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Biophysical Chemistry 99 (2002) 199–207

Biophysical Chemistry

www.elsevier.com/locate/bpc

Viscosity behavior of some α-amino acids and their groups in water–sodium acetate mixtures

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Received 17 April 2002; accepted 6 June 2002

Abstract

Viscosities of glycine, DL-α-alanine, DL-α-amino-*n*-butyric acid, DL-valine and DL-leucine have been determined in water–sodium acetate mixtures at 298.15 and 308.15 K. The viscosity *B*-coefficients have been calculated. The corresponding activation free energies ($\Delta\mu_2^{0\neq}$) for viscous flow have been evaluated with the help of the Feakins equation. The contributions of the charged end group (NH_3^+,COO^-) and CH_2 groups of the amino acids to *B*-coefficient and $\Delta\mu_2^{0\neq}$ have been also determined using the linear correlation between *B*-coefficient or $\Delta\mu_2^{0\neq}$ and the number of carbon atoms in alkyl chains of the amino acids. The results have been interpreted in the light of the solute–solvent interactions in aqueous media.

Keywords: α-Amino acids; Viscosity *B*-coefficient; Activation free energy; Aqueous sodium acetate solutions

1. Introduction

Physicochemical studies of model compounds in aqueous solutions are of fundamental importance in understanding intermolecular interactions in liquids [1,2] and the effect of these compounds on water structure [3]. Tanford [4] cited evidence suggesting that the relative stability of the structure of viruses, DNA and globular proteins depend upon the molecular structure of water associated with them. Properties of amino acids in aqueous solutions have been extensively studied in order to obtain a better understanding of solute–solvent interactions and their role on the conformational stability of proteins [5]. Even though in recent years attention has been given to their behavior in different simple salt–water mixed solvents [6–17], there are only very few studies about properties of amino acid in organic salts–water mixtures [18–20] probably due to the complex nature of their interactions. Sodium acetate (CH_3COONa) is known to influence the dissociation of proteins in solution [21] and cause a salting-out of nonelectrolyte [22]. Therefore, it is interesting to investigate the behavior of model compounds of proteins in aqueous sodium acetate solutions.

Numerous studies have shown that the volumetric and viscosity measurements are very useful in providing information regarding solute–solute and

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0301-4622/02/$ - see front matter
PII: S0301-4622(02)00200-4

solute–solvent interactions in solutions [23]. As a part of the continuing studies on the thermodynamic and transport properties of amino acids in aqueous solutions of organic salts [19,20,24–26], the present work reports the viscosity and the thermodynamic free energy of the viscous flow for the amino acids. In addition, the contributions of the charged end group (NH_3^+,COO^-) and CH_2 groups to *B*-coefficients and $\Delta\mu_2^{0\neq}$ have also been reported based on the linear correlation between *B*-coefficients or $\Delta\mu_2^{0\neq}$ and the number of carbon atoms in the alkyl chains of the amino acids. The results have been interpreted in the light of solute–solvent intermolecular interactions in aqueous media.

2. Materials and experimental techniques

Glycine (Shanghai Chem. Co.), DL-α-alanine (Shanghai Chem. Co.), DL-α-amino-*n*-butyric acid (Shanghai Chem. Co.), DL-valine (Fluka) and DL-leucine (Baker) were recrystallized twice from aqueous ethanol solutions and dried under vacuum at 348 K for 6 h. Then they were stored over P_2O_5 in a desiccator before use. Analytical reagent grade anhydrous sodium acetate (Tianjin Nankai Chem. Co.) was used after drying under vacuum at 383 K. Water with a specific conductivity of 1.2 $\mu\Omega^{-1}\,cm^{-1}$ was obtained by distilling deionized water from alkaline $KMnO_4$ to remove any organic matter. All solutions were prepared freshly by weighing on the molality scale.

