Enthalpies of Interaction of L-Valine and L-Threonine with Pyridine and Methylpyridine in Aqueous Solutions at 298.15 K

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Enthalpies of mixing in aqueous solutions of L-valine and L-threonine with pyridine and methylpyridine isomers and their enthalpies of dilution have been determined by flow microcalorimetry at 298.15 K. The results have been analyzed using the excess function concept, and heterotactic enthalpic pairwise interaction coefficients, h_{xy}, of the virial expansion of the excess enthalpy have been obtained. These are briefly discussed in terms of intermolecular interactions between the hydrated solute species. In addition, the results obtained in the present paper along with literature data have been treated in terms of the Savage−Wood additivity group (SWAG), and values of the functional group interaction parameters for α-amino acids + pyridine and α-amino acids + methylpyridine systems have been estimated. The SWAG approach has been appraised in terms of the results obtained.

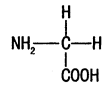
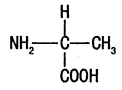
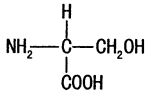
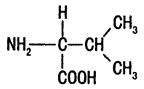
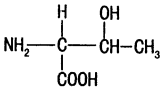
Introduction

Interactions between the solvent and various functional groups on the protein, along with the various noncovalent bonding interactions among protein constituent groups, are very important factors that determine the folded conformation of a globular protein.[1] As proteins are large complex molecules, small solutes that incorporate some of the structural features found in proteins have been used as models for specific aspects of proteins in aqueous solution.[2,3] Amino acids are basic components of proteins and are considered to be one of the important model compounds of protein molecules.[4,5]

The majority of proteins exist in aqueous mixed solvents containing many organic substances.[4] Pyridine and its derivatives are an important category of aromatic compound. They have attracted some attention because many alkaloids and important natural products contain pyridine ring or hydrogenized pyridine ring structures.[6] Methylpyridine isomers, generally called picoline, are a kind of compound of most significance among the derivatives of pyridine. They are all very important organic synthesis materials, applied in the fields of medicine, pesticides, and polymer chemistry.

As an extension to our previous study,[7,8] the present work reports the calorimetric measurement results of the noncovalent bonding interactions between some amino acids (L-valine and L-threonine) and pyridine and methylpyridine. The enthalpic coefficients of interaction of the systems have been calculated according to the McMillan−Mayer model.[9] The results obtained in the present paper together with those reported in the earlier paper about the enthalpic interactions of glycine, L-alanine, and L-serine with the same organic solvent in aqueous solutions have also been discussed using the additivity group concept by Savage and Wood (SWAG).[10] Table 1 depicts the chemical structures of the five amino acids studied in this paper and our previous work.[7,8]

Table 1. Chemical Structures of α-Amino Acids Studied in This Work and Our previous work

Amino acid	Chemical structure
Glycine	
L-Alanine	
L-Serine	
L-Valine	
L-Threonine	

Materials and Methods

Biochemical reagent grade L-valine and L-threonine, purchased from Shanghai Chem. Co., were used after recrystallization from methanol−water mixtures and drying in a vaccum over P_2O_5 at room temperature for at least 72 h. Analytical reagent grade pyridine and methylpyridine, manufactured by Shanghai Chem. Co., were used

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without any pretreatment. The water used in all experiments was deionized and distilled using a quartz subboiling purifier. All the aqueous solutions were prepared by mass with a Mettler AE 200 balance with a precision of ±0.0001 g.

