Volumetric and Conductometric Behavior at $T = 298.15$ K of 2-[(2-Aminoacetyl)amino]acetic Acid, 2-[(2-Aminoacetyl)amino]-3-methylbutanoic Acid, and (2*S*)-2-[(2-Aminoacetyl)amino]-4-methylpentanoic Acid with Sodium Hexanoate

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Densities and conductivity data for aqueous solutions of 2-[(2-aminoacetyl)amino]acetic acid (commonly known as glycylglycine), 2-[(2-aminoacetyl)amino]-3-methylbutanoic acid (common name glycyl-L-valine), and (2*S*)-2-[(2-aminoacetyl)amino]-4-methylpentanoic acid (commonly known as glycyl-L-leucine) with sodium hexanoate (commonly known as sodium caproate) were determined at $T = 298.15$ K. The apparent molar volumes of the dipeptides ($V_{2,\phi}$) and limiting molar conductivity of sodium caproate (Λ_o) have been derived. The standard partial molar volumes $V^o_{2,\phi}$ obtained from $V_{2,\phi}$ have been used to calculate the standard partial molar volumes of transfer, $\Delta_t V^o$, for glycyl dipeptides from water to aqueous sodium caproate solutions. The hydration numbers, n_H, and volumetric interaction coefficients have also been calculated. The dependence of above thermodynamic functions on concentration and nature of solute has been discussed in terms of various interactions taking place between hydrophobic and hydrophilic parts of peptides and sodium caproate. The decrease in Λ_o values of sodium caproate with an increase in dipeptide concentration is attributed to the interaction of sodium caproate with the dipeptides and increasing viscosity of solvent. The limiting ionic molar conductivities and the Stokes' radii of Na^+ and the caproate anion were also estimated and discussed.

Introduction

Most biochemical processes occur in aqueous solutions, so the studies on the thermodynamic properties of biological molecules in aqueous solutions are important. The behavior of biomolecules such as proteins, peptides, and amino acids in mixtures is governed by many factors such as pH, chemical structure, surface charge distribution, solvent properties, and electrolyte type as well as concentration. The influence of electrolytes on the behavior of proteins, peptides, and amino acids is one of the most important topics in the physical chemistry of the substances.

In a previous study,[1] it has been shown that if the large-size anions were introduced into the solution, the protein acquires the "A" state, which has been proposed as an important intermediate form, and could be a key step in understanding the protein folding problem. Sodium carboxylate containing the large-size anions is known to influence the dissociation of proteins in solutions.[2] Some workers[3−7] and our group[8−12] have investigated the effect of sodium acetate, magnesium acetate, calcium acetate, sodium butyrate, and sodium caproate on the physicochemical properties of amino acids. However, few studies[3,13,14] on the thermodynamic properties of the peptides have been carried out in aqueous sodium carboxylate solutions. The peptides are important molecules because of their wide application in drug production and their role as signal transmitters in cell communications.[15] Systematic study of peptides can provide valuable information about their behavior in solutions. Furthermore, peptides contain more complex structure and more components of proteins, and the studies with peptides as solutes also assist in the interpretation of the thermodynamics of more complex biological molecules, such as proteins. In recent years there have been some investigations on thermodynamic properties of some peptides in aqueous solutions[16−21] and aqueous simple salt solutions.[22−29] However, there are only few studies about properties of peptides in aqueous organic salt solutions,[3,13,14,30−32] probably due to the complex nature of their interactions.

Therefore, in view of the above and in continuation of our work on the physicochemical properties of peptides, in the present paper, we report measurements of density and conductivity for aqueous solutions of 2-[(2-aminoacetyl)amino]acetic acid (commonly known as glycylglycine), 2-[(2-aminoacetyl)amino]-3-methylbutanoic acid (common name glycyl-L-valine), and (2*S*)-2-[(2-aminoacetyl)amino]-4-methylpentanoic acid (commonly known as glycyl-L-leucine) with sodium hexanoate (commonly known as sodium caproate) at $T = 298.15$ K. The apparent molar volumes of the dipeptides ($V_{2,\phi}$) and limiting molar conductivity of sodium caproate (Λ_o) have been derived. The standard partial molar volume, $V^o_{2,\phi}$, the standard partial molar volumes of transfer, $\Delta_t V^o$, the hydration numbers, n_H, volumetric interaction coefficients of dipeptides, and limiting molar conductivity of sodium caproate have been calculated. These parameters have been discussed in terms of various interactions taking place between dipeptides and sodium caproate.

