4000	1.026355	110.55	0.3999	1.028828	110.72	0.4000	1.031282	110.84
0.6000	1.038690	110.67	0.5997	1.041016	110.81	0.6000	1.043332	110.94
0.8000	1.050487	110.78	0.7999	1.052677	110.93	0.8000	1.054859	111.05
1.0000	1.061769	110.90	1.0000	1.063834	111.04	1.0000	1.065893	111.15
1.2000	1.072574	111.01	1.2000	1.074529	111.14	1.2000	1.076481	111.24
m_{Ala}/mol·kg^{-1} = 0.1499			m_{Ala}/mol·kg^{-1} = 0.2500			m_{Ala}/mol·kg^{-1} = 0.3500		
0.2000	1.014757	110.56	0.2000	1.017391	110.64	0.2000	1.019967	110.76
0.4000	1.027591	110.65	0.4000	1.030072	110.76	0.4000	1.032504	110.86
0.6000	1.039863	110.74	0.6000	1.042206	110.84	0.6000	1.044501	110.95
0.8000	1.051580	110.87	0.8000	1.053786	110.98	0.8000	1.055958	111.07
1.0000	1.062805	110.97	1.0000	1.064895	111.07	1.0000	1.066933	111.18
1.2000	1.073553	111.08	1.2000	1.075516	111.18	1.2000	1.077445	111.29
Xylose in Alanine Solutions								
m_{Ala}/mol·kg^{-1} = 0.09995			m_{Ala}/mol·kg^{-1} = 0.2000			m_{Ala}/mol·kg^{-1} = 0.3000		
0.2000	1.010506	95.68	0.2000	1.013188	95.77	0.2000	1.015823	95.83
0.3923	1.020299	95.75	0.4000	1.023241	95.85	0.4000	1.025770	95.88
0.6000	1.030462	95.84	0.6000	1.032904	95.92	0.6000	1.035324	95.96
0.8000	1.039879	95.90	0.8000	1.042212	95.98	0.8000	1.044521	96.03
1.0000	1.048940	95.97	1.0000	1.051152	96.06	1.0000	1.053367	96.11
1.2000	1.057651	96.05	1.2000	1.059777	96.13	1.2000	1.061890	96.18
m_{Ala}/mol·kg^{-1} = 0.1500			m_{Ala}/mol·kg^{-1} = 0.2500			m_{Ala}/mol·kg^{-1} = 0.3500		
0.2000	1.011851	95.75	0.2000	1.014513	95.79	0.2000	1.017129	95.84
0.3920	1.021568	95.81	0.4000	1.024507	95.87	0.4000	1.027015	95.90
0.6000	1.031691	95.88	0.6000	1.034117	95.94	0.6000	1.036511	95.99
0.8000	1.041052	95.94	0.8000	1.043356	96.02	0.8000	1.045653	96.06
1.0000	1.050048	96.02	1.0000	1.052253	96.10	1.0000	1.054446	96.15
1.2000	1.058715	96.09	1.2000	1.060820	96.17	1.2000	1.062927	96.21
Ribose in Alanine Solutions								
m_{Ala}/mol·kg^{-1} = 0.1000			m_{Ala}/mol·kg^{-1} = 0.2000			m_{Ala}/mol·kg^{-1} = 0.3000		
0.2000	1.010556	95.37	0.2000	1.013251	95.45	0.2000	1.015879	95.54
0.4000	1.020796	95.44	0.4000	1.023364	95.53	0.4000	1.025872	95.61
0.6000	1.030652	95.49	0.6000	1.033092	95.60	0.6000	1.035488	95.67
0.8000	1.040114	95.58	0.8000	1.042456	95.66	0.8000	1.044742	95.74
1.0000	1.049238	95.64	1.0000	1.051461	95.74	1.0000	1.053659	95.80
1.2000	1.058030	95.70	1.2000	1.060145	95.80	1.2000	1.062223	95.88
m_{Ala}/mol·kg^{-1} = 0.1500			m_{Ala}/mol·kg^{-1} = 0.2500			m_{Ala}/mol·kg^{-1} = 0.3500		
0.2000	1.011916	95.42	0.2000	1.014573	95.49	0.2000	1.017188	95.53
0.4000	1.022092	95.49	0.4000	1.024628	95.56	0.4000	1.027114	95.64
0.6000	1.031878	95.56	0.6000	1.034306	95.62	0.6000	1.036675	95.70
0.8000	1.041300	95.62	0.8000	1.043599	95.71	0.8000	1.045882	95.76
1.0000	1.050355	95.69	1.0000	1.052565	95.77	1.0000	1.054734	95.84
1.2000	1.059092	95.76	1.2000	1.061198	95.83	1.2000	1.063282	95.90

[a] m_S = molality of monosaccharide in water. m_{Ala} = molality of alanine in water.

belohde viscometer, which was placed in a water thermostat (Schott, Germany), with a flow time of about 200 s for water at 298.15 K. The temperature of the water thermostat was controlled to be as precise as the density measurements. The viscometer was calibrated at (298.15 and 308.15) K with water. The viscosities for water at different temperatures were taken from the literature.[29] Flow time measurements were performed by a Schott AVS310 photoelectric time unit with a resolution of 0.01 s. The estimated uncertainty of experimental viscosity is ± 0.25 %. Solution viscosity η is given by the following equation:

$$\eta/\rho = Ct - K/t \qquad (1)$$

where C and K are the cell constants and t is the flow time. The details of the experimental procedure are given elsewhere.[30]

Results and Discussion

Apparent Molar Volume. Densities of solutions ρ are listed in Tables 1 and 2. Apparent molar volumes of monosaccharides $V_{\Phi,S}$ were calculated from the equation:[31]

$$V_{\Phi,S} = \frac{M_S}{\rho} - \frac{(1000 + m_A M_A)(\rho - \rho_A)}{m_S \rho \rho_A} \qquad (2)$$

where M_S and M_A are the molar masses of monosaccharide and

Table 3. Standard Partial Molar Volumes and the Experimental Slopes for Monosaccharides in Water and in Glycine Solutions at 298.15 K