The enthalpies of dilution and mixing were carried out at (298.15 ± 0.01) K with a mixing-flow microcalorimeter (LKB-2277 BioActivity Monitor, made in Sweden). The baseline stability (over a period of 24 h) of the LKB-2277 BioActivity Monitor is 0.2 μW. When the thermostated system and detection system of the microcalorimeter come to a thermal balance, the baseline is determined using water and the electric calibration is carried out by the power which is the next gear smaller than the mesurement range used. The variation in flow rates during the measuring processes was less than 0.2%. The flow rates are determined by weighing the masses of the liquids going through each pump within 8 min. The relative mean deviation in weighing was 0.01%. The relative mean deviation of the thermal powers determined was 0.3%, and at last, the relative mean deviation of the dilution enthalpies and mixing enthalpies was less than 1%. The details of the experimental techniques have been described elsewhere.[7,8]

The enthalpy of dilution ΔH_{dil}/J·kg^{-1} and final molality m_x/kg·mol^{-1} are determined by measuring the thermal power P/μW and the flow rates of the solution and the solvent (f_A and f_B/mg·s^{-1}):

$$\Delta H_{dil} = P/(f_A + f_B - m_{x,i}M_x f_A) \quad (1)$$

$$m_x = m_{x,i}f_A/[f_B(m_{x,i}M_x + 1) + f_A] \quad (2)$$

in which M_x is the molar mass of the solute (kg·mol^{-1}) and $m_{x,i}$ is the initial molality (kg·mol^{-1}).

The enthalpy of mixing ΔH_{mix}/J·kg^{-1} of an aqueous x solution and an aqueous y solution is calculated from the equation

$$\Delta H_{mix} = P^*/(f_x + f_y - m_{x,i}M_x f_x - m_{y,i}M_y f_y) \quad (3)$$

where P^* is the mixing thermal power and f_x and f_y are the flow rates of solution x and y, respectively, and $m_{x,i}$ and $m_{y,i}$ are the initial molalities of the two kinds of aqueous solutions before mixing.

The treatment of the experimental data concerning the dilution experiments for the aqueous solutions is based on the excess enthalpy expression.[9,11,12]

$$H^E(m_x,m_y)/w_1 = (H(m_x,m_y)/w_1) - h^*_w - m_x H^\infty_{x,m} - m_y H^\infty_{y,m} = h_{xx}m_x^2 + 2h_{xy}m_x m_y + h_{yy}m_y^2 + h_{xxx}m_x^3 + 3h_{xxy}m_x^2 m_y + 3h_{xyy}m_x m_y^2 + h_{yyy}m_y^3 + ... \quad (4)$$

where $H^E(m_x,m_y)/w_1$ represents the excess enthalpy of a solution containing 1 kg of water, m_x is the moles of x and m_y is the moles of y, $H(m_x,m_y)/w_1$ is the absolute enthalpy of the solution, h^*_w is the standard enthalpy of 1 kg of pure water, and $H^\infty_{x,m}$ and $H^\infty_{y,m}$ are the limiting partial molar enthalpies of species x and y, respectively. h_{ij} and h_{iij} are the enthalpic virial coefficients characterizing the pairwise and triplet interactions of the solvated species, and m_x and m_y are the molalities of the solutes x and y, respectively. $\Delta H_{dil}(x)$, $\Delta H_{dil}(y)$, and ΔH_{mix} have been determined. To evaluate these coefficients, the excess enthalpies of the binary solutions must be known. Introducing an auxiliary function ΔH^*, defined as

$$\Delta H^* = \Delta H_{mix} - \Delta H_{dil}(x) - \Delta H_{dil}(y) = H^E(m_x,m_y) - H^E(m_x) - H^E(m_y) \quad (5)$$

and combining eqs 4 and 5, it follows that

$$\Delta H^*/w_1 = 2h_{xy}m_x m_y + 3h_{xxy}m_x^2 m_y + 3h_{xyy}m_x m_y^2 + ... \quad (6)$$

Experimental Results and Discussion

The experimental values of enthalpies of dilution and mixing of aqueous L-valine and L-threonine solutions (x) and aqueous pyridine and methylpyridine isomers (y) solutions together with the initial and final molalities are given in Table 2. The heterotactic enthalpic interaction coefficients of the solutions studied in this work and those of the solutions reported previously are listed in Table 3. As there are some difficulties in the interpretation of the higher h coefficients, only the pairwise interaction coefficients h_{xy} are considered here.