Viscosity measurements were carried out with a suspended level Ubbelhode viscometer, which has a flow time of approximately 200 s for water at 298.15 K. The viscometer was calibrated with water. Flow time measurements are performed by a SCHOTT AVS 310 photoelectric time unit with a resolution of 0.01 s. The repeatability for reading was ± 0.02 s. At least three time recordings reproducible to 0.02 s were obtained, and the average value was used. Viscosity of solution, η, is given by the following equation

$$\eta/\rho = Ct - K/t \tag{1}$$

where ρ is the solution density, *t* is the flow time, *C* and *K* are the viscometer constants which were obtained by the measurements on water at 298.15 and 308.15 K. The viscometer were thermostated using SCHOTT thermostat units which have a thermal stability of ± 0.005 K.

The density data reported in the previous papers [24,25] were used in the present work. The relative viscosities $\eta_r = \eta/\eta_0$ were calculated from the solution and solvent viscosities, respectively.

3. Results

The viscosity data obtained for both solvent and solutions as a function of amino acid concentration and temperature are reported in Table 1 and Table 2. The viscosity *B*-coefficients for the amino acids in aqueous sodium acetate solutions were calculated from the following equation [27]

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

where *c* is the molarity of amino acid in solution. Viscosity *B*-coefficients were obtained by the least-squares method and are given in Table 3 together with their standard deviations.

In Eyring's simple model [28], the molecules move one-by-one from their equilibrium positions through their transition-states, in which intermolecular bonds are stretched, to other equilibrium positions. For a pure liquid he found the equation

$$\eta_0 = (hN_A/V_{1,\phi}^0)\exp(\Delta\mu_1^{0\neq}/RT) \tag{3}$$

where *h* is the Planck constant, N_A is the Avagadro's number, $\Delta\mu_1^{0\neq}$ is the contribution per mole of solvent to the free energy of activation for viscous flow of the solution. When a solution flows, both the solute and the solvent molecules move under the shearing force. The activation energy per mole of solution can be written:

$$\Delta G^{0\neq} = x_1\Delta\mu_1^{0\neq} + x_2\Delta\mu_2^{0\neq} \tag{4}$$

where x_1 and x_2 are the mole fraction of the solvent and solute, respectively. $\Delta\mu_2^{0\neq}$ as defined by Eq. (4) includes any change in the free energy of activation of the solvent molecules caused by the presence of the solute, as well as a contribution from the movement of the solute itself. According to the Feakins et al. the *B*-coefficient is related to $\Delta\mu_2^{0\neq}$ by Eq. (5), [29]

Table 1
Viscosities η for α-amino acid + sodium acetate + water systems as a function of molarities of amino acids (c) and sodium acetate (m_s) at 298.15 K