Experimental Section

Chemicals. 2-[(2-Aminoacetyl)amino]acetic acid (commonly known as glycylglycine with CAS # 556-50-3) was supplied

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by Sigma with a mass fraction purity of 0.99, 2-[(2-aminoacetyl)-amino]-3-methylbutanoic acid (with CAS # 1963-21-9 and common name glycyl-L-valine) also supplied by Sigma with mass fraction purity of 0.99, and (2*S*)-2-[(2-aminoacetyl)amino]-4-methylpentanoic acid (commonly known as glycyl-L-leucine with CAS # 869-19-2) also supplied by Sigma with mass fraction purity of 0.99. Each sample was recrystallized twice from aqueous ethanol solutions and dried for 24 h under vacuum at room temperature. They were stored over P_2O_5 in a desiccator before use. Analytical reagent grade sodium caproate (mass fraction purity > 0.99, Shanghai Chemical Co.) was twice recrystallized from aqueous ethanol and dried under vacuum at $T = 383$ K for 48 h before use. Potassium chloride (mass fraction purity of 0.99999 was supplied by Aldrich Chemical Co.) that was dried for 48 h at $T = 373$ K was used to determine the conductance cell constant. Water with a conductivity of < $1.0 \cdot 10^{-4}$ S·m^{-1} was obtained by distilling deionized water from alkaline $KMnO_4$ to remove any organic matter. In densimetry, all of the solutions were prepared gravimetrically with a Shimadzu AY 120 balance with an uncertainty of ± 0.1 mg. The uncertainty in molality was ± 0.0002 mol·kg^{-1}. In conductometric experiments, all of the mass determinations were done on a Satorius BP 211D digital balance having an uncertainty of ± 0.01 mg and the molalities calculated found to be uncertain to ± 0.00001 mol·kg^{-1}.

Apparatus and Procedures. Solution densities were measured with an Anton Paar DMA 60/602 vibrating-tube digital densimeter at $T = 298.15$ K. The temperature of the densimeter cell was maintained using Schott thermostat units, which have a thermal stability of ± 0.005 K. The vibrational period of the densimeter tube containing the solution of interest was measured three times each, and the average value used to determine the density. The reproducibility of the density measurements was on average ± $3 \cdot 10^{-6}$ g·cm^{-3}. The calibration of the densimeter was performed every day with dry air and water with a conductivity less than $1.0 \cdot 10^{-4}$ S·m^{-1}. The accuracy was checked by measuring the densities of aqueous sodium chloride, and the results were found to be in excellent agreement with the literature values.[33]

Specific conductivity of the (sodium caproate + dipeptide + water) was measured as a function of the sodium caproate concentration using a conductivity meter (Model 145A+, Thermo Orion) with precision of ± 0.5 %. The concentration of the sample solution was successively increased by a stepwise addition of (0.10 or 0.20) cm^3 of the concentrated ternary solution to 20.0 cm^3 of aqueous dipeptide solution, being initially placed in a cell for conductivity measurements. After each addition, the solution was stirred to ensure the homogeneous mixing and then was subjected to the conductivity measurement. The conductance cell was equipped with a water circulating jacket, and the temperature was controlled within ± 0.02 K with a low temperature thermostat (Model DC-2006, Shanghai Hengping Instrument Factory). The cell constant is 1.092 cm^{-1}, which was calculated by repeated measurements of KCl solutions. All data were corrected to a temperature of 298.15 K with a specific conductivity of the solvent.

Results and Discussion

The apparent molar volumes, $V_{2,\phi}$ (cm^3·mol^{-1}), of the glycyl dipeptides in (0.5, 1.0, 1.5, and 2.0) mol·kg^{-1} aqueous sodium caproate solutions were calculated from the measured density data using the following equation

$$V_{2,\phi} = M/\rho - 10^3(\rho - \rho_o)/m_p\rho\rho_o \quad (1)$$

where M is the molar mass of the glycyl dipeptides, m_p is the molality of the glycyl dipeptides in sodium caproate−water mixtures, ρ and ρ_o are the densities of the ternary system and solvent (aqueous sodium caproate solution), respectively. The uncertainty in $V_{2,\phi}$ resulting from various experimentally measured quantities has been calculated. It comes out to be in the range from 0.146 cm^3·mol^{-1} to 0.010 cm^3·mol^{-1} for the lower (≤ 0.02 mol·kg^{-1}) and higher concentration range in aqueous NaC_6 solutions for the studied dipeptides, respectively. The results of the density measurements at $T = 298.15$ K are given in Table 1 as a function of the molality of the glycyl dipeptides (m_p) and sodium caproate (m_{NaC_6}). Calculated apparent molar volumes for glycyl dipeptides are also listed in Table 1. The results can be fitted by the equation

