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Ion-Solvent Interaction of Amino Acids. The Role of the "Zwitterionic" and the "Ionic" Forms in the Modification of Water Structure over the Temperature Range 25—45 °C

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Viscosities and densities of aqueous glycine, glycinium chloride, sodium glycinate, betaine, betainium chloride [$(CH_3)_3\overset{+}{N}CH_2COOH \cdot Cl^-$], and tetramethylammonium bromide solutions have been measured at 25, 30, and 40 °C over the concentration range 0.01 to 0.1 M. The sequence of the viscosity B-coefficient values obtained is in the order: $B_{anion} > B_{cation} > B_{zwitterion}$ for the glycine and betaine systems. The comparatively higher structure promoting behavior of the anion has been discussed in terms of the charge delocalization effect. Apparent molal volumes at infinite dilution have also been calculated, and the ratio B/ϕ_v° furnishes important information about the nature of solvation around the ion. The present study indicates that in the betaine molecule, the opposing nature of ion-water interaction at the two charge centers renders the system neither a "structure maker" nor a "breaker" in aqueous solution.

In an earlier communication[1] viscosity studies on amino acids at different pH's in presence of free acids and alkalis, and at different temperatures have been reported. It was found that the viscosity data of amino acids in the acidic and basic solutions used could not be processed properly using the Jones-Dole equation[2]

$$\eta/\eta_0 = 1 + A\sqrt{c} + Bc, \quad (1)$$

as unreasonable negative A coefficient values, together with B-values with large standard deviations, were obtained. Instead, the use of the following equation, generally obeyed by uncharged molecules and neutral (zwitterionic) amino acids,[3] viz.

$$\eta/\eta_0 = 1 + Bc \quad (2)$$

was found to be more satisfactory. The B-coefficient values obtained from the above two equations are of course not the same, and in fact significant differences were observed.[3]

For a dilute solution of spherical particles, the Einstein equation[4] $\eta/\eta_0 = 1 + 2.5\theta$, ($\theta$=solute volume fraction) when combined with Eq. 2 gives the hydrodynamic volume per mole (V_h) of the (solute) particles, which tend to rotate in the fluid streamlines:

$$B = 2.5 V_h \times 10^{-3} \quad (3)$$

For ellipsoidal particles at low concentrations a more general expression for V_h may also be derived:[5]

$$B = k V_h \times 10^{-3} \quad (4)$$

where k is a shape factor, being equal to 2.5 for spherical molecules. Since the apparent molal volume at infinite dilution: ϕ_v° ($=\overline{V}^\circ$) and V_h are approximately equal, the magnitude of the ratio B/ϕ_v° is expected to offer valuable information about the nature of interaction of solute molecules with the solvent.

Both neutral glycine and tetramethylammonium ion are the lowest members in the respective series of compounds, and also are well-known structure breakers[3,6] in aqueous solutions due to the presence of peripheral charge. It is interesting to investigate how these moieties, when conjoined in the form of a single molecule (e.g., in betaine) interact with the solvent water. The study of betaine and its homologues is also important in view of the current interest[7] in the potential utilization of their surfactant properties for tertiary oil recovery. Further, the purpose of the present work is also to investigate the comparative applicability of the Jones-Dole equation (Eq. 1) or Eq. 2, using amino acid salts in water only, instead of in acids or alkalis as done earlier,[1] and also the effects of the "zwitterionic" and the "ionic" form surface charges on the solvent water while either keeping unaltered, or else altering suitably, the size of the solute molecule.

With these objects in view, we have measured the viscosities of solutions of glycine, glycinium chloride, sodium glycinate, tetramethylammonium bromide, betaine, and betainium chloride, at three different temperatures over the range 25—40 °C. For betaine solutions measurements were also made at two other temperatures (35 and 45 °C). The density measurements enable the calculation of the apparent molal volumes directly, which further enables us to study the ion-solvent interactions from the complementary view points of viscosity and apparent molal volume.