$m_s = 0.5000$		$m_s = 1.0000$		$m_s = 1.4999$		$m_s = 2.0001$	
c/mol l^{-1}	η/mPa S	c/mol l^{-1}	η/mPa S	c/mol l^{-1}	η/mPa S	c/mol l^{-1}	η/mPa S
Glycine							
0.0000	1.043	0.0000	1.214	0.0000	1.411	0.0000	1.645
0.03106	1.048	0.03273	1.220	0.03227	1.419	0.03418	1.655
0.06198	1.052	0.06296	1.225	0.06120	1.424	0.06564	1.664
0.1029	1.058	0.1049	1.232	0.1026	1.433	0.1081	1.673
0.1637	1.067	0.1581	1.242	0.1544	1.444	0.1594	1.685
0.1987	1.073	0.2109	1.252	0.2131	1.457	0.2142	1.698
0.2413	1.079	0.2563	1.260	0.2529	1.465	0.2594	1.709
DL-α-alanine							
0.03104	1.051	0.03137	1.224	0.03199	1.424	0.03468	1.662
0.06389	1.061	0.06005	1.233	0.06148	1.435	0.06472	1.674
0.1030	1.071	0.1002	1.246	0.1019	1.449	0.1065	1.693
0.1396	1.082	0.1499	1.264	0.1536	1.470	0.1587	1.716
0.2091	1.101	0.1997	1.279	0.2021	1.488	0.2081	1.739
0.2489	1.113	0.2482	1.295	0.2494	1.508	0.2552	1.762
DL-α-aminobutyric acid							
0.03172	1.054	0.03281	1.229	0.03470	1.430	0.03207	1.664
0.06330	1.066	0.06256	1.243	0.06377	1.445	0.06208	1.683
0.1039	1.081	0.1035	1.261	0.1074	1.468	0.1024	1.707
0.1493	1.099	0.1543	1.284	0.1596	1.495	0.1561	1.742
0.2073	1.128	0.2084	1.309	0.2053	1.521	0.2071	1.774
0.2577	1.142	0.2578	1.331	0.2560	1.548	0.2543	1.808
DL-valine							
0.03091	1.057	0.03282	1.232	0.03215	1.433	0.03305	1.669
0.05599	1.071	0.06282	1.248	0.06149	1.451	0.06329	1.692
0.1039	1.091	0.1031	1.270	0.1006	1.477	0.1047	1.725
0.1554	1.115	0.1562	1.299	0.1524	1.510	0.1527	1.762
0.2055	1.141	0.2013	1.326	0.2024	1.544	0.2033	1.801
0.2578	1.165	0.2496	1.354	0.2507	1.578	0.2548	1.844
DL-leucine							
0.01977	1.054	0.01531	1.223	0.01560	1.423	0.01069	1.655
0.03022	1.059	0.03081	1.233	0.02613	1.432	0.02157	1.664
0.04123	1.064	0.04639	1.243	0.04208	1.443	0.03220	1.674
0.05098	1.070	0.05699	1.250	0.05286	1.452	0.04344	1.684
0.06304	1.076	0.06749	1.257	0.05772	1.456	0.04865	1.690

$$B = (V^0_{1,\phi} - V^0_{2,\phi})/1000 + \left(V^0_{1,\phi}/1000\right)(\Delta\mu^{0\neq}_2 - \Delta\mu^{0\neq}_1)/RT \quad (5)$$

It can be rearranged as follows:

$$\Delta\mu^{0\neq}_2 = \Delta\mu^{0\neq}_1 + \left(RT/V^0_{1,\phi}\right)[1000B - (V^0_{1,\phi} - V^0_{2,\phi})] \quad (6)$$

Table 4 gives values of $\Delta\mu^{0\neq}_2$ for the amino acids in aqueous sodium acetate solutions at 298.15 and 308.15 K.

According to the transition-state theory [29] every solvent molecule in one mole of solution interacts more or less strongly with the solute. Each solvent molecule must pass through the transition-state, in which it must also interact with the solute. Thus, $\Delta\mu^{0\neq}_2$ contains the free energy of

Table 2
Viscosities η for α-amino acid + sodium acetate + water systems as a function of molarities of amino acids (c) and sodium acetate (m_s) at 308.15 K