m_A [a] mol·kg^{-1}	$V^0_{\Phi,S}$ cm^3·mol^{-1}	S_V cm^3·kg·mol^{-2}	m_A mol·kg^{-1}	$V^0_{\Phi,S}$ cm^3·mol^{-1}	S_V cm^3·kg·mol^{-2}
	Glucose			Galactose	
0	111.81 ± 0.01 111.99 ± 0.01[b] 111.79[c]	0.69 ± 0.01	0	110.21 ± 0.02 110.52 ± 0.02[b] 110.29 ± 0.04[d]	0.57 ± 0.03
0.1000	112.09 ± 0.01	0.57 ± 0.02	0.1000	110.33 ± 0.01	0.61 ± 0.02
0.1500	112.19 ± 0.004	0.55 ± 0.005	0.1500	110.43 ± 0.03	0.60 ± 0.04
0.2000	112.27 ± 0.01	0.53 ± 0.01	0.2000	110.51 ± 0.01	0.57 ± 0.02
0.2500	112.33 ± 0.01	0.52 ± 0.01	0.2500	110.58 ± 0.01	0.56 ± 0.01
0.3000	112.40 ± 0.004	0.49 ± 0.01	0.3000	110.66 ± 0.01	0.55 ± 0.01
0.3500	112.50 ± 0.01	0.49 ± 0.01	0.3500	110.74 ± 0.01	0.53 ± 0.01
	Xylose			Ribose	
0	95.47 ± 0.01 95.4 ± 0.3[d] 95.60[e]	0.41 ± 0.01	0	95.22 ± 0.01 95.26[f]	0.38 ± 0.01
0.1000	95.64 ± 0.004	0.36 ± 0.01	0.1000	95.31 ± 0.02	0.38 ± 0.02
0.1500	95.68 ± 0.01	0.36 ± 0.01	0.1500	95.40 ± 0.02	0.36 ± 0.02
0.2000	95.71 ± 0.003	0.37 ± 0.004	0.2000	95.44 ± 0.01	0.33 ± 0.01
0.2500	95.76 ± 0.02	0.38 ± 0.02	0.2500	95.47 ± 0.005	0.34 ± 0.01
0.3000	95.85 ± 0.01	0.35 ± 0.01	0.3000	95.52 ± 0.02	0.34 ± 0.02
0.3500	95.92 ± 0.01	0.32 ± 0.01	0.3500	95.58 ± 0.01	0.35 ± 0.02

[a] m_A = molality of glycine in water. [b] Ref 21. [c] Ref 34a. [d] Ref 34b. [e] Ref 34c. [f] Ref 34d.

Table 4. Standard Partial Molar Volumes and the Experimental Slopes for Monosaccharides in Water and in Alanine Solutions at 298.15 K

m_A [a] mol·kg^{-1}	$V^0_{\Phi,S}$ cm^3·mol^{-1}	S_V cm^3·kg·mol^{-2}	m_A mol·kg^{-1}	$V^0_{\Phi,S}$ cm^3·mol^{-1}	S_V cm^3·kg·mol^{-2}
	Glucose			Galactose	
0.1001	112.06 ± 0.01	0.51 ± 0.01	0.1000	110.32 ± 0.003	0.57 ± 0.004
0.1500	112.13 ± 0.01	0.49 ± 0.01	0.1499	110.43 ± 0.01	0.54 ± 0.02
0.2002	112.26 ± 0.01	0.48 ± 0.01	0.2000	110.50 ± 0.01	0.54 ± 0.01
0.2500	112.36 ± 0.01	0.44 ± 0.01	0.2500	110.54 ± 0.01	0.54 ± 0.02
0.2999	112.41 ± 0.01	0.44 ± 0.01	0.3000	110.63 ± 0.04	0.51 ± 0.05
0.3502	112.42 ± 0.01	0.47 ± 0.01	0.3500	110.63 ± 0.01	0.55 ± 0.01
	Xylose			Ribose	
0.09995	95.61 ± 0.01	0.36 ± 0.01	0.1000	95.31 ± 0.01	0.33 ± 0.01
0.1500	95.67 ± 0.01	0.35 ± 0.01	0.1500	95.35 ± 0.003	0.34 ± 0.004
0.2000	95.70 ± 0.005	0.36 ± 0.01	0.2000	95.39 ± 0.01	0.34 ± 0.01
0.2500	95.72 ± 0.003	0.38 ± 0.004	0.2500	95.43 ± 0.01	0.34 ± 0.01
0.3000	95.74 ± 0.01	0.37 ± 0.01	0.3000	95.46 ± 0.01	0.34 ± 0.01
0.3500	95.75 ± 0.01	0.39 ± 0.02	0.3500	95.49 ± 0.02	0.34 ± 0.02

[a] m_A = molality of alanine in water.

Table 5. Solution Densities ρ and Apparent Molar Volumes and Standard Partial Molar Volumes for Amino Acids in Water at 298.15 K

m_A [a] mol·kg^{-1}	ρ_A g·cm^{-3}	$V_{\Phi,A}$ cm^3·mol^{-1}	$V^0_{\Phi,A}$ cm^3·mol^{-1}	m_A mol·kg^{-1}	ρ_A g·cm^{-3}	$V_{\Phi,A}$ cm^3·mol^{-1}	$V^0_{\Phi,A}$ cm^3·mol^{-1}
	Glycine				Alanine		
0.1000	1.000217	43.27	43.19 ± 0.01[b]	0.1000	0.999915	60.34	60.25 ± 0.01[b]
0.1500	1.001783	43.33	42.54 ± 0.02[c]	0.1500	1.001328	60.40	60.19 ± 0.01[c]
0.2000	1.003340	43.37	43.20 ± 0.03[d]	0.2000	1.002727	60.45	60.41 ± 0.01[e]
0.2500	1.004883	43.42	43.16 ± 0.02[e]	0.2500	1.004113	60.50	
0.3000	1.006417	43.47		0.3000	1.005485	60.56	
0.3500	1.007940	43.51		0.3500	1.006847	60.60	

[a] m_A = molality of glycine or alanine in water. [b] The experimental slope (S_V) is 0.93 ± 0.03 cm^3·kg·mol^{-2} and 1.02 ± 0.03 cm^3·kg·mol^{-2} for glycine and alanine, respectively. [c] Ref 34e. [d] Ref 34f. [e] Ref 34g.

amino acid; m_S and m_A are the molalities of monosaccharide and amino acid; and ρ and ρ_A are the densities of saccharide + amino acid + water and amino acid + water solutions, respectively. The results are also included in Tables 1 and 2. The uncertainty of $V_{\Phi,S}$ is ± 0.06 at the lowest molality and ± 0.01 cm^3·mol^{-1} at the highest molality. It has been observed that plots of $V_{\Phi,S}$ versus m_S are very linear. Therefore, infinite-dilution apparent molar volumes ($V^0_{\Phi,S}$), which are equal to the standard partial molar volumes, were obtained by least-squares weighted fitting experimental data to the following equation:[32,33]

$$V_{\Phi,S} = V^0_{\Phi,S} + S_V m_S \tag{3}$$

where S_V is the experimental slope. The weighing factor of $V_{\Phi,S}$ used in the regression analysis is $(\delta V_{\Phi,S})^{-2}$, where $\delta V_{\Phi,S} = -(M + 1000/m)\,\delta\rho/\rho^2$, $\delta\rho$ is uncertainty of the solution density and is taken as a constant,[32,33] and M is the molar mass of the solute. The resulting values of $V^0_{\Phi,S}$, $V^0_{\Phi,A}$, and S_V for monosaccharide or amino acid are summarized in Tables 3 to 5. They are in good agreement with those in the literature.[34] The partial molar volumes of transfer of monosaccharides from water to aqueous amino acid solutions at infinite dilution $\Delta_t V^0_{\Phi,S}$ were evaluated from

$$\Delta_t V^0_{\Phi,S} = V^0_{\Phi,S}(\text{in aqueous amino acid}) - V^0_{\Phi,S}(\text{in water}) \tag{4}$$