1. Heterotactic Enthalpic Pairwise Interaction of L-Valine and L-Threonine with Pyridine and Methylpyridine in Aqueous Solutions. The process of interaction of two solvated species can be represented as consisting of two successive stages: the partial dehydration of the solutes and the further direct interaction caused by the short-range molecular forces.[13,14] The partial dehydrations of the hydration shell of the amino acid zwitterions, pyridine, and methylpyridine isomers are all endothermic processes. The direct solute−solute interaction between amino acid and pyridine or methylpyridine plays the dominant role in the process of interaction. As mentioned in the literature,[7] the direct interaction of α-amino acid with pyridine and methylpyridine comprises three kinds of interactions: the hydrophilic−hydrophilic interaction, the hydrophobic−hydrophobic interaction, and the hydrophobic−hydrophilic interaction.

Enthalpic pairwise interaction coefficients, h_{xy}, represent the result of the balance between the above effects. The experimentally observed positive values of h_{xy} indicate that endothermic processes are dominant during the interaction processes of L-valine and L-threonine with pyridine and methylpyridine isomers. The changes of h_{xy} are closely related with the differences in the structures of the two interaction molecules. A concrete analysis of the tendency of h_{xy} values shown by Figure 1 has been conducted as follows.

a. Enthalpic Pairwise Interactions of Different Amino Acids with Pyridine and Methylpyridine Isomers in Aqueous Solution. As can be seen from Table 1, the side chain of L-threonine can be considered as a substitute for one hydroxyl group of one of the methyl groups of L-valine. The main differences of the interactions of L-valine and L-threonine with pyridine and methylpyridine isomers lie in the following: there exist hydrophobic−hydrophobic and hydrophobic−hydrophilic interactions (both making positive contributions to h_{xy}) of the methyl group of L-valine with the apolar group and the nitrogen atom of pyridine and methylpyridine, and there also exist hydrophilic−hydrophobic (making positive contributions to h_{xy}) and hydrophilic−hydrophilic interactions (making negative contributions to h_{xy}) of the hydroxyl group on the side chain of L-threonine with the apolar group and the nitrogen atom of pyridine and methylpyridine isomers. So the comparative magnitude of h_{xy}(L-valine) and h_{xy}(L-threonine) depends on the competitive balance of the above varied interactions. In methylpyridine aqueous solutions,

Table 2. Enthalpies of Dilution and Enthalpies of Mixing for α-Amino Acids (*x*) + Pyridine (*y*) and α-Amino Acids (*x*) + Methylpyridine (*y*) in Aqueous Solutions at 298.15 K