$$V_{2,\phi} = V^o_{2,\phi} + S_v m_p \quad (2)$$

where $V^o_{2,\phi}$ is the infinite dilution apparent molar volume that equals the standard partial molar volume and S_v is an experimentally determined parameter. Values of $V^o_{2,\phi}$ have been evaluated by weighted least-squares regression analysis.[16] The standard partial molar volumes for the glycyl dipeptides in aqueous solutions of sodium caproate are presented in Table 2 along with their standard deviations.

The $V^o_{2,\phi}$ values, which are, in all cases, positive in aqueous sodium caproate at all of the molalities, show an increase with increasing molality of NaC_6. Further the $V^o_{2,\phi}$ values increase from glycylglycine to glycylvaline to glycylleucine. This phenomenon is plausibly due to the increase in the size of alkyl side chain of amino acids constituting the peptides, leading to a decrease of the hydrogen bonding behavior of these compounds because of the increasing hydrophobic character of the alkyl side chain.

The standard partial molar volumes of transfer for the glycyl dipeptides from water to aqueous solutions of sodium caproate were calculated by

$$\Delta_t V^o = V^o_{2,\phi}(\text{in aqueous } NaC_6) - V^o_{2,\phi}(\text{in water}) \quad (3)$$

where $V_{2,\phi}{}^o$(in water) is the standard partial molar volume for glycyl dipeptides in water and is taken from our earlier publication.[13] The results are presented in Table 3. As seen from Table 3, $\Delta_t V^o$ values of dipeptides from water to aqueous sodium caproate solutions are positive and increase with increasing concentration of NaC_6. The cosphere overlap model[34] can be utilized to rationalize this phenomenon in terms of solute−cosolute interactions. The hydration shell's overlap of cosolute ions and dipeptides probably comes into play because of the following interactions: (a) ($-NH_3^+$, COO^-) charged ends of dipeptides and ions of the cosolute (NaC_6), (b) peptide backbone unit ($-CH_2CONH$) of dipeptides and ions of cosolute, (c) the hydrophobic parts of the glycyl dipeptides and cosolute ions, and the charged ends/hydrophilic parts of dipeptides and the hydrophobic parts of the cosolute, and (d) the hydrophobic parts of the dipeptides and hydrophobic parts of cosolute. Ion−ion and ion−peptide backbone unit interactions result in positive $\Delta_t V^o$ values, whereas ion−hydrophobic and hydrophobic−hydrophobic group interactions result in negative $\Delta_t V^o$ values according to the cosphere model.[34] The presently observed positive $\Delta_t V^o$ values for dipeptides suggest that ion−ion interactions and ion−peptide group interactions are stronger than ion−nonpolar and hydrophobic−hydrophobic group interactions.

Table 1. Solution Densities, ρ, and Apparent Molar Volumes, $V_{2,\phi}$, for the Glycyl Dipeptides in Aqueous Sodium Caproate Solutions as a Function of the Molality of the Glycyl Dipeptides (m_p) and Sodium Caproate (m_{NaC_6}) at $T = 298.15$ K