$m_s = 0.5000$		$m_s = 1.0000$		$m_s = 1.4999$		$m_s = 2.0001$	
c /mol l^{-1}	η /mPa S	c/mol l^{-1}	η/mPa S	c/mol l^{-1}	η/mPa S	c/mol l^{-1}	η/mPa S
Glycine							
0.0000	0.8390	0.0000	0.9708	0.0000	1.119	0.0000	1.293
0.03055	0.8443	0.03262	0.9749	0.03215	1.125	0.03406	1.299
0.06055	0.8461	0.06274	0.9803	0.06098	1.131	0.06540	1.306
0.1007	0.8511	0.1046	0.9863	0.1022	1.137	0.1077	1.313
0.1624	0.8593	0.1576	0.9943	0.1538	1.146	0.1588	1.324
0.1820	0.8610	0.2102	1.001	0.2123	1.156	0.2134	1.335
0.2592	0.8710	0.2554	1.008	0.2520	1.162	0.2584	1.343
DL-α-alanine							
0.03116	0.8450	0.03126	0.9781	0.03187	1.128	0.03455	1.306
0.06048	0.8513	0.05984	0.9857	0.06125	1.138	0.06447	1.316
0.09997	0.8595	0.09983	0.9959	0.1015	1.149	0.1061	1.329
0.1523	0.8705	0.1494	1.007	0.1530	1.163	0.1580	1.346
0.2044	0.8820	0.1992	1.021	0.2014	1.179	0.2073	1.364
0.2570	0.8939	0.2473	1.033	0.2485	1.192	0.2542	1.381
DL-α-aminobutyric acid							
0.03373	0.8477	0.03269	0.9821	0.03457	1.133	0.03267	1.308
0.06198	0.8559	0.06234	0.9915	0.06353	1.143	0.06184	1.320
0.1019	0.8692	0.1031	1.006	0.1070	1.161	0.1020	1.339
0.1497	0.8809	0.1538	1.028	0.1589	1.180	0.1555	1.365
0.2003	0.8962	0.2077	1.040	0.2045	1.200	0.2063	1.387
0.2489	0.9107	0.2568	1.058	0.2550	1.219	0.2534	1.410
DL-valine							
0.03272	0.8494	0.03270	0.9844	0.03203	1.135	0.03292	1.310
0.06419	0.8601	0.06260	0.9953	0.06126	1.149	0.06305	1.327
0.1054	0.8744	0.1027	1.012	0.1002	1.167	0.1043	1.349
0.1512	0.8909	0.1556	1.034	0.1518	1.192	0.1521	1.377
0.1982	0.9087	0.2006	1.053	0.2017	1.217	0.2025	1.406
0.2485	0.9276	0.2487	1.075	0.2498	1.240	0.2538	1.434
DL-leucine							
0.01456	0.8441	0.01525	0.9773	0.01554	1.129	0.01065	1.300
0.03037	0.8510	0.03070	0.9843	0.02603	1.134	0.02149	1.308
0.04538	0.8567	0.04623	0.9924	0.04191	1.143	0.03208	1.314
0.05710	0.8619	0.05679	0.9975	0.05266	1.149	0.04327	1.321
0.06608	0.8657	0.06725	1.002	0.05749	1.152	0.04846	1.325

transfer of the solute from the ground to the transition-state solvents, $\Delta G_2^0(1-1')$. It will also contain the free energy of solute through its own viscous transition state, $\Delta G_2^0(2-2')$. $\Delta G_2^0(1-1')$ can be obtained from the measured $\Delta\mu_2^{0\neq}$ values and $\Delta G_2^0(2-2')$, which equal to $\Delta\mu_1^{0\neq}$ [30]. The values of $\Delta G_2^0(1-1')$ have been collected in Table 5.

4. Discussion

The values of *B*-coefficient for the amino acids in aqueous sodium acetate solutions, as given in Table 3, reflect the net effects of the charged groups and the hydrophobic CH_2 groups on the amino acids. These two effects can be separated by noting that the *B*-coefficients are linear in n_C,

Table 3
Viscosity *B*-coefficients for α-amino acids in aqueous sodium acetate solutions at 298.15 and 308.15 K

Amino acid	$B/\mathrm{dm^3\ mol^{-1}}$			
	$m_s=0.5$	$m_s=1.0$	$m_s=1.5$	$m_s=2.0$
298.15 K				
Gly	0.1438±0.0009	0.1466±0.0007	0.1505±0.0009	0.151±0.002
DL-ala	0.268±0.001	0.269±0.002	0.272±0.002	0.275±0.002
DL-abu	0.372±0.006	0.3750±0.0003	0.377±0.001	0.381±0.003
DL-val	0.454±0.003	0.457±0.003	0.466±0.002	0.469±0.003
DL-leu	0.506±0.004	0.518±0.002	0.545±0.005	0.551±0.004
308.15 K				
Gly	0.147±0.002	0.151±0.001	0.153±0.001	0.1521±0.0008
DL-ala	0.251±0.002	0.257±0.001	0.260±0.001	0.266±0.004
DL-abu	0.341±0.003	0.349±0.001	0.352±0.003	0.357±0.001
DL-val	0.418±0.004	0.423±0.003	0.430±0.001	0.435±0.002
DL-leu	0.477±0.005	0.491±0.001	0.505±0.002	0.518±0.004