Experimental

Glycine used was medicinal grade (E. Merck) and was purified as described earlier.[1] Sodium glycinate and glycinium chloride were prepared by mixing equivalent amounts of glycine and the corresponding alkali or acid as required. Betaine was obtained from betaine monohydrate (Fluka, Purum) by dissolving in hot absolute ethanol and precipitating white anhydrous betaine by adding anhydrous ether;[5] it was dried in vacuo at 100 °C, and stored in a desiccator under a reduced pressure. Betainium chloride (B.D.H.) was purified by precipitating from a saturated aqueous solution with ethyl alcohol.[8] It was dried at 110 °C for a few hours and stored in a desiccator. Tetramethylam-

Table 1. Viscosity and Density data ($g\,cm^{-3}$) for the Glycine and Betaine Systems and Tetramethylammonium Bromide, in aqueous Solution at Different Temperatures

Glycine			Glycinium chloride		
Concn (C/M)	Density	(η/η_0-1)	Concn ($C^{1/2}$/M$^{1/2}$)	Density	$(\eta/\eta_0-1)/C^{1/2}$
	25°C			25°C	
0.13555	1.01806	0.01800	0.31904	1.00153	0.05650
0.06447	0.99914	0.00760	0.25203	0.99991	0.04570
0.02765	0.99795	0.00370	0.15201	0.99812	0.03060
0.01582	0.99760	0.00200			
0.00818	0.99734	0.00092			
				30°C	
			0.18260	0.99752	0.0296
			0.16940	0.99729	0.0279
			0.15480	0.99676	0.0255
			0.10970	0.99599	0.0184
				40°C	
			0.22516	0.99440	0.0396
			0.20856	0.99392	0.0358
			0.17204	0.99337	0.0290
			0.13531	0.99294	0.0241
			0.09434	0.99265	0.0188

Sodium glycinate			Betaine		
Concn ($C^{1/2}$/M$^{1/2}$)	Density	$(\eta/\eta_0-1)/C^{1/2}$	Concn (C/M)	Density	(η/η_0-1)
	25°C			25°C	
0.31555	1.00272	0.11120	0.08251	0.99880	0.0179
0.24747	1.00060	0.08850	0.06337	0.99857	0.0139
0.20005	0.99938	0.07190	0.03987	0.99783	0.0077
0.15669	0.99826	0.06010	0.02452	0.99752	0.0051
0.07959	0.99723	0.03350			
	30°C			30°C	
0.27510	0.99986	0.0953	0.08496	0.99739	0.0191
0.23619	0.99864	0.0829	0.06009	0.99667	0.0136
0.21220	0.99803	0.0769	0.04339	0.99650	0.0105
0.16120	0.99728	0.0601	0.02499	0.99613	0.0055
0.10469	0.99629	0.0431	0.02002	0.99602	0.0040
			0.01295	0.99596	0.0032
	40°C				
0.29799	0.99668	0.1008			
0.25104	0.99531	0.0831			
0.21045	0.99437	0.0747			
0.17510	0.99328	0.0639			
0.15530	0.99328	0.0549			
0.11920	0.99272	0.0417			

Betaine hydrochloride			Tetramethylammonium bromide		
Concn ($C^{1/2}$/M$^{1/2}$)	Density	$(\eta/\eta_0-1)/C^{1/2}$	Concn ($C^{1/2}$/M$^{1/2}$)	Density	$(\eta/\eta_0-1)/C^{1/2}$
	25°C			25°C	
0.38850	1.00205	0.0970	0.25069	0.99952	0.0257
0.31980	1.00018	0.0808	0.22578	0.99903	0.0247
0.17086	0.99776	0.0454	0.17640	0.99829	0.0199
0.11920	0.99751	0.0335			
	30°C			30°C	
0.38763	1.00027	0.0982	0.40899	1.00206	0.0477
0.34531	0.99924	0.0866	0.30587	0.99918	0.0375
0.32040	0.99876	0.0811			
0.27109	0.99788	0.0690	0.29189	0.99942	0.0358
0.24430	0.99736	0.0634	0.2300	0.99758	0.0291
0.19519	0.99683	0.0521			

Table 1. (Continued)

Betaine hydrochloride			Tetramethylammonium bromide		
Concn ($C^{1/2}/M^{1/2}$)	Density	$(\eta/\eta_0-1)/C^{1/2}$	Concn ($C^{1/2}/M^{1/2}$)	Density	$(\eta/\eta_0-1)/C^{1/2}$
	40 °C				
0.29375	0.99476	0.0747			
0.24361	0.99381	0.0635			
0.19219	0.99322	0.0518			
0.15931	0.99278	0.0433			

Betaine 35 °C			Betaine 45 °C		
Concn (C/M)	Density	(η/η_0-1)	Concn (C/M)	Density	(η/η_0-1)
0.18457	0.99738	0.0409	0.10806	0.99213	0.0233
0.09755	0.99582	0.0212	0.10552	0.99203	0.0228
0.06222	0.99519	0.0128	0.07349	0.99152	0.0153
0.04413	0.99485	0.0093	0.04640	0.99103	0.0096
0.03126	0.99459	0.0059	0.03473	0.99082	0.0072
0.02431	0.99447	0.0050	0.02645	0.99064	0.0047
0.01873	0.99436	0.0037			