$m_{NaC_6} = 0.5$ mol·kg^{-1}			$m_{NaC_6} = 1.0$ mol·kg^{-1}			$m_{NaC_6} = 1.5$ mol·kg^{-1}			$m_{NaC_6} = 2.0$ mol·kg^{-1}		
m_p	ρ	$V_{2,\phi}$	m_p	ρ	$V_{2,\phi}$	m_p	ρ	$V_{2,\phi}$	m_p	ρ	$V_{2,\phi}$
mol·kg^{-1}	g·cm^{-3}	cm^3·mol^{-1}	mol·kg^{-1}	g·cm^{-3}	cm^3·mol^{-1}	mol·kg^{-1}	g·cm^{-3}	cm^3·mol^{-1}	mol·kg^{-1}	g·cm^{-3}	cm^3·mol^{-1}
Glycylglycine											
0.0000	1.014429		0.0000	1.028531		0.0000	1.040025		0.0000	1.049202	
0.04141	1.016530	80.76	0.04092	1.030538	81.93	0.03899	1.041842	83.81	0.03889	1.050952	84.91
0.06155	1.017544	80.82	0.06071	1.031506	81.89	0.05992	1.042824	83.62	0.06063	1.051909	85.15
0.08219	1.018590	80.71	0.08319	1.032601	81.88	0.07883	1.043717	83.44	0.08379	1.052941	85.08
0.1009	1.019523	80.78	0.09906	1.033385	81.75	0.09953	1.044665	83.56	0.1029	1.053786	85.08
0.1464	1.021792	80.78	0.1517	1.035941	81.69	0.1508	1.047062	83.33	0.1533	1.056020	84.97
0.1976	1.024298	80.92	0.2017	1.038341	81.70	0.1969	1.049171	83.36	0.2000	1.058072	84.92
0.2428	1.026514	80.91	0.2524	1.040769	81.65	0.2393	1.051100	83.36	0.2480	1.060168	84.87
0.2961	1.029125	80.84	0.3063	1.043326	81.62	0.3016	1.053978	83.15	0.3051	1.062663	84.76
Glycyl-L-valine											
0.0000	1.014429		0.0000	1.028531		0.0000	1.040891		0.0000	1.049279	
0.01988	1.015376	125.36	0.04080	1.030356	126.86	0.02833	1.041967	132.16	0.02453	1.050180	132.54
0.04056	1.016344	125.65	0.06263	1.03133	126.77	0.04272	1.042530	131.74	0.04156	1.050806	132.45
0.05927	1.017211	125.80	0.08307	1.032239	126.72	0.06114	1.043254	131.38	0.06047	1.051518	132.11
0.08230	1.018274	125.88	0.1032	1.033133	126.65	0.07755	1.043902	131.14	0.08243	1.052339	131.92
0.1007	1.019086	126.24	0.1501	1.035186	126.64	0.09458	1.044571	130.98	0.1025	1.053078	131.88
0.1422	1.020967	126.27	0.1967	1.037216	126.56	0.1115	1.045235	130.86	0.1514	1.054871	131.77
0.2035	1.023691	126.38	0.2460	1.039346	126.48	0.1619	1.047211	130.54	0.2008	1.056676	131.63
						0.2275	1.049735	130.37			
Glycyl-L-leucine											
0.0000	1.014429		0.0000	1.028343		0.0000	1.040110		0.0000	1.050351	
0.02086	1.015344	142.82	0.01908	1.029120	144.41	0.04128	1.041547	148.59	0.03903	1.051412	154.41
0.03981	1.016168	142.86	0.04164	1.030036	144.36	0.06051	1.042211	148.58	0.05443	1.051855	153.94
0.06061	1.017073	142.79	0.06078	1.030814	144.25	0.08158	1.042936	148.55	0.06743	1.052234	153.62
0.08223	1.017997	142.88	0.07937	1.031568	144.17	0.1013	1.043594	148.68	0.08100	1.052645	153.20
0.1019	1.018835	142.91	0.09961	1.032383	144.12	0.1190	1.044201	148.61	0.1135	1.053593	152.85
0.1231	1.019731	142.95	0.1225	1.033300	144.08	0.1468	1.045121	148.70	0.1435	1.054483	152.51
0.1513	1.020911	143.01	0.1480	1.034333	143.93				0.1935	1.055958	152.13

Table 2. Standard Partial Molar Volumes, $V^o_{2,\phi}$, for the Glycyl Dipeptides in Aqueous Sodium Caproate Solutions at $T = 298.15$ K

	$V^o_{2,\phi}$/cm^3·mol^{-1}			
m_{NaC_6}	0.5 mol·kg^{-1}	1.0 mol·kg^{-1}	1.5 mol·kg^{-1}	2.0 mol·kg^{-1}
glycylglycine	80.74 ± 0.04	81.94 ± 0.03	83.73 ± 0.07	85.22 ± 0.01
glycylvaline	125.44 ± 0.11	126.88 ± 0.03	131.98 ± 0.17	132.52 ± 0.11
glycylleucine	142.77 ± 0.02	144.48 ± 0.02	148.52 ± 0.05	154.64 ± 0.20

Table 3. Standard Partial Molar Volumes of Transfer, $\Delta_t V^o$, for the Glycyl Dipeptides from Water to Aqueous Sodium Caproate Solutions at $T = 298.15$ K