the number of carbon atom in alkyl chain, i.e.

$$B = B(\mathrm{NH_3^+},\mathrm{COO^-}) + n_C B(\mathrm{CH_2}) \quad (7)$$

The regression parameters, $B(\mathrm{NH_3^+},\mathrm{COO^-})$, the charged end group contribution and $B(\mathrm{CH_2})$, the methylene group contribution to *B*-coefficients, are listed in Table 6. Similar linear correlation has been found for some amino acids in aqueous potassium thiocyanate [16], guanidine hydrochloride [20], urea [31] and sodium butyrate [26] solutions. However, it should be pointed out that $B(\mathrm{CH_2})$ obtained here characterizes the mean contribution of CH and CH_3 groups to *B*-coefficients of the amino acids.

The *B* value of glycine increases with increasing temperature in all the solvent compositions. Since $(\mathrm{d}B/\mathrm{d}T)$ is positive for a structure-breaking solute [32], we can classify glycine as a structure breaker in water–sodium acetate mixtures. The other amino acids, which have negative $\mathrm{d}B/\mathrm{d}T$ values, are structure-makers. The $\mathrm{d}B/\mathrm{d}T$ values obtained in this work for the groups (Table 6) confirm that

Table 4
Activation free energies, $\Delta\mu_2^{0\neq}$, for viscous flow of amino acids in aqueous sodium acetate solutions at 298.15 and 308.15 K

Amino acid	$\Delta\mu_2^{0\neq}/\mathrm{kJ\ mol^{-1}}$			
	$m_s=0.5$	$m_s=1.0$	$m_s=1.5$	$m_s=2.0$
298.15 K				
Gly	32.7±0.1	33.30±0.09	34.0±0.1	34.3±0.3
DL-ala	51.9±0.1	52.1±0.3	52.3±0.3	52.7±0.3
DL-abu	68.0±0.8	68.17±0.04	68.2±0.1	68.6±0.4
DL-val	81.1±0.4	81.2±0.4	81.9±0.3	82.0±0.4
DL-leu	90.4±0.5	91.5±0.3	94.6±0.7	94.9±0.5
308.15 K				
Gly	33.6±0.3	34.4±0.1	34.9±0.1	34.9±0.1
DL-ala	50.6±0.3	51.4±0.1	51.8±0.1	52.6±0.3
DL-abu	65.2±0.4	66.2±0.1	66.3±0.4	66.8±0.1
DL-val	78.1±0.6	78.5±0.4	79.0±0.1	79.4±0.3
DL-leu	88.7±0.7	90.1±0.1	91.5±0.3	92.8±0.5

Table 5
Thermodynamic activation parameters of transfer for the amino acids from ground-state to transition-state in aqueous sodium acetate solutions at 298.15 and 308.15 K