Plots of $\Delta_t V^0_{\Phi,S}$ versus the molalities of amino acids are represented in Figures 1 and 2. Since $V^0_{\Phi,S}$ is, by definition,

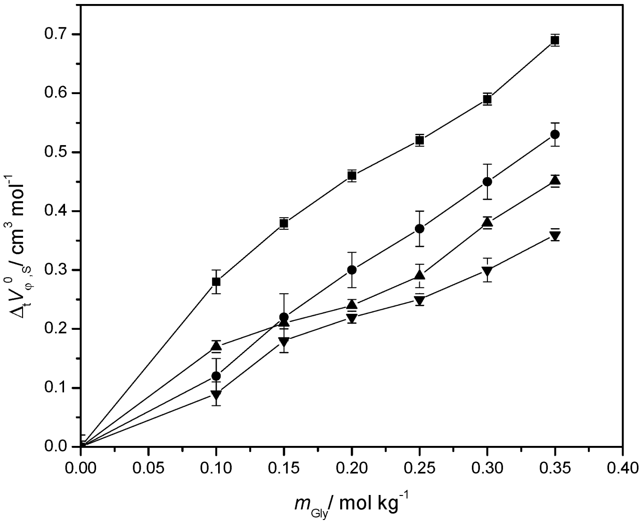

Figure 1. Standard volumes of transfer of monosaccharides from water to aqueous glycine solutions as a function of molality of glycine: ■, glucose; ●, galactose; ▲, xylose; ▼, ribose. Vertical bars indicate the standard deviations of $\Delta_t V^0_{\Phi,S}$, which are calculated from the standard deviations of $V^0_{\Phi,S}$ in glycine + water and in water by $\sigma(\Delta_t V^0_{\Phi,S}) = [\sigma(V^0_{\Phi,S}\text{ in glycine + water})^2 + \sigma(V^0_{\Phi,S}\text{ in water})^2]^{1/2}$.

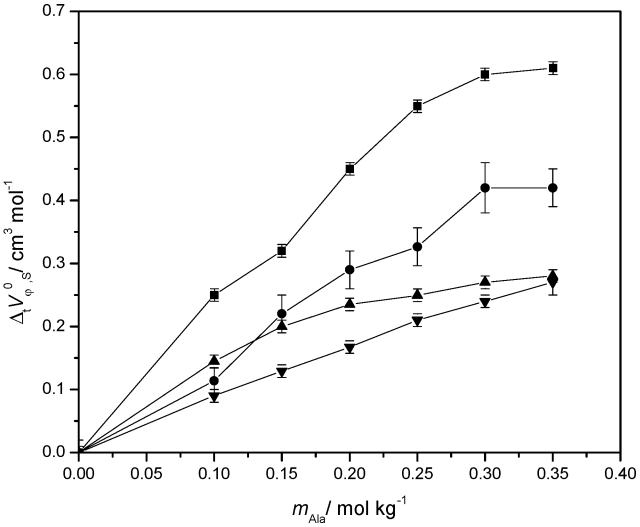

Figure 2. Standard volumes of transfer of monosaccharides from water to aqueous alanine solutions as a function of molality of alanine: ■, glucose; ●, galactose; ▲, xylose; ▼, ribose. Vertical bars indicate the standard deviations of $\Delta_t V^0_{\Phi,S}$ (see the caption of Figure 1).

Table 6. Dominant Conformations of Monosaccharides in Water

carbohydrates	dominant conformations[a]
D-glucose	1*e*2*e*3*e*4*e*6*exo*
D-galactose	1*e*2*e*3*e*4*a*6*exo*
D-xylose	1*e*2*e*3*e*4*e*
D-ribose	1*e*2*e*3*a*4*e*

[a] Axial (*a*), equatorial (*e*), or exocyclic (*exo*) hydroxy groups.

free from solute−solute interactions, it provides some information about solute−cosolute interactions.

(a) Dependence of Volumetric Properties on Different Monosaccharides. For a given amino acid, the differences in transfer volumes for different saccharides are ascribed mainly to those in the stereo structure of monosaccharides, whose dominant conformations in water are illustrated in Table 6.

First, it is seen from Figures 1and 2 that the $\Delta_t V^0_{\Phi,S}$ values for all saccharides studied are positive and increase with increasing molalities of amino acids. This can be rationalized by the cosphere overlap model, as developed by Friedman and Krishnan.[35] The interactions between the monosaccharide and amino acid molecules can be classified as follows: (1) hydrophilic−ionic interactions between the OH groups of monosac-

Table 7. Volumetric Pair and Triplet Interaction Parameters for Monosaccharides + Glycine + Water Solutions at 298.15 K

	ν_{SA}	ν_{SAA}	
monosaccharides	cm^3·mol^{-2}·kg	cm^3·mol^{-2}·kg^2	R^a
glucose	1.423 ± 0.084	−0.897 ± 0.194	0.990
galactose	0.677 ± 0.042	0.162 ± 0.097	0.998
xylose	0.683 ± 0.098	−0.115 ± 0.226	0.973
ribose	0.558 ± 0.056	−0.101 ± 0.130	0.989

[a] Correlation coefficient.

Table 8. Volumetric Pair and Triplet Interaction Parameters for Monosaccharides + Alanine + Water Solutions at 298.15 K

	ν_{SA}	ν_{SAA}	
monosaccharides	cm^3·mol^{-2}·kg	cm^3·mol^{-2}·kg^2	R^a
glucose	1.395 ± 0.094	−0.940 ± 0.216	0.988
galactose	0.775 ± 0.093	−0.278 ± 0.213	0.981
xylose	0.838 ± 0.025	−0.849 ± 0.057	0.992
ribose	0.472 ± 0.009	−0.161 ± 0.021	0.999

[a] Correlation coefficient.

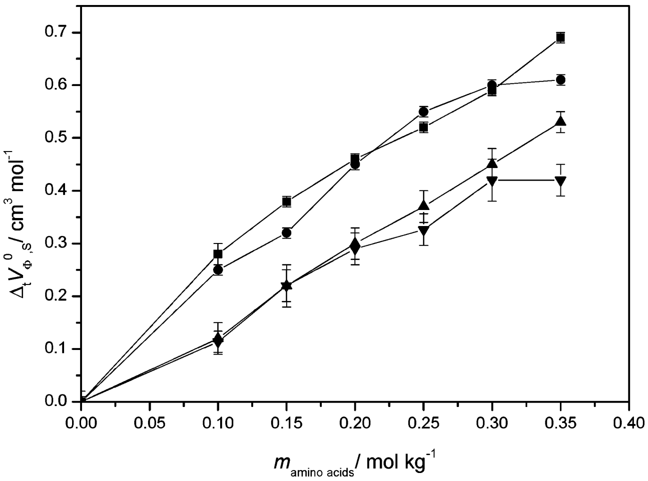

Figure 3. Standard volumes of transfer of glucose and galactose from water to aqueous amino acid solutions as a function of molality of amino acid: ■, glucose in glycine; ●, glucose in alanine; ▲, galactose in glycine; ▼, galactose in alanine. Vertical bars indicate the standard deviations of $\Delta_t V^0_{\Phi,S}$ (see the caption of Figure 1).