	$\Delta_t V^o$/cm^3·mol^{-1}			
m_{NaC_6}	0.5 mol·kg^{-1}	1.0 mol·kg^{-1}	1.5 mol·kg^{-1}	2.0 mol·kg^{-1}
glycylglycine	4.45 ± 0.08	5.68 ± 0.07	7.44 ± 0.10	8.93 ± 0.07
glycylvaline	3.19 ± 0.12	4.63 ± 0.06	9.73 ± 0.18	10.27 ± 0.12
glycylleucine	3.08 ± 0.10	4.79 ± 0.10	8.83 ± 0.11	14.95 ± 0.22

The standard partial molar volumes of the dipeptides were used to determine the hydration number of dipeptides using the method described below. The values of $V^o_{2,\phi}$ for the dipeptides can be expressed by[35]

$$V^\circ_{2,\phi} = V^\circ_{2,\phi}(\text{elect}) + V^\circ_{2,\phi}(\text{int}) \quad (4)$$

where $V^o_{2,\phi}$(int) is the intrinsic partial molar volume of the dipeptides and $V^o_{2,\phi}$(elect) is the electrostriction partial molar volume due to the hydration of the dipeptides. The $V^o_{2,\phi}$(int) term can be further divided into two terms: the van der Waals volume and the volume due to packing effects. The values of $V^o_{2,\phi}$(int) for the glycyl dipeptides were calculated from the crystal molar volumes as below[36]

$$V^\circ_{2,\phi}(\text{int}) = (0.7/0.634)\, M/\rho_r \quad (5)$$

where ρ_r is the crystal density of the glycyl dipeptide. The values of crystal densities of glycylglycine, glycyl-L-valine, and glycyl-L-leucine determined by single-crystal X-ray diffraction are (1.534, 1.251, and 1.176) g·cm^{-3}, respectively. The values of $V^o_{2,\phi}$(elect) were obtained from the experimentally measured $V^o_{2,\phi}$ values using eq 4. Further, the decrease in the volume due to electrostriction can be related[36] to the hydration number n_H of the dipeptides.

Table 4. Values of Hydration Number, n_H, for the Glycyl Dipeptides in Aqueous Sodium Caproate Solutions at $T = 298.15$ K

	n_H			
NaC_6	0.5 mol·kg^{-1}	1.0 mol·kg^{-1}	1.5 mol·kg^{-1}	2.0 mol·kg^{-1}
		Water + NaC_6		
glycylglycine	4.3	4.0	3.4	3.0
glycylvaline	8.5	8.1	6.6	6.4
glycylleucine	10.1	9.6	8.4	6.5
		Water + NaC_4[a]		
glycylglycine	4.8	4.3	3.8	3.4
glycylvaline	8.7	8.6	7.9	7.6
glycylleucine	10.5	10.1	9.8	9.5
		Water + NaC_2[b]		
glycylglycine	4.9	4.4	3.9	3.7
glycylvaline	8.8	8.6	7.9	7.7
glycylleucine	10.6	10.2	9.9	9.6

[a] Ref 37. [b] Ref 13.

Table 5. Pair, V_{xy}, and Triplet, V_{xyy}, Interaction Coefficients for Glycyl Dipeptides in Aqueous Sodium Caproate Solution at $T = 298.15$ K

	V_{xy}	V_{xyy}
peptide	m^3·mol^{-2}·kg	m^3·mol^{-3}·kg^2
glycylglycine	3.9386 ± 0.6121	−0.5908 ± 0.2376
glycylvaline	3.1014 ± 0.9927	−0.1376 ± 0.3853
glycylleucine	1.5118 ± 0.6748	0.7146 ± 0.2619

$$n_H = V^o_{2,\phi}(\text{elect})/(V^o_e - V^o_b) \quad (6)$$

where V^o_e is the molar volume of electrostricted water and V^o_b is the molar volume of bulk water. The value of $(V^o_e - V^o_b)$ is calculated to be -3.3 cm^3·mol^{-1} at $T = 298.15$ K.[36] The obtained hydration numbers have been given in Table 4. It can be seen that the calculated n_H values of the dipeptides in aqueous NaC_6 are observed to vary in the following order:

$$n_H(\text{glycylleucine}) > n_H(\text{glycylvaline}) > n_H(\text{glycylglycine})$$