Amino acid	$\Delta G_2^{o}(1\text{–}1')/\mathrm{kJ\ mol^{-1}}$			
	$m_s=0.5$	$m_s=1.0$	$m_s=1.5$	$m_s=2.0$
298.15 K				
Gly	23.1±0.1	23.31±0.09	23.6±0.1	23.5±0.1
DL-ala	42.3±0.1	42.1±0.3	41.9±0.3	41.9±0.8
DL-abu	58.4±0.8	58.18±0.04	57.8±0.1	57.8±0.4
DL-val	71.5±0.4	71.2±0.4	71.5±0.3	71.2±0.5
DL-leu	80.8±0.5	81.5±0.3	84.2±0.7	84.1±0.4
308.15 K				
Gly	24.3±0.3	24.6±0.1	24.8±0.1	24.4±0.1
DL-ala	41.3±0.3	41.6±0.1	41.6±0.1	42.1±0.3
DL-abu	55.9±0.4	56.4±0.1	56.1±0.4	56.3±0.1
DL-val	68.8±0.6	68.7±0.4	68.8±0.1	68.9±0.3
DL-leu	79.4±0.7	80.3±0.1	81.3±0.3	82.3±0.5

Table 6
Contributions of zwitterionic group (NH_3^+,COO^-) and CH_2 group to viscosity *B*-coefficients of the amino acids at 298.15 and 308.15 K

Group	B/dm^3 mol^{-1}			
	$m_s=0.5$	$m_s=1.0$	$m_s=1.5$	$m_s=2.0$
298.15 K				
(NH_3^+,COO^-)	0.076±0.027	0.074±0.024	0.067±0.016	0.067±0.017
CH_2–	0.091±0.008	0.093±0.007	0.098±0.005	0.099±0.005
308.15 K				
(NH_3^+,COO^-)	0.079±0.017	0.080±0.015	0.077±0.013	0.076±0.013
CH_2–	0.083±0.005	0.085±0.005	0.087±0.004	0.090±0.004

the charged end groups are structure-breakers and CH_2 groups are structure-makers. In glycine the hydrophobic stabilization effect of CH_2 is over-compensated by structure breaking of (NH_3^+,COO^-). In the case of other amino acids, owing to the increase of alkyl chain, the hydrophobic stabilization is effective and we observed a negative dB/dT as a result of net structure-making effect. On the other hand, *B*-coefficient values of the amino acids increase with concentration of sodium acetate, indicating the promotion of liquid structure in the presence of sodium acetate.

It is interesting to note that at a given concentration of sodium acetate, the variation of the viscosity of amino acid + sodium acetate + water solutions with the concentration of amino acids can be expressed by the following equation

$$\eta = a_1 \exp(a_2 c) \quad (8)$$

Values of the fitted parameters a_1 and a_2 are listed in Table 7.

The values of $\Delta\mu_1^{0\neq}$ for 0.5, 1.0, 1.5 and 2.0 mol kg^{-1} sodium acetate solutions are 9.58, 9.99, 10.39, 10.80 kJ mol^{-1} at 298.15 K and 9.35, 9.76, 10.15, 10.55 kJ mol^{-1} at 308.15 K, respectively. It is evident from the data in Table 4 and Table 5 that $\Delta\mu_2^{0\neq}$ and $\Delta G_2^0(1-1')$ values are positive and much larger than $\Delta\mu_1^{0\neq}$. This suggests that the formation of the transition state is less favored in the presence of the amino acids, and the formation of the transition state is accompanied by the breaking and distortion of the intermolecular bonds. On the other hand, the values of $\Delta G_2^0(1-1')$ increase from glycine to leucine at given temperatures. Thus, more energy is need for the amino acids, which have longer alkyl chains, transferring from the ground-state solvent to the transition-state solvent. Accordingly, more solute–solvent bonds must be broken to form the transition state. Therefore $\Delta\mu_2^{0\neq}$ should increase gradually from glycine to leucine. From the data in Table 5, the same conclusion can be drawn. Because the interactions of the charged end groups for different amino acids with sodium acetate are the same, and those of the charged end groups for different amino acids with water are also the same, it can be deduced that the increasing $\Delta\mu_2^{0\neq}$ comes from the difference in interactions of the alkyl groups of the amino acids with sodium acetate and in those with water molecules in the solvent mixtures. The interaction between amino acids and water increases with the size of the nonpolar part of the molecule [33]. The results obtained from volumetric properties of amino acids in aqueous sodium acetate [24,25] showed that more hydrophobic amino acids undergo more dehydration effect of sodium acetate. The study on the interaction between amino acid and alkyl-chloride [13] also showed that the more the ion–dipole interaction, the more the dehydration affects. Thus, sodium acetate has larger effect on amino acids with longer alkyl chain. Palecz [34] has determined the enthalpic pair interaction coefficients values of the interaction between L-α-amino acids and electrolyte in water and suggested that an amino acid–NaCl interaction in water became more endothermic and grew up according to the growth