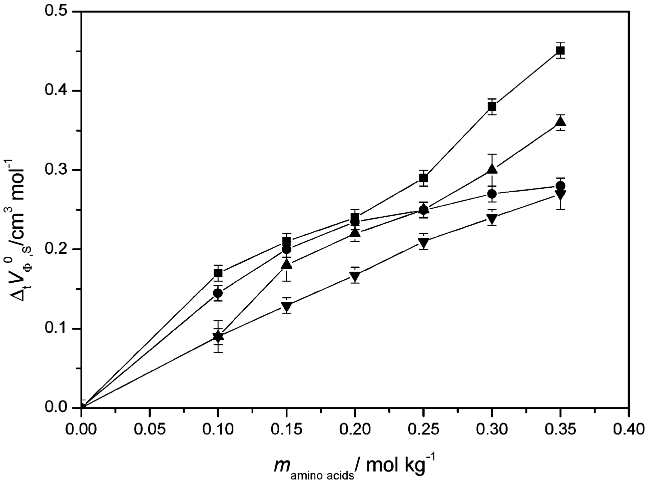

Figure 4. Standard volumes of transfer of xylose and ribose from water to aqueous amino acid solutions as a function of molality of amino acid: ■, xylose in glycine; ●, xylose in alanine; ▲, ribose in glycine; ▼, ribose in alanine. Vertical bars indicate the standard deviations of $\Delta_t V^0_{\Phi,S}$ (see the caption of Figure 1).

Table 9. Viscosities η of the Monosaccharide + Water and Monosaccharide + Glycine + Water Solutions at 298.15 K

c^a mol·dm^{-3}	η mPa·s	c mol·dm^{-3}	η mPa·s	c mol·dm^{-3}	η mPa·s	c mol·dm^{-3}	η mPa·s
Glucose							
m_{Gly}/mol·kg^{-1} = 0		m_{Gly}/mol·kg^{-1} = 0.1500		m_{Gly}/mol·kg^{-1} = 0.2500		m_{Gly}/mol·kg^{-1} = 0.3500	
0	0.8904^b	0	0.910	0	0.922	0	0.935
0.1951	0.974	0.1937	0.996	0.1930	1.010	0.1922	1.025
0.3818	1.065	0.3793	1.091	0.3778	1.106	0.3762	1.122
0.5606	1.166	0.5571	1.195	0.5548	1.211	0.5526	1.230
0.7320	1.270	0.7276	1.308	0.7240	1.326	0.7213	1.346
0.8964	1.389	0.8853	1.427	0.8876	1.452	0.8826	1.472
1.0756	1.517	1.0481	1.553	1.0439	1.582	1.0400	1.610
m_{Gly}/mol·kg^{-1} = 0.1000		m_{Gly}/mol·kg^{-1} = 0.2000		m_{Gly}/mol·kg^{-1} = 0.3000			
0	0.903	0	0.916	0	0.929		
0.1942	0.988	0.1934	1.003	0.1926	1.018		
0.3802	1.083	0.3786	1.099	0.3770	1.114		
0.5583	1.186	0.5560	1.203	0.5537	1.221		
0.7283	1.298	0.7261	1.317	0.7232	1.336		
0.8929	1.418	0.8893	1.439	0.8944	1.466		
1.0502	1.540	1.0461	1.572	1.0321	1.591		
Galactose							
m_{Gly}/mol·kg^{-1} = 0		m_{Gly}/mol·kg^{-1} = 0.1500		m_{Gly}/mol·kg^{-1} = 0.2500		m_{Gly}/mol·kg^{-1} = 0.3500	
0.1951	0.971	0.1939	0.994	0.1897	1.006	0.1922	1.023
0.3820	1.060	0.3795	1.086	0.3780	1.102	0.3764	1.117
0.5611	1.158	0.5576	1.188	0.5554	1.204	0.5531	1.221
0.7329	1.266	0.7284	1.298	0.7255	1.316	0.7226	1.335
0.8978	1.379	0.8923	1.419	0.8889	1.438	0.8854	1.459
1.0563	1.505	1.0500	1.551	1.0459	1.572	1.0417	1.594
m_{Gly}/mol·kg^{-1} = 0.1000		m_{Gly}/mol·kg^{-1} = 0.2000		m_{Gly}/mol·kg^{-1} = 0.3000			
0.1943	0.986	0.1935	1.001	0.1926	1.016		
0.3804	1.077	0.3788	1.094	0.3772	1.110		
0.5584	1.179	0.5565	1.196	0.5542	1.213		
0.7253	1.286	0.7270	1.306	0.7240	1.326		
0.8943	1.409	0.8898	1.429	0.8871	1.449		
1.0521	1.534	1.0480	1.562	1.0439	1.583		
Xylose							
m_{Gly}/mol·kg^{-1} = 0		m_{Gly}/mol·kg^{-1} = 0.1500		m_{Gly}/mol·kg^{-1} = 0.2500		m_{Gly}/mol·kg^{-1} = 0.3500	
0.1957	0.953	0.1942	0.976	0.1936	0.990	0.1928	1.004
0.3842	1.023	0.3815	1.047	0.3802	1.061	0.3786	1.077
0.5658	1.096	0.5613	1.122	0.5600	1.139	0.5577	1.155
0.7410	1.175	0.7365	1.203	0.7335	1.220	0.7305	1.238
0.9102	1.257	0.9046	1.289	0.9010	1.308	0.8876	1.321
1.0732	1.343	1.0671	1.384	1.0626	1.401	1.0584	1.420
m_{Gly}/mol·kg^{-1} = 0.1000		m_{Gly}/mol·kg^{-1} = 0.2000		m_{Gly}/mol·kg^{-1} = 0.3000			
0.1948	0.968	0.1940	0.983	0.1932	0.997		
0.3825	1.039	0.3810	1.054	0.3794	1.070		
0.5635	1.115	0.5608	1.131	0.5588	1.147		
0.7380	1.195	0.7350	1.212	0.7320	1.230		
0.9064	1.281	0.9027	1.298	0.8991	1.317		
1.0690	1.372	1.0647	1.391	1.0605	1.409		
Ribose							
m_{Gly}/mol·kg^{-1} = 0		m_{Gly}/mol·kg^{-1} = 0.1500		m_{Gly}/mol·kg^{-1} = 0.2500		m_{Gly}/mol·kg^{-1} = 0.3500	
0.1957	0.950	0.1944	0.971	0.1936	0.984	0.1926	0.998
0.3842	1.010	0.3818	1.034	0.3802	1.049	0.377	1.063
0.5659	1.075	0.5624	1.102	0.5601	1.117	0.5578	1.133
0.7412	1.145	0.7364	1.173	0.7337	1.190	0.7306	1.207
0.9103	1.215	0.9048	1.250	0.9012	1.268	0.8975	1.285
1.0737	1.292	1.0672	1.328	1.0630	1.348	1.0589	1.369
m_{Gly}/mol·kg^{-1} = 0.1000		m_{Gly}/mol·kg^{-1} = 0.2000		m_{Gly}/mol·kg^{-1} = 0.3000			
0.1949	0.963	0.1919	0.977	0.1932	0.991		
0.3826	1.026	0.3810	1.041	0.3794	1.057		
0.5636	1.094	0.5601	1.109	0.5589	1.126		
0.7382	1.165	0.7352	1.182	0.7322	1.199		
0.8881	1.233	0.9030	1.259	0.8983	1.276		
1.0653	1.318	1.0651	1.339	1.0609	1.358		