This trend is maintained in all molalities of NaC_6 studied. With increase in the molality of NaC_6, the n_H value has a decreasing trend which is more in the case of glycylleucine. This is attributable to stronger interaction of glycylleucine with NaC_6 leading to a reduction in the electrostriction and hence the observed values of hydration numbers. We have made a comprehensive comparison of the hydration number of the dipeptides studied in a variety of sodium carboxylate systems. It is found from Table 4 that n_H values in aqueous NaC_6 are smaller than those in aqueous sodium acetate (NaC_2)[13] and in aqueous sodium butyrate (NaC_4)[37] solutions. Because the interaction of the Na^+ for different sodium carboxylates with given dipeptides is the same, it can be deduced that the decreased n_H value comes from the difference in the interactions of carboxylate ion with NH_3^+ group, peptide group, and side chain of the dipeptides. Since the studied glycyl dipeptides have shorter alkyl side chain, hydration shells of the charged ends and peptide group overlap that of the side chains of dipeptides.[38] The carboxylate anions of sodium carboxylate interact mainly with the charged groups and peptide groups. The caproate anion has a bigger hydrophobic hydration sphere and larger destructive effect on the hydration sphere of charged groups and peptide groups than acetate and butyrate anions. The electrostriction of water caused by these polar groups of dipeptides will be largely reduced, which results in a decrease in n_H values. This indicates

Table 6. Molar Conductivity of Sodium Caproate in Aqueous Peptide Solution at $T = 298.15$ K

$m_p = 0.05$ mol·kg^{-1}		$m_p = 0.1$ mol·kg^{-1}		$m_p = 0.15$ mol·kg^{-1}		$m_p = 0.2$ mol·kg^{-1}	
c / mol·m^{-3}	$10^4\Lambda$ / S·m^2·mol^{-1}	c / mol·m^{-3}	$10^4\Lambda$ / S·m^2·mol^{-1}	c / mol·m^{-3}	$10^4\Lambda$ / S·m^2·mol^{-1}	c / mol·m^{-3}	$10^4\Lambda$ / S·m^2·mol^{-1}
			Water + Glycylglycine				
3.8330	69.88	5.4939	67.18	3.0233	67.16	2.9728	65.92
5.6763	69.51	6.9879	66.89	4.7817	66.68	4.8111	65.70
7.0188	69.14	8.4299	66.46	6.2529	66.54	6.3298	65.47
8.5412	68.97	9.8646	66.32	7.7742	66.31	7.7571	65.12
9.7920	68.64	11.124	66.08	9.3908	66.06	9.1922	64.94
10.988	68.42	12.433	65.81	11.092	65.78	10.695	64.70
12.342	68.09	13.764	65.48	12.663	65.56	12.118	64.49
13.584	67.90	15.059	65.22	14.097	65.32	13.534	64.29
15.055	67.58	16.432	65.02	15.602	65.05	14.907	64.16
16.346	67.32	17.644	64.89	17.167	64.85	16.172	63.94
17.598	67.07	18.966	64.81	18.684	64.73	17.355	63.74
19.017	66.95	20.251	64.69	19.826	64.53	18.649	63.71
19.886	66.83	21.477	64.51	21.095	64.38	19.932	63.56
21.040	66.59	22.782	64.27	22.322	64.22	21.100	63.41
22.088	66.45	23.598	64.18	23.603	64.02	22.279	63.24
23.264	66.24					23.120	63.16
			Water + Glycylvaline				
2.2481	68.90	2.1502	64.96	2.9898	64.26	3.6689	62.07
3.4877	68.44	3.5547	64.53	4.3304	63.54	5.3372	61.50
4.7079	67.99	4.9836	64.48	5.7731	63.18	6.7894	61.06
6.2500	67.81	6.2410	64.03	7.0433	62.80	8.2286	60.74
7.7164	67.48	7.5818	63.67	8.2917	62.43	9.6813	60.54
9.2602	66.93	8.8778	63.37	9.5720	62.19	11.127	60.23
10.870	66.67	9.9878	63.09	10.708	61.92	12.492	59.95
12.290	66.28	11.193	62.83	11.979	61.64	13.817	59.66
13.714	65.96	12.456	62.64	13.277	61.29	15.025	59.45
15.222	65.68	13.699	62.39	14.434	61.15	16.334	59.16
16.586	65.39	14.925	62.13	15.565	60.92	17.669	58.96
17.963	65.27	16.116	61.95	16.666	60.70	19.019	58.91
19.369	64.98	17.255	61.73	17.774	60.48	20.333	58.65
20.684	64.79	18.343	61.66	18.910	60.43	21.676	58.45
21.872	64.56	19.481	61.53	20.166	60.25	22.956	58.24
23.170	64.33	20.377				24.176	58.06
24.358	64.13					25.383	57.88
			Water + Glycylleucine				
6.6283	65.69	4.1501	64.98	3.9128	62.14	4.1507	59.63
8.1278	65.27	5.7838	64.57	5.4094	61.71	5.7111	59.41
9.5599	64.86	7.4099	64.11	6.8443	61.38	7.1041	58.98
11.011	64.65	9.0126	63.74	8.3258	61.22	8.6190	58.76
12.419	64.27	10.603	63.35	9.7851	60.91	10.163	58.43
13.785	64.00	12.054	62.98	11.179	60.65	11.636	58.08
15.201	63.72	13.442	62.65	12.556	60.35	12.975	57.81
16.571	63.47	14.850	62.38	13.907	60.06	14.448	57.59
17.802	63.19	16.323	62.11	15.461	59.75	15.832	57.32
19.059	62.93	17.770	61.84	16.705	59.56	17.227	57.05
20.310	62.87	19.108	61.63	18.023	59.26	18.407	56.84
21.580	62.61	20.476	61.52	19.381	59.06	19.806	56.63
22.892	62.42	21.779	61.30	20.663	58.94	21.133	56.49
24.101	62.19	23.031	61.06	21.970	58.72	22.630	56.28
25.465	61.95	24.400	60.86	23.166	58.56	23.791	56.10
		25.343	60.71	24.386	58.37	24.951	55.91
				25.600	58.12	25.590	55.79
			Pure Water				
3.5275	72.50	9.0742	70.10	14.591	68.54	19.969	67.48
4.9904	71.54	10.442	69.65	15.935	68.21	21.223	67.22
6.2685	71.13	11.809	69.32	17.307	67.89	22.675	66.90
7.7480	70.48	13.196	68.87	18.662	67.73		