of alkyl group of side chain in the order glycine < alanine < aminobutyrate < valine < leucine. Therefore, the interactions of the alkyl groups with sodium acetate and water molecules increase with increasing alkyl chains length of the amino acids, and $\Delta\mu_2^{0\neq}$ increase gradually from glycine to leucine.

As for the *B*-coefficient, $\Delta\mu_2^{0\neq}$ also vary linearly with n_C. The regression of $\Delta\mu_2^{0\neq}-n_C$ data using Eq. (9) gives $\Delta\mu_2^{0\neq}(NH_3^+,COO^-)$ and $\Delta\mu_2^{0\neq}(CH_2)$ as the respective contributions of (NH_3^+,COO^-) and the CH_2 groups.

$$\Delta\mu_2^{0\neq} = \Delta\mu_2^{0\neq}(NH_3^+,COO^-) + n_C\Delta\mu_2^{0\neq}(CH_2) \quad (9)$$

It can be seen from Table 8 that $\Delta\mu_2^{0\neq}(CH_2)$ decreases whereas $\Delta\mu_2^{0\neq}(NH_3^+,COO^-)$ increases from 298.15 to 308.15 K, giving a positive and negative $\Delta S_2^{0\neq}$ values, respectively. Similar trends are observed in aqueous guanidine hydrochloride [20] and urea [13]. The positive $\Delta S_2^{0\neq}(CH_2)$ shows that the transition state is attained by considerable

Table 8
Contributions of zwitterionic group (NH_3^+,COO^-) and CH_2 group to the activation free energies of the amino acids at 298.15 and 308.15 K

Group	$\Delta\mu_2^{0\neq}$/kJ mol^{-1}			
	$m_s=0.5$	$m_s=1.0$	$m_s=1.5$	$m_s=2.0$
298.15 K				
(NH_3^+,COO^-)	21.4±3.6	21.6±3.2	21.0±2.2	21.4±2.2
CH_2–	14.5±1.1	14.5±1.0	15.1±0.7	15.0±0.7
308.15 K				
(NH_3^+,COO^-)	21.9±2.3	22.6±2.2	22.5±1.8	22.6±1.8
CH_2–	13.8±0.7	13.8±0.7	14.1±0.5	14.2±0.6

Table 7
Coefficients a_1 and a_2 of Eq. (8) for α-amino acids in aqueous sodium acetate solutions at 298.15 and 308.15 K