[a] c = molarity of monosaccharides (in mol·dm^{-3}). [b] Ref 29.

charide and the zwitterionic center of amino acid; (2) hydrophilic−hydrophilic interactions between the OH groups of monosaccharide and the OH groups of amino acid mediated through the hydrogen bond; (3) hydrophilic−hydrophobic interactions between the OH groups of monosaccharide/amino acid and the nonpolar groups of the amino acid /monosaccharide; (4) hydrophobic−hydrophobic interactions between the nonpolar groups of monosaccharide and amino acid. The interations of types (1) and (2) make positive contributions to the transfer volume, whereas the contributions of types (3) and (4) are opposite. Therefore, the observed increasing positive transfer volumes suggest that the first two interactions are predominant in the ternary systems studied. In addition, an increase in concentration of amino acid leads to stronger interactions of

Table 10. Viscosities η of the Monosaccharide + Water and Monosaccharide + Alanine + Water Solutions at 298.15 K

c^a / mol·dm^{-3}	η / mPa·s	c / mol·dm^{-3}	η / mPa·s	c / mol·dm^{-3}	η / mPa·s
		Glucose			
m_{Ala}/mol·kg^{-1} = 0.1000		m_{Ala}/mol·kg^{-1} = 0.2000		m_{Ala}/mol·kg^{-1} = 0.3000	
0	0.912	0	0.935	0	0.958
0.1939	0.999	0.1928	1.024	0.1916	1.049
0.3795	1.093	0.3773	1.121	0.3752	1.149
0.5574	1.197	0.5542	1.226	0.5504	1.256
0.7279	1.307	0.7209	1.336	0.7199	1.372
0.8916	1.429	0.8867	1.464	0.8808	1.499
1.0486	1.561	1.0431	1.601	1.0375	1.640
m_{Ala}/mol·kg^{-1} = 0.1500		m_{Ala}/mol·kg^{-1} = 0.2500		m_{Ala}/mol·kg^{-1} = 0.3500	
0	0.923	0	0.946	0	0.970
0.1933	1.011	0.1922	1.036	0.1911	1.062
0.3784	1.106	0.3763	1.134	0.3741	1.163
0.5558	1.211	0.5526	1.240	0.5496	1.273
0.7259	1.322	0.7219	1.355	0.7179	1.393
0.8892	1.445	0.8843	1.482	0.8795	1.519
1.0459	1.580	1.0403	1.619	1.0348	1.661
		Galactose			
m_{Ala}/mol·kg^{-1} = 0.1000		m_{Ala}/mol·kg^{-1} = 0.2000		m_{Ala}/mol·kg^{-1} = 0.3000	
0.1940	0.995	0.1928	1.020	0.1917	1.045
0.3798	1.087	0.3775	1.115	0.3754	1.143
0.5579	1.188	0.5545	1.219	0.5516	1.248
0.7289	1.298	0.7247	1.330	0.7207	1.364
0.8929	1.413	0.8880	1.446	0.8832	1.484
1.0506	1.545	1.0341	1.575	1.0393	1.620
m_{Ala}/mol·kg^{-1} = 0.1500		m_{Ala}/mol·kg^{-1} = 0.2500		m_{Ala}/mol·kg^{-1} = 0.3500	
0.1934	1.007	0.1923	1.032	0.1911	1.059
0.3787	1.101	0.3765	1.128	0.3744	1.157
0.5564	1.203	0.5532	1.233	0.5501	1.264
0.7268	1.314	0.7228	1.347	0.7188	1.381
0.8905	1.429	0.8856	1.465	0.8809	1.506
1.0478	1.561	1.0421	1.599	1.0365	1.641
		Xylose			
m_{Ala}/mol·kg^{-1} = 0.1000		m_{Ala}/mol·kg^{-1} = 0.2000		m_{Ala}/mol·kg^{-1} = 0.3000	
0.1945	0.978	0.1934	1.003	0.1923	1.028
0.3780	1.047	0.3797	1.075	0.3775	1.101
0.5626	1.123	0.5594	1.152	0.5562	1.181
0.7368	1.204	0.7327	1.234	0.7286	1.265
0.9050	1.286	0.9000	1.319	0.8951	1.349
1.0674	1.376	1.0616	1.409	1.0558	1.443
m_{Ala}/mol·kg^{-1} = 0.1500		m_{Ala}/mol·kg^{-1} = 0.2500		m_{Ala}/mol·kg^{-1} = 0.3500	
0.1940	0.990	0.1928	1.015	0.1917	1.041
0.3783	1.060	0.3786	1.088	0.3765	1.115
0.5610	1.138	0.5578	1.166	0.5547	1.195
0.7348	1.219	0.7307	1.250	0.7266	1.281
0.9025	1.301	0.8975	1.333	0.8926	1.366
1.0644	1.394	1.0588	1.428	1.0531	1.463
		Ribose			
m_{Ala}/mol·kg^{-1} = 0.1000		m_{Ala}/mol·kg^{-1} = 0.2000		m_{Ala}/mol·kg^{-1} = 0.3000	
0.1945	0.972	0.1934	0.997	0.1923	1.022
0.3820	1.035	0.3788	1.061	0.3776	1.088
0.5627	1.102	0.5595	1.130	0.5563	1.158
0.7370	1.174	0.7329	1.203	0.7288	1.233
0.9053	1.245	0.9003	1.276	0.8953	1.307
1.0678	1.325	1.0619	1.356	1.0560	1.389
m_{Ala}/mol·kg^{-1} = 0.1500		m_{Ala}/mol·kg^{-1} = 0.2500		m_{Ala}/mol·kg^{-1} = 0.3500	
0.1940	0.984	0.1928	1.009	0.1917	1.035
0.3809	1.048	0.3787	1.074	0.3765	1.102
0.5611	1.116	0.5579	1.144	0.5548	1.173
0.7349	1.188	0.7308	1.218	0.7268	1.249
0.9028	1.260	0.8978	1.292	0.8928	1.323
1.0648	1.340	1.0591	1.373	1.0533	1.407

[a] c is the molarity of monosaccharides (in mol·dm^{-3}).

types (1) and (2); consequently, the $\Delta_t V^0_{\Phi,S}$ values of saccharides increase.