Table 7. Values of Limiting Molar Conductivity Λ_0 for Sodium Caproate in Water and Water−Dipeptide Mixtures at $T = 298.15$ K

m_p / mol·kg^{-1}	$10^4\Lambda_0$ / S·m^2·mol^{-1}
Water	
0.0000	77.16 ± 0.34
	77.45[a]
Water + Glycylglycine	
0.05000	71.74 ± 0.19
0.1000	70.47 ± 0.57
0.1500	68.29 ± 0.12
0.2000	67.22 ± 0.14
Water + Glycylvaline	
0.05000	71.13 ± 0.31
0.1000	70.04 ± 0.62
0.1500	66.67 ± 0.33
0.2000	64.27 ± 0.20
Water + Glycylleucine	
0.05000	69.25 ± 0.32
0.1000	67.98 ± 0.25
0.1500	64.01 ± 0.18
0.2000	61.83 ± 0.17

[a] Ref 41.

Table 8. Values of Limiting Ionic Molar Conductivity λ_0 and Stokes' Radii for Na^+ and Caproate Anion in Water−Dipeptide Mixtures at $T = 298.15$ K

m_p / mol·kg^{-1}	$10^4\lambda_0(Na^+)$ / S·m^2·mol^{-1}	$r_{st}(Na^+)$ / nm	$10^4\lambda_0(C_6^-)$ / S·m^2·mol^{-1}	$r_{st}(C_6^-)$ / nm
Water + Glycylglycine				
0.0500	48.84	0.1846	22.91	0.3935
0.1000	47.89	0.1848	22.58	0.3921
0.1500	46.54	0.1868	21.75	0.3998
0.2000	45.82	0.1864	21.42	0.3990
Water + Glycylvaline				
0.0500	46.26	0. 1937	24.86	0.3605
0.1000	45.72	0. 1901	24.32	0.3575
0.1500	43.54	0. 1938	23.13	0.3649
0.2000	42.29	0.1939	21.97	0.3733
Water + Glycylleucine				
0.0500	47.27	0.1889	21.98	0.4063
0.1000	45.51	0.1896	22.39	0.3852
0.1500	43.82	0.1904	21.19	0.3937
0.2000	42.52	0.1900	19.31	0.4183

that with increasing hydrocarbon chain length of the carboxylate ion, the dehydration effect increases. The same observation has also obtained for α-amino acids in aqueous sodium carboxylate solutions.[12]