$m_{x,i}$,[a] mol· kg^{-1}	$m_{y,i}$, mol· kg^{-1}	$m_{x,f}$, mol· kg^{-1}	$m_{y,f}$, mol·kg^{-1}	$\Delta H_{dil(x)}/w_1$, J·kg^{-1}	$\Delta H_{dil(y)}/w_1$, J·kg^{-1}	$\Delta H_{mix}/w_1$, J·kg^{-1}	$\Delta H^*/w_1$, J·kg^{-1}
			L-Valine + Pyridine				
0.1000	0.1000	0.0503	0.0493	−2.23 (0.02)	−3.54 (0.04)	5.74 (0.06)	11.52
0.1500	0.1500	0.0752	0.0737	−4.66 (0.04)	−7.32 (0.07)	8.56 (0.09)	20.54
0.1800	0.1800	0.0901	0.0884	−6.30 (0.06)	−10.61 (0.11)	10.09 (0.10)	27.00
0.2000	0.2000	0.1000	0.0981	−8.19 (0.08)	−12.70 (0.13)	11.66 (0.12)	32.55
0.2200	0.2200	0.1099	0.1078	−10.03 (0.10)	−15.77 (0.16)	12.31 (0.12)	38.11
0.2500	0.2500	0.1246	0.1224	−12.78 (0.13)	−19.73 (0.20)	14.30 (0.14)	46.81
0.2800	0.2800	0.1393	0.1369	−15.07 (0.15)	−25.43 (0.25)	15.54 (0.16)	56.04
0.3000	0.3000	0.1491	0.1466	−18.32 (0.18)	−28.93 (0.29)	16.73 (0.17)	63.99
0.3200	0.3200	0.1589	0.1562	−20.23 (0.20)	−33.13 (0.33)	17.52 (0.18)	70.89
0.3500	0.3500	0.1735	0.1707	−23.30 (0.23)	−39.62 (0.40)	18.93 (0.19)	81.84
0.3800	0.3800	0.1880	0.1851	−28.18 (0.28)	−46.18 (0.46)	20.35 (0.20)	94.70
0.4000	0.4000	0.1977	0.1947	−31.12 (0.31)	−51.78 (0.52)	21.30 (0.21)	104.20
0.4200	0.4200	0.2074	0.2043	−37.52 (0.38)	−55.12 (0.55)	21.49 (0.21)	114.13
0.4500	0.4500	0.2218	0.2186	−43.62 (0.44)	−64.75 (0.65)	23.74 (0.24)	132.12
0.5000	0.5000	0.2458	0.2424	−49.25 (0.49)	−81.50 (0.82)	26.42 (0.26)	157.18
			L-Valine + 2-Methylpyridine				
0.1000	0.1000	0.0540	0.0453	−1.49 (0.01)	−0.47 (0.01)	13.86 (0.14)	15.82
0.1500	0.1500	0.0808	0.0677	−4.42 (0.04)	−1.92 (0.02)	19.82 (0.20)	26.16
0.1800	0.1800	0.0968	0.0811	−6.39 (0.06)	−3.32 (0.03)	28.35 (0.28)	38.06
0.2000	0.2000	0.1075	0.0901	−8.03 (0.08)	−4.83 (0.05)	32.70 (0.33)	45.56
0.2200	0.2200	0.1181	0.0990	−10.24 (0.10)	−5.72 (0.06)	36.72 (0.34)	52.67
0.2500	0.2500	0.1340	0.1123	−12.55 (0.13)	−8.30 (0.08)	42.57 (0.43)	63.41
0.2800	0.2800	0.1499	0.1256	−15.67 (0.16)	−11.80 (0.12)	48.10 (0.48)	75.57
0.3000	0.3000	0.1604	0.1344	−18.07 (0.18)	−13.04 (0.13)	52.68 (0.53)	83.80
0.3200	0.3200	0.1709	0.1432	−21.60 (0.22)	−15.17 (0.15)	57.79 (0.58)	94.56
0.3500	0.3500	0.1866	0.1564	−24.16 (0.24)	−19.69 (0.20)	62.55 (0.63)	106.41
0.3800	0.3800	0.2023	0.1696	−28.14 (0.28)	−23.91 (0.24)	68.93 (0.69)	120.98
0.4000	0.4000	0.2127	0.1783	−30.07 (0.30)	−27.30 (0.27)	73.54 (0.74)	130.91
0.4200	0.4200	0.2231	0.1871	−34.48 (0.34)	−31.04 (0.31)	77.38 (0.77)	142.90