Second, as presented in Figures 1 and 2, the $\Delta_t V^0_{\Phi,S}$ values for monosaccharides in a given aqueous amino acid solution are in the order: glucose > galactose > xylose > ribose except at low molality of amino acids (m_A = 0.13 mol·kg^{-1}). For pentoses or hexoses, their molecules are essentially all structural isomers differing only in the stereochemical configurations of hydroxyl group on the ring (equatorial or axial position), as a result, their properties in aqueous solutions, such as their equilibrium anomeric ratios, are distinct.[36] Consequently, the $\Delta_t V^0_{\Phi,S}$ values seem to depend on the contribution of different kinds of OH groups: equatorial (*e*), axial (*a*), and exocyclic (*exo*) OH groups. We can observe from the experimental results

Table 11. Viscosity *B*-Coefficients of Monosaccharides in Aqueous Glycine Solutions at 298.15 K

$\frac{m_A}{\text{mol·kg}^{-1}}$	$\frac{B}{\text{dm}^3\text{·mol}^{-1}}$	$\frac{m_A}{\text{mol·kg}^{-1}}$	$\frac{B}{\text{dm}^3\text{·mol}^{-1}}$	$\frac{m_A}{\text{mol·kg}^{-1}}$	$\frac{B}{\text{dm}^3\text{·mol}^{-1}}$	$\frac{m_A}{\text{mol·kg}^{-1}}$	$\frac{B}{\text{dm}^3\text{·mol}^{-1}}$
Glucose		Galactose		Xylose		Ribose	
0	0.440 ± 0.004 0.45[a]	0	0.416 ± 0.004	0	0.336 ± 0.001	0	0.319 ± 0.004
0.1000	0.441 ± 0.001	0.1000	0.424 ± 0.004	0.1000	0.343 ± 0.002	0.1000	0.318 ± 0.002
0.1500	0.442 ± 0.003	0.1500	0.426 ± 0.006	0.1500	0.345 ± 0.004	0.1500	0.321 ± 0.003
0.2000	0.443 ± 0.005	0.2000	0.429 ± 0.007	0.2000	0.349 ± 0.003	0.2000	0.323 ± 0.004
0.2500	0.445 ± 0.005	0.2500	0.432 ± 0.006	0.2500	0.352 ± 0.004	0.2500	0.324 ± 0.003
0.3000	0.446 ± 0.007	0.3000	0.436 ± 0.007	0.3000	0.353 ± 0.002	0.3000	0.324 ± 0.002
0.3500	0.449 ± 0.006	0.3500	0.438 ± 0.008	0.3500	0.355 ± 0.003	0.3500	0.326 ± 0.004

[a] Ref 39.

Table 12. Viscosity *B*-Coefficients of Monosaccharides in Aqueous Alanine Solutions at 298.15 K

$\frac{m_A}{\text{mol·kg}^{-1}}$	$\frac{B}{\text{dm}^3\text{·mol}^{-1}}$	$\frac{m_A}{\text{mol·kg}^{-1}}$	$\frac{B}{\text{dm}^3\text{·mol}^{-1}}$	$\frac{m_A}{\text{mol·kg}^{-1}}$	$\frac{B}{\text{dm}^3\text{·mol}^{-1}}$	$\frac{m_A}{\text{mol·kg}^{-1}}$	$\frac{B}{\text{dm}^3\text{·mol}^{-1}}$
Glucose		Galactose		Xylose		Ribose	
0.1000	0.443 ± 0.006	0.1000	0.422 ± 0.005	0.1000	0.347 ± 0.002	0.1000	0.317 ± 0.002
0.1500	0.444 ± 0.007	0.1500	0.426 ± 0.004	0.1500	0.349 ± 0.003	0.1500	0.320 ± 0.002
0.2000	0.445 ± 0.007	0.2000	0.427 ± 0.005	0.2000	0.351 ± 0.002	0.2000	0.322 ± 0.002
0.2500	0.446 ± 0.007	0.2500	0.428 ± 0.003	0.2500	0.353 ± 0.003	0.2500	0.324 ± 0.002
0.3000	0.448 ± 0.006	0.3000	0.430 ± 0.004	0.3000	0.355 ± 0.003	0.3000	0.327 ± 0.003
0.3500	0.448 ± 0.005	0.3500	0.433 ± 0.004	0.3500	0.356 ± 0.003	0.3500	0.329 ± 0.003

that the interaction of *e*-OH with amino acids contributes more positive value to $\Delta_t V^0_{\Phi,S}$ than the *a*-OH group. Therefore, the values of $\Delta_t V^0_{\Phi,S}$ for galactose and ribose are smaller than those for glucose and xylose, respectively. On the other hand, the positive contribution of *e*-OH to $\Delta_t V^0_{\Phi,S}$ is larger than the sum of *a*-OH and *exo*-OH at low molality of amino acids so that there are smaller values for galactose than for xylose at $m_A = 0.13$ mol·kg^{-1} (see Figures 1 and 2). But at high concentration of amino acids ($m_A > 0.13$ mol·kg^{-1}), the *a*-OH and *exo*-OH play an important role and lead to the order of $\Delta_t V^0_{\Phi,S}$ values: galactose > xylose.

McMillan and Mayer[37] proposed a theory of solutions that permits the formal separation of the interactions between two or more solute molecules. According to this treatment, at infinite dilution, $\Delta_t V^0_{\Phi,S}$ can be expressed as[22,23]

$$\Delta_t V^0_{\Phi,S} = 2\nu_{SA} m_A + 3\nu_{SAA} m^2_{AA} + ... \tag{5}$$

where ν_{SA} and ν_{SAA} are pair and triplet interaction parameters, respectively. These parameters were obtained from the fit of experimental data to the equation and given in Tables 7 and 8 together with correlation coefficients. It appears from Tables 7 and 8 that ν_{SAA} lacks precision because of experimental errors. However, this is not too important because we are interested principally in the pair interaction parameter ν_{SA}, which is most important in dilute solutions. The values of ν_{SA} follow the order: glucose > xylose > galactose > ribose, which may be due to the difference in stereo structure of monosaccharides (Table 6). It proves further the conclusion that, at very dilute solutions of amino acids, the contribution of *e*-OH to $\Delta_t V^0_{\Phi,S}$ is predominant over the sum of *a*-OH and *exo*-OH.