Friedman and Kirshnan[39] suggested that the standard thermodynamic properties of transfer can reflect the interaction between solute and solvent. The volume behavior of a solute at infinite dilution is dependent on the solute−solvent interactions and thus determined only by the respective intrinsic value and the solute−solvent interactions. The standard transfer volumes can be expressed as

$$\Delta_t V^\circ = 2V_{xy} m_{NaC_6} + 3V_{xyy} m_{NaC_6}^2 \quad (7)$$

where x stands for peptides and y stands for NaC_6, respectively. The V_{xy} and V_{xyy} are the pair and triplet volumetric interaction coefficients, respectively for the studied peptides. These results are given in Table 5. It can be seen from Table 5 that all pair volumetric interaction parameters V_{xy} are positive and are larger than V_{xyy} values. These values suggest the interactions between studied peptides and NaC_6 are mainly pair interactions. In addition, V_{xy} decreases from glycylglycine to glycylleucine. The decrease in V_{xy} values comes from the difference in the interactions of the alkyl side chains of peptides with NaC_6, as the interaction contribution of types (a) and (b) expressed above are the same for different glycyl dipeptides. This suggests that the alkyl side chains of dipeptides play an important role in modulating the volumes of transfer. Therefore, the dipeptide with a longer hydrophobic alkyl side chain may undergo stronger dehydration effects in the presence of NaC_6. Because of this fact, glycylleucine having longer alkyl chains has smaller values of V_{xy}. The triplet volumetric interaction coefficient of glycylleucine is positive. This indicates that there are triplet interactions between glycylleucine and NaC_6 with the increasing of alkyl side chain length.

The conductance data (Λ) of sodium caproate in aqueous and aqueous dipeptide solutions of (0.05, 0.1, 0.15, and 0.2) mol·kg^{-1} are listed in Table 6. Limiting molar conductivity (Λ_0) of NaC_6 was obtained by least-squares fitting the experimental data in Table 6 to the expression[40]

$$\Lambda = \Lambda_0 - \frac{A\sqrt{c}}{1 + B\sqrt{c}} \quad (8)$$

where Λ_0, A, and B are fitting parameters and c is the molarity of NaC_6 and was obtained by converting from molality with the density. The resulting values are given in Table 7.

Table 7 shows that the Λ_0 value for NaC_6 decreases with an increase of peptide content and is very low as compared with that in water. This can be ascribed to the facts that (i) with the increase in microscopic viscosity of the mixtures, the mobility of ions decreases and (ii) with the increase in peptide content of mixtures, the attraction between the NaC_6 and the peptide increases, and hence some of the water molecules around to the ion are replaced by peptide molecules. It is plausible that the microscopic region around the ion becomes bulkier, resulting in a decrease in ionic mobility and consequently a decrease in Λ_0 in peptide solutions.

To investigate the specific behavior of the individual ions comprising sodium caproate, it is necessary to split the limiting molar conductance into their ionic components. The limiting ionic molar conductance of Na^+, $\lambda_0(Na^+)$, in aqueous dipeptide solutions has been obtained by using the "reference electrolyte" methods.[42] The limiting ionic molar conductance of caproate anion $\lambda_0(C_6^-)$ value was calculated by subtracting the $\lambda_0(Na^+)$ value from $\Lambda_0(NaC_6)$ values. The calculated values of the caproate anion $\lambda_0(C_6^-)$ are recorded in Table 8 along with $\lambda_0(Na^+)$. For a particle of macroscopic dimension moving in a hydrodynamic continuum, it is possible to calculate the dimension of the particle as a function of the ionic molar conductance and viscosity value of the medium. The hydrodynamic radii of the Na^+ and C_6^- can be determined with the Stokes' equation[43]

$$r_{st} = \frac{Z_\pm F^2}{6\pi N_A \lambda_\pm^o \eta} \quad (9)$$

where $Z_\pm$ is the charge number of the ion, F is the Faraday constant, N_A is the Avogadro number, and $\lambda_\pm^\circ$ is the limiting ionic molar conductance. The calculated r_{st} values from eq 9 are included in Table 8. For comparison reasons, the crystallographic radius (r_{cr}) of 0.161 nm for Na^+ was taken from the literature.[44] The r_{cr} of 0.306 nm for C_6^- ion was calculated using the method provided by Bondi.[45] It can be seen from Table 8 that the Stokes' radii are much higher than their crystallographic radii, suggesting that these ions are significantly solvated in peptide−water mixtures.

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