Table 2. B-Coefficient $(kg\,mol^{-1})^{-1}$ and $A\,(kg\,mol^{-1})^{-1/2}$ Values of the Viscosity Plots

System		25 °C	30 °C
Betaine	B coeff.	0.227±0.009	0.226±0.015
Betaine hydrochloride	B coeff.	0.236±0.0007	0.237±0.002
	A coeff.	0.0052±0.0001	0.0052±0.0005
Glycine	B coeff.	0.132±0.008	0.137±0.009
Sodium glycinate	B coeff.	0.327±0.004	0.306±0.002
	A coeff.	0.0076±0.0007	0.011±0.0004
Glycinium chloride	B coeff.	0.155±0.0007	0.155±0.0007
	A coeff.	0.0069±0.0002	0.0014±0.0001
Tetramethylammonium bromide	B coeff.	0.081±0.002	0.107±0.001
	A coeff.	0.0058±0.0004	0.0043±0.0003

System	35 °C	40 °C	45 °C
Betaine	0.225±0.008		0.225±0.006
Betaine hydrochloride		0.232±0.002	
		0.0067±0.0003	
Glycine		0.145±0.004	
Sodium glycinate		0.319±0.009	
		0.0054±0.0018	
Glycinium chloride		0.156±0.003	
		0.0034±0.0006	
Tetramethylammonium bromide			

monium bromide was purified as described earlier.[9] All the amino acids and their salts were dried at 100 °C for about two hours before being dissolved in redistilled water (from an all Pyrex still), and the solutions were prepared and dilutions made on molal basis.

Details of the method of viscosity measurement have been described earlier.[1] The densities were measured in a 30 cm^3 Sprengel type bicapillary pycnometer, fitted with ground glass caps, and are precise to $\pm 10^{-5}$ g cm^{-3} (bouyancy corrections not made). A constant temperature bath, controlled to within ±0.005 °C was used. The literature values[10] of the density of water used in the calculations were 0.99707, 0.99568, 0.99406, 0.99220, and 0.99024 g cm^{-3} at 25, 30, 35, 40, and 45 °C, respectively. The viscosity and density data at different concentrations and at different temperatures are recorded in Table 1.

Calculations and Results. For the computerised least squares analysis of the viscosity data of glycine and betaine Eq. 2 was used, whereas for the salt forms of the amino acids both Eqs. 1 and 2 were tried. In the case of the salts, the acceptable positive values of the intercepts as also B-values with comparatively smaller standard deviations obtained, showed the better applicability of the Jones-Dole equation (Eq. 1) rather than Eq. 2 in contrast to the earlier finding.[1] The B and A-values thus obtained, at different temperatures, are recorded in Table 2 (together with the s.d. of fit only).

The apparent molal volumes were calculated from the density data by the use of the usual equation $\phi_v=\frac{1}{m}[(1000+mM_2)/\rho_m-(1000/\rho_o)]$; the values at infinite dilution for the salts were obtained from a least-squares fit of the Redlich-Meyer equation[11]

$$\phi_v - S_v\sqrt{c} = \phi_v^\circ + hC \qquad (5)$$

where h is an empirical constant, and S_v the Debye-Hückel limiting slope, the different values of which at the different temperatures were taken from literature.[11] The "hydrolysis effect" corrections[12] for the ϕ_v values have been made, but

Table 3. ϕ_v° Values ($cm^3\,mol^{-1}$) at Different Temperature

System	25 °C	30 °C	35 °C	40 °C	45 °C
Betaine	100	102	103		103
Betaine hydrochloride	123			123	
Glycinium chloride	66			66	
Sodium glycinate	40	43			
Tetramethylammonium bromide	114			116	
Glycine		39	42	43	

Table 4. Ionic values of B, ϕ_v°, and B/ϕ_v° at Different Temperatures

System	25 °C B_{ion} / kg mol^{-1}	25 °C $\phi_{v(ion)}^\circ$ / cm^3 mol^{-1}	B/ϕ_v°	30 °C B_{ion} / kg mol^{-1}	30 °C $\phi_{v(ion)}^\circ$ / cm^3 mol^{-1}	B/ϕ_v°
Glycinium chloride	0.162	44	3.8	0.156		
Sodium glycinate	0.241	46	5.3	0.221	49	4.6
Betaine hydrochloride	0.243	101	2.4	0.238		
Tetramethylammonium bromide	0.123	85	1.4	0.142		
Betaine			2.3			2.2
Glycine			3.5			