(b) Dependence of Volumetric Properties on Different Amino Acids. Transfer volumes for different amino acids depend on their structures. Figures 3 and 4 show roughly that the $\Delta_t V^0_{\Phi,S}$ values for each of four monosaccharides considered decrease overall at given m_A in the same order: glycine > alanine. Glycine is the simplest amino acid in nature. The interactions between glycine and saccharides in water include types (1) and (3), and the former is dominant. This results in positive values of $\Delta_t V^0_{\Phi,S}$. Alanine is regarded as a derivate of glycine whose one hydrogen atom of the α-carbon is replaced by a methyl group. Therefore, the hydrophobility of alanine is stronger than glycine. The interactions between alanine and monosaccharides include types (1), (3), and (4). As a result, the $\Delta_t V^0_{\Phi,S}$ values for monosaccharides from water to alanine + water are more negative than to glycine + water, as reported in the literature.[34e]

Viscosity B-Coefficient. The experimental viscosity data for the systems studied are collected in Tables 9 and 10. The relative viscosity η_r can be analyzed using the Jones−Dole equation:[38]

$$\eta_r = \eta/\eta_0 = 1 + Bc + Dc^2 \tag{6}$$

where η is the viscosity of the ternary solutions, η_0 is the viscosity of the binary solvents (amino acid + water), c (mol·dm^{-3}) is the molarity of monosaccharides, and B and D are empirical coefficients known as the viscosity *B*- and *D*-coefficients. Equation 6 can be rearranged as

$$(\eta_r - 1)/c = B + Dc \tag{7}$$

Values of B and D were obtained from a linear plot of left-hand side of eq 7 versus c. The *B*-coefficients are collected in Tables 11 and 12. Recent literature data[39] for glucose in water are also represented in these tables. The *B*-coefficients measure the size and shape effects as well as the structural effect induced by solute−solvent interactions,[40] whereas *D*-coefficients reflect solute−solute interactions as well as solute−solvent interactions. Therefore, *D*-coefficients are too complex to analyze especially in the presence of amino acid and are not considered here.

It can be seen from Tables 11 and 12 that all the viscosity *B*-coefficients for monosaccharides are positive and that they decrease both in water and in aqueous amino acid solutions in the order: glucose > galactose > xylose > ribose. Glucose and galactose have similar size and shape, similarly for xylose and ribose; consequently, this order of viscosity *B*-coefficients may be explained in terms of the solute−solvent interactions. Glucose or xylose interacts with amino acids stronger than galactose or ribose. It can be concluded that the *e*-OH interacts with amino acids stronger than *a*-OH. The stronger interaction offers the larger resistance to the movement of solute particles (monosaccharides). Therefore, there is the order: *B*(glucose) > *B*(galactose), *B*(xylose) > *B*(ribose). Similarly, we can explain why the viscosity *B*-coefficients increases with increasing the amino acids content in the ternary system. In addition, hexose has larger volume than pentose, and the size effect of solute molecules results in larger viscosity *B*-coefficients of hexose than pentose. On the other hand, the *B*-coefficient values for monosaccharides in aqueous amino acids are larger than in water, indicating that the presence of amino acids strengthens the structure of the solution.

Literature Cited

(1) Rademacher, T. W.; Parekh, R. B.; Dwek, R. A. Glycobiology. *Annu. Rev. Biochem.* **1988**, *57*, 785−838.

(2) Franks, F.; Grigera, J. R. In *Water Science Reviews*; Franks, F., Ed.; Cambridge University Press: Cambridge, 1990; Vol. 5, p 187.

(3) Mitchell, J. R. In *Polysaccharides in Foods*; Blanshard, J. M. V., Mitchel, J. R., Eds.; Butterworth: London, 1979; p 187.

(4) Fahy, G. M.; Levy, D. I.; Ali, S. E. Some emerging principles underlying the physical properties, biological actions, and utility of vitrification solutions. *Cryobiology* **1987**, *24*, 196−213.

(5) Metzler, D. E. *Biochemi. The Chemical Reactions of Living Cells*; Academic Press: New York, 1977; Vol. 1.

(6) Newcomer, M. E.; Lewis, B. A.; Quiocho, F. A. The radius of gyration of L-arabinose-binding protein decreases upon binding of ligand. *J. Biol. Chem.* **1981**, *254*, 3218−3222.

(7) Quiocho, F. A.; Vyas, N. K. Novel stereospecificity of the L-arabinose-binding protein. *Nature (London)* **1984**, *310*, 381−386.

(8) Bundle, D. B. Antibody combining sites and oligosaccharide determinants studies by competitive binding, sequencing and X-ray crystallography. *Pure Appl. Chem.* **1989**, *61*, 1171−1180.

(9) Quiocho, F. A. Protein−carbohydrate interactions: basic molecular features. *Pure Appl. Chem.* **1989**, *61*, 1293−1306.

(10) Johnson, M. A.; Rotondo, A.; Pinto, B. M. NMR studies of the antibody-bound conformation of a carbohydrate-mimetic peptide. *Biochemistry* **2002**, *41*, 2149−2157.

(11) Bock, K. The preferred conformation of oligosaccharides in solution inferred from high-resolution NMR data and hard sphere exo-anomeric calculations. *Pure Appl. Chem.* **1983**, *55*, 605−622.

(12) Thogersen, H.; Lemieux, R. U.; Bock, K.; Meyer, B. Further justification for the exo-anomeric effect. Conformational analysis based on nuclear magnetic resonance spectroscopy of oligosaccharides. *Can. J. Chem.* **1982**, *60*, 44−57.

(13) Bock, K.; Breimer, M. E.; Brignole, A.; Hansson, G. C.; Karlsson, K. A.; Larson, G.; Leffler, H.; Samuelsson, B. E.; Stromberg, N.; Eden, C. S.; Thurin, J. Specificity of binding of a strain of uropathogenic *Escherichia coli* to Gal-α1−4-Gal-containing glycosphingolipids. *J. Biol. Chem.* **1985**, *260*, 8545−8551.

(14) Karlsson, K. A. Site-directed processing of N-linked oligosaccharides: the role of three-dimensional structure. *Pure Appl. Chem.* **1987**, *59*, 1465−1476.

(15) Osawa, T.; Tsuji, T. Fractionation and structural assessment of oligosaccharides and glycopeptides by use of immobilized lectins. *Annu. Rev. Biochem.* **1987**, *56*, 21−42.

(16) Miller, D. M.; Olson, J. S.; Pflugrath, J. W.; Quiocho, F. A. Rates of ligand-binding to periplasmic proteins involved in bacterial transport and chemotaxis. *J. Biol. Chem.* **1983**, *258*, 3665−3672.

(17) Miller, D. M.; Olson, J. S.; Quiocho, F. A. The mechanism of sugar binding to the periplasmic receptor for galactose chemotaxis and transport in *Escherichia coli*. *J. Biol. Chem.* **1980**, *255*, 2465−2471.

(18) Gabius, H. J. Biological information transfer beyond the genetic code: the sugar code. *Naturwissenschaften* **2000**, *87*, 108−121.

(19) Hindley, M. L.; Lee, K. C.; Davis, J. T. The peptide can influence sugar conformation in small Asn glycopeptides. *J. Carbohydr. Chem.* **2005**, *24*, 261−273.

(20) Sears, P.; Wong, C. H. Carbohydrate mimetics: a new strategy for tacking the problem of carbohydrate-mediated biological recognition. *Angew. Chem., Int. Ed. Engl.* **1999**, *38*, 2301−2324.