Amino acid	298.15 K			308.15 K		
	a_1	a_2	σ^a	a_1	a_2	σ^a
$m_s=0.5$						
Gly	1.0429±0.0003	0.142±0.002	0.0003	0.8397±0.0007	0.139±0.005	0.0009
DL-ala	1.0433±0.0004	0.258±0.003	0.0005	0.8385±0.0002	0.248±0.001	0.0002
DL-abu	1.0417±0.0018	0.365±0.012	0.0022	0.8389±0.0009	0.330± ±0.006	0.0010
DL-val	1.0439±0.0009	0.428±0.006	0.0011	0.8378±0.0003	0.409±0.002	0.0003
DL-leu	1.0437±0.0005	0.483±0.011	0.0004	0.8383±0.0003	0.487±0.006	0.0003
$m_s=1.0$						
Gly	1.2139±0.0001	0.1455±0.0007	0.0001	0.9709±0.0004	0.148±0.003	0.0005
DL-ala	1.2142±0.0006	0.261±0.004	0.0007	0.9708±0.0004	0.250±0.003	0.0005
DL-abu	1.2152±0.0003	0.356±0.002	0.0004	0.9722±0.0022	0.333±0.014	0.0027
DL-val	1.2139±0.0002	0.438±0.002	0.0003	0.9706±0.0005	0.407±0.003	0.0006
DL-leu	1.2139±0.0002	0.514±0.004	0.0002	0.9702±0.0005	0.482±0.012	0.0005
$m_s=1.5$						
Gly	1.4120±0.0003	0.145±0.002	0.0004	1.1203±0.0004	0.146±0.003	0.0005
DL-ala	1.4118±0.0004	0.263±0.003	0.0005	1.1199±0.0005	0.251±0.003	0.0006
DL-abu	1.4123±0.0002	0.359±0.002	0.0003	1.1196±0.0004	0.335±0.003	0.0005
DL-val	1.4123±0.0003	0.441±0.002	0.0003	1.1202±0.0003	0.409±0.002	0.0003
DL-leu	1.4118±0.0006	0.529±0.014	0.0005	1.1196±0.0004	0.495±0.001	0.00003
$m_s=2.0$						
Gly	1.6476±0.0003	0.141±0.002	0.0003	1.2930±0.0003	0.148±0.002	0.0004
DL-ala	1.6464±0.0004	0.263±0.002	0.0005	1.2945±0.0005	0.252±0.002	0.0007
DL-abu	1.6443±0.0005	0.370±0.003	0.0006	1.2936±0.0004	0.340±0.003	0.0005
DL-val	1.6448±0.0004	0.449±0.003	0.0005	1.2927±0.0005	0.410±0.003	0.0006
DL-leu	1.6446±0.0003	0.556±0.008	0.0003	1.2932±0.0004	0.501±0.011	0.0003

[a] Standard deviations of the fit.

Table 9
Parameters A_1 and A_2 of Eq. (10) for the amino acids in aqueous sodium acetate solutions at 298.15 and 308.15 K

m_s(mol kg^{-1})	$-A_1$/dm^3 mol^{-1}	A_2	R^a	σ^b
298.15 K				
0.5	0.097±0.040	5.8±0.5	0.989	0.025
1.0	0.111±0.036	6.1±0.4	0.992	0.022
1.5	0.135±0.026	6.4±0.3	0.996	0.016
2.0	0.145±0.025	6.6±0.3	0.997	0.015
308.15 K				
0.5	0.076±0.026	5.2±0.3	0.994	0.016
1.0	0.088±0.022	5.5±0.3	0.996	0.014
1.5	0.101±0.019	5.7±0.2	0.997	0.011
2.0	0.115±0.020	5.9±0.2	0.997	0.012

[a] R the correlation coefficient.
[b] σ the standard deviations of the fit.

solvent–solute bond breaking. For polar (NH_3^+,COO^-) groups, the solute–solvent bonds will be made in the transition state.

Moreover, it is observed that B-coefficients show a linear correlation with the standard partial molar volumes $V^o_{2,\phi}$ reported previously [24,25] for the α-amino acids in aqueous sodium acetate solutions. That means

$$B = A_1 + A_2 V^0_{2,\phi} \quad (10)$$

The coefficients A_1 and A_2 are given in Table 9 together with their standard deviations and the correlation coefficients. The A_2 value reflects the size and shape of the solute and lies between 0 and 2.5 for unsolvated spherical species [35]. It can be noted from Table 9 that the value is greater than 2.5 and increases with molality of sodium acetate at given temperatures. This can be explained that if one assumes that the increase in viscosity is predominately due to the increased resistance offered by the more structured solvent to the moving amino acid moiety, though solvation effects may also contribute.

Acknowledgments

We wish to acknowledge the financial support from the Youth Science Foundation of Henan Province and the Science Foundation of the State Education Commission of China.

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