System	40 °C B_{ion} / kg mol^{-1}	40 °C $\phi_{v(ion)}^\circ$ / cm^3 mol^{-1}	B/ϕ_v°
Glycinium chloride	0.145	44	3.3
Sodium glycinate	0.235		
Betaine hydrochloride	0.221	101	2.2
Tetramethylammonium bromide		87	
Betaine			2.2
Glycine			3.4

the correction for the "dissociation effect" was found to be negligibly small (<1 $cm^3\,mol^{-1}$).[12] The ϕ_v values for the neutral amino acids were analyzed according to the equation:

$$\phi_v = \phi_v^\circ + a\,C \qquad (6)$$

where a is an empirical constant. The ϕ_v° values for all the systems mentioned are shown in Table 3. Both B and ϕ_v° values for the salts of amino acids have been further reduced to the corresponding ionic values, and then the ratio B/ϕ_v° for the ions calculated for different temperatures; these are incorporated in Table 4.

Discussion

A comparison of the B-value of glycine at 25 °C (0.132)† with literature data shows that our value is slightly lower than that reported by Devine and Lowe[3] (0.143) and Mason and Kampmeyer[13] (0.142), but is close to that reported by Tsangaris and Martin[8] and Tyrrell and Kennerly[5] when these values are extrapolated to 25 °C. Our earlier found value for glycine at 40 °C also agreed well with that reported by Tsangaris and Martin.[8] Both the latter two groups of workers reported B-values for betaine which are significantly different from each other, the present value at 25 °C (0.226) is close to the extrapolated value (0.224) for the same system reported by Tyrrell and Kennerley.[5] The B-value of tetramethylammonium bromide at 25 °C agrees with that reported by Kay et al.[14] Tsangaris and Martin's reported B-value for glycinium chloride at 40 °C (0.15)[8] agrees satisfactorily with ours (0.152), but their own calculated B-value for betainium chloride at 16 °C (−0.06) from the data procured from other sources seems to be in error, and thus largely disagrees with the present value (0.236 at 25 °C).

The ϕ_v° value for betaine at 25 °C (100) is consistent with the value reported by Tyrrell and Kennerley[5] at 20 °C (98.4 $cm^3\,mol^{-1}$). Our ϕ_v° values for glycinium chloride and sodium glycinate at 25 °C (66 and 40 cm^3 respectively) are slightly lower than those reported by Shahidi[12] for the same systems (67.22 and 42.81 respectively).

The earlier found better suitability of Eq. 2 (valid for uncharged species in solution) for reproducing the concentration variation of the viscosity of amino acids in acidic or alkaline medium was suprising, because amino acids are known to be present in such solutions rather as salts. The said experimental observation was also apparently justified on the basis of theoretical calculations according to the Fuoss–Onsager theory[15] of mixed electrolyte solutions, which showed that the

† All B values expressed in kg mol^{-1} units.

net electrostatic contribution part: $(A_{mix}-A_{HCl\text{ or }NaOH})\sqrt{I}$ out of the total relative viscosity value, was negligibly small, thereby apparently rendering redundant the applicability of the Jones-Dole equation (Eq. 1). In the present more comprehensive investigation where purely aqueous solutions of salts of different amino acids of varying cationic and anionic sizes were taken, the experimental results at all the temperatures have convincingly shown the better applicability of Eq. 1 rather.

The observed sequence of B-coefficient values for the present systems is: $B_{anion}>B_{cation}>B_{zwitterion}$, which was also obtained by Tsangaris and Martin[8] for the glycine system. However, for the betaine system, they reported a different sequence, i.e., $B_{zwitterion}>B_{cation}$, which is quite at variance with the observation in the present case. As mentioned, their reported negative value for betainium chloride at 16 °C appears unacceptable.

The ionisation of glycine is as follows:

$$^{+}NH_3CH_2COOH \underset{}{\overset{+H^+}{\rightleftharpoons}} {}^{+}NH_3CH_2COO^- \overset{+OH^-}{\rightleftharpoons} NH_2CH_2COO^- + H_2O$$

The different B-values obtained for the three different ionic species, having almost identical sizes and structures, indicate substantially different types of solvent-solute interactions, due entirely to the varying nature of charge on the three molecules. The high B value of the glycinate anion clearly points to extra structure promotion by this ion. This type of structure enhancement was also observed by Laurence and Wolfenden[16] for the acetate anion (B_{HAc}=0.117 and B_{Ac^-}=0.245). The glycinate ion being essentially the amino acetate ion, the exactly similar observation here is quite in order. The fact that the acetate anion is stabilized by the extremely effective delocalization of charge between the two canonical structures of identical energy involved, accounts for the extra order produced by this ion, compared to the zwitterion or acetic acid. By contrast, for the glycinium cation any such delocalization effect would be much less effective because it would first involve a separation of charge in the COOH group; this is seen reflected in the lower value of B-coefficient for this cation.††