(21) Zhuo, K. L.; Wang, J. J.; Yue, Y. K.; Wang, H. Q. Volumetric properties for the monosaccharide (D-xylose, D-arabinose, D-glucose, D-galactose)−NaCl−water systems at 298.15 K. *Carbohydr. Res.* **2000**, *328*, 383−391.

(22) Zhuo, K. L.; Wang, J. J.; Wang, H. Q.; Yue, Y. K. Densities, apparent molar volumes, and interaction parameters for the monosaccharide (D-xylose, D-arabinose, D-glucose, D-galactose)−NaBr−water systems at 298.15 K. *Z. Phys. Chem.* **2001**, *215*, 561−573.

(23) Zhuo, K. L.; Wang, J. J.; Zheng, H. H.; Xuan, X. P.; Zhao, Y. Volumetric parameters of interaction of monosaccharides (D-xylose, D-arabinose, D-glucose, D-galactose) with NaI in water at 298.15 K. *J. Solution Chem.* **2005**, *34*, 155−170.

(24) Zhuo, K. L.; Wang, J. J.; Wang, H. Q. Activity coefficients for NaCl−monosaccharide (D-glucose, D-galactose, D-xylose, D-arabinose)−water systems at 298.15 K. *Carbohydr. Res.* **2000**, *325*, 46−55.

(25) Zhuo, K. L.; Wang, J. J.; Zhou, J. G.; Lu, J. S. Thermodynamics of the interaction of HCl with D-glucose in water at 278.15−318.15 K. *J. Phys. Chem. B* **1997**, *101*, 3447−3451.

(26) Zhuo, K. L.; Wang, J. J.; Cao, Y. L.; Lu, J. S. Thermodynamics of the interaction of HCl with D-fructose in water at 278.15−318.15 K. *J. Phys. Chem. B* **1998**, *102*, 3574−3577.

(27) Wang, J. J.; Zhuo, K. L.; Zhang, Q. F.; Yan, Z. N.; Wang, H. Q. Thermodynamics of the interaction of HCl with D-galactose in water at 278.15−318.15 K. *J. Chem. Soc., Faraday Trans.* **1998**, *94*, 3359−3363.

(28) Kell, G. S. Precise representation of volume properties of water at one atmosphere. *J. Chem. Eng. Data* **1967**, *12*, 66−69.

(29) James, C. J.; Mulcahy, D. E.; Steel, B. J. Viscometer calibration standards: viscosities of water between 0 and 60 °C and of selected aqueous sucrose solutions at 25 °C from measurements with a flared capillary viscometer. *J. Phys. D: Appl. Phys.* **1984**, *17*, 225−230.

(30) Yan, Z. N.; Wang, J. J.; Lu, J. S. Viscosity behavior of some α-amino acids and their groups in water−sodium acetate mixtures. *Biophys. Chem.* **2002**, *99*, 199−207.

(31) Visser, C. D.; Perron, G.; Desnoyers, J. E. Volumes and heat capacities of ternary aqueous systems at 25 °C. Mixtures of urea, *tert*-butyl alcohol, dimethylformamide, and water. *J. Am. Chem. Soc.* **1977**, *99*, 5894−5900.

(32) Hedwig, G. R. Thermodynamics properties of peptide solutions. 3. Partial molar volumes and partial molar heat-capacities of some tripeptides in aqueous-solution. *J. Solution Chem.* **1988**, *17*, 383−397.

(33) Zielenkiewicz, W.; Perlovich, G. L.; Nikitina, G. E.; Semeykin, A. S. Volumetric properties of tetraphenylporphine, their metallo-complexes and some substituted tetraphenylporphines in benzene solution. *J. Solution Chem.* **1996**, *25*, 135−153.

(34) (a) Jasra, R. V.; Ahluwalia, J. C. Enthalpies and heat-capacities of dissolution, apparent molar heat-capacities, and apparent molar volumes of some mono-saccharides, di-saccharides, tri-saccharides, and tetra-saccharides in water. *J. Chem. Thermodyn.* **1984**, *16*, 583−590. (b) Hoiland, H.; Holvik, H. Partial molar volumes and compressibilities of carbohydrates in water. *J. Solution Chem.* **1978**, *7*, 587−596. (c) Jasra, R. V.; Ahluwalia, J. C. Enthalpies of solution, partial molar heat-capacities and apparent molar volumes of sugars and polyols in water. *J. Solution Chem.* **1982**, *11*, 325−338. (d) Banipal, P. K.; Banipal T. S.; Ahluwalia, J. C.; Lark, B. S. Partial molar heat capacities and volumes of transfer of some saccharides from water to aqueous sodium chloride solutions at T =298.15 K. *J. Chem. Thermodyn.* **2002**, *34*, 1825−1846. (e) Li, S. Q.; Sang, W. Q.; Lin, R. S. Partial molar volumes of glycine, L-alanine, and L-serine in aqueous glucose solutions at T = 298.15 K. *J. Chem. Thermodyn.* **2002**, *34*, 1761−1768. (f) Wadi, R. K.; Ramasami, P. Partial molar volumes and adiabatic compressibilities of transfer of glycine and DL-alanine from water to aqueous sodium sulfate at 288.15, 298.15 and 308.15 K. *J. Chem. Soc., Faraday Trans.* **1997**, *93*, 243−247. (g) Banipal, T. S.; Kaur, D.; Banipal, P. K. Apparent molar volumes and viscosities of some amino acids in aqueous sodium acetate solutions at 298.15 K. *J. Chem. Eng. Data* **2004**, *49*, 1236−1246.

(35) Friedman, H. L.; Krishnan, C. V. In *Water: A Comprehensive Treatise*; Franks, F., Ed.; Plenum: New York, 1973; Vol. 3, Chapter 1.

(36) Suggett, A. In *Water: A Comprehensive Treatise*; Franks, F., Ed.; Plenum: New York, 1975; Vol. 4, pp 519−567.

(37) McMillian, W. G.; Mayer, J. The statistical thermodynamics of multicomponent systems. *J. Chem. Phys.* **1945**, *13*, 276−305.

(38) Jones, G.; Dole, M. The viscosity of aqueous solutions of strong electrolytes with special reference of barium chloride. *J. Am. Chem. Soc.* **1929**, *51*, 2950−2964.

(39) Miyajima, K.; Sawada, M.; Nakagaki, M. Studies on aqueous of saccharides. II. Viscosity *B*-coefficients of D-glucose, maltose, and maltotriose in aqueous solutions. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 1954−1957.

(40) Stokes, R. H.; Milles, R. *International Encyclopedia of Physical Chemistry and Chemical Physics*; Pergamon: New York, 1965.

Received for review October 6, 2005. Accepted February 28, 2006. This work was supported by grants from the Outstanding Youth Science Foundation of Henan Province (Grant 0112000500), the Innovator Foundation of Colleges and Universities of Henan Province.

JE050412T