The simultaneous presence of the two charge centers in the zwitterion makes it a unique system, as is seen from the abrupt reduction of B-coefficient value compared to either of the two ionic forms. An exactly similar situation arises also in the case of the $\overline{V}^\circ$ values of the dipolar ions. In the zwitterionic glycine system, the electron-withdrawing inductive effect[19] of the NH_3^+ from the acetate anion largely reduces the availability of the negative charge at the other end, thereby resulting in a net reduction of both the B-coefficient and $\overline{V}^\circ$ values.

The temperature coefficient of the B-value of glycine is positive, while that for both glycinate and glycinium ions are negative, thus indicating the latter two to be net structure makers in water, over the temperature range investigated. Both the ions are therefore solvated to some extent, and definitely have their primary solvation sheath.

In the context of the above discussion, the betaine system appears to be very interesting. The betaine molecule is obtained by substituting the three hydrogen atoms of the charged nitrogen atom by methyl groups, the result of which is faithfully reflected in the higher B-coefficient value (Einstein volume effect). The comparatively slightly higher value of B-coefficient of the betaine cation ($(CH_3)_3\overset{+}{N}CH_2COOH$) as compared to that for betaine itself, may be due to the same reason as mentioned earlier in the case of the glycinium cation.

The temperature coefficient of the B-value of betaine better reflects its structural interaction with the solvent than does the B-coefficient value itself. The B value remains almost unchanged over the temperature range (25—45 °C) investigated; this was also observed by Tyrrell and Kennerley over the range 5—20 °C (whose results are consistent with ours). By introducing three methyl groups at the charged nitrogen atom of the glycine molecule, this part of the betaine molecule virtually becomes a tetramethylammonium moiety. It therefore appears that in betaine, the extent of structure breaking by the "tetramethyl" moiety and structure making by the acetate moiety within the molecule are evenly balanced, therefore rendering the betaine molecule neither a "maker" nor a "breaker" in the solvent at all the temperatures.

The temperature coefficient of betaine cation is also negative, making it a structure maker like the glycinium cation. In both these molecular ions, the localized positive charge facilitates the separation of proton on the other end through the inductive effect, and therefore, not as much available at the periphery of the molecule as in the tetramethylammonium ion, thus causing it to behave like a structure maker.

The B/ϕ_V° values are important indicators[5] as to whether a particular solute is solvated or unsolvated, since a value between 0 and 2.5 points to unsolvated species, and any higher value to solvated ones. Based upon this criterion, the tetramethylammonium and betaine systems fall in the "unsolvated" category, whereas the glycinium, glycinate, and glycine are well

†† Nightingale[17] also explained the higher B-value of the iodate ion in comparison to that of the periodate ion, as due to the more effective delocalization of charge by the oxygen atoms in the former, thus permitting more extensive interaction with the solvent. Were localization of charge the more effective solvent puller (than the charge-delocalization effect) for such larger molecular ions, as observed by Gurney,[18] glycinium cation or periodate ion would give rise to higher B-values.

within the "solvated" class having definite primary solvation sheaths. Tyrrell and Kennerley[5] also observed similar interaction with the solvent for the glycine, tetramethylammonium, and betaine systems. The high value of B/ϕ_v°, together with the very low value of ϕ_v° for the glycinate anion, clearly indicates that this system interacts much more strongly with the solvent molecules, as compared to either the glycine or glycinium systems.

The betaine cation seems to have a primary solvation sheath, as is also evident from the negative temperature dependence of B/ϕ_v° value. The peculiar behavior of betaine is also reflected in the value of B/ϕ_v° and its temperature invariance. The fact that the ϕ_v values of betaine decrease with concentration at all temperatures is another point of departure from the common trend shown by amino acids. This type of concentration dependence was also noted by Tyrrell and Kennerley[5] for the same system, and by Wen and Saito[20] for the larger tetraalkylammonium bromide system. The explanation furnished for the latter was that when the cosphere of the bromide ion interacts with that of the tetraalkylammonium cation, there results a negative contribution to the partial molal volume. It is highly probable that in the betaine system a similar interaction between the hydration spheres of the tetramethylammonium and the "acetate" moieties takes place, resulting in a diminution of apparent molal volumes.

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