			L-Valine + 3-Methylpyridine				
0.1000	0.1000	0.0540	0.0453	−1.49 (0.01)	−3.22 (0.03)	8.65 (0.09)	13.36
0.1500	0.1500	0.0808	0.0677	−4.42 (0.04)	−7.50 (0.08)	11.66 (0.12)	23.58
0.1800	0.1800	0.0968	0.0811	−6.39 (0.06)	−13.09 (0.13)	16.06 (0.16)	35.54
0.2000	0.2000	0.1075	0.0901	−8.03 (0.08)	−16.66 (0.17)	18.07 (0.18)	42.76
0.2200	0.2200	0.1181	0.0990	−10.24 (0.10)	−19.57 (0.20)	19.52 (0.20)	49.33
0.2500	0.2500	0.1340	0.1123	−12.55 (0.13)	−25.38 (0.25)	22.27 (0.22)	60.20
0.2800	0.2800	0.1499	0.1256	−15.67 (0.16)	−32.18 (0.32)	24.97 (0.25)	72.82
0.3000	0.3000	0.1604	0.1344	−18.07 (0.18)	−36.82 (0.37)	26.59 (0.27)	81.48
0.3200	0.3200	0.1709	0.1432	−21.60 (0.22)	−41.40 (0.41)	28.57 (0.29)	91.57
0.3500	0.3500	0.1866	0.1564	−24.16 (0.24)	−49.78 (0.50)	30.96 (0.31)	104.90
0.3800	0.3800	0.2023	0.1696	−28.14 (0.28)	−57.91 (0.58)	33.14 (0.33)	119.19
0.4000	0.4000	0.2127	0.1783	−30.07 (0.30)	−61.89 (0.62)	35.37 (0.35)	127.33
0.4200	0.4200	0.2231	0.1871	−34.48 (0.34)	−68.19 (0.68)	37.82 (0.38)	140.49
0.4500	0.4500	0.2387	0.2001	−43.14 (0.43)	−78.90 (0.79)	42.94 (0.43)	164.98
			L-Valine + 4-Methylpyridine				
0.1000	0.1000	0.0540	0.0453	−1.49 (0.01)	−3.96 (0.04)	11.26 (0.11)	16.71
0.1500	0.1500	0.0808	0.0677	−4.42 (0.04)	−8.75 (0.09)	16.65 (0.17)	29.81
0.1800	0.1800	0.0968	0.0811	−6.39 (0.06)	−16.18 (0.16)	19.58 (0.20)	42.15
0.2000	0.2000	0.1075	0.0901	−8.03 (0.08)	−20.56 (0.21)	21.94 (0.22)	50.53
0.2200	0.2200	0.1181	0.0990	−10.24 (0.10)	−24.02 (0.24)	23.33 (0.23)	57.59
0.2500	0.2500	0.1340	0.1123	−12.55 (0.13)	−31.09 (0.31)	25.95 (0.26)	69.59
0.2800	0.2800	0.1499	0.1256	−15.67 (0.16)	−39.02 (0.39)	28.31 (0.28)	82.99
0.3000	0.3000	0.1604	0.1344	−18.07 (0.18)	−44.30 (0.44)	30.15 (0.30)	92.52
0.3200	0.3200	0.1709	0.1432	−21.60 (0.22)	−50.63 (0.51)	31.92 (0.32)	104.15
0.3500	0.3500	0.1866	0.1564	−24.16 (0.24)	−59.65 (0.60)	34.32 (0.34)	118.13
0.3800	0.3800	0.2023	0.1696	−28.14 (0.28)	−70.60 (0.71)	36.29 (0.36)	135.03
0.4000	0.4000	0.2127	0.1783	−30.07 (0.30)	−73.54 (0.74)	38.39 (0.38)	142.00
0.4200	0.4200	0.2231	0.1871	−34.48 (0.34)	−82.10 (0.82)	40.49 (0.40)	157.06
0.4500	0.4500	0.2387	0.2001	−43.14 (0.43)	−93.88 (0.94)	45.98 (0.46)	183.00
			L-Threonine + Pyridine				
0.1000	0.1000	0.0504	0.0493	0.22 (0.01)	−3.54 (0.04)	10.06 (0.10)	13.39
0.1500	0.1500	0.0753	0.0737	0.73 (0.01)	−7.32 (0.07)	15.62 (0.16)	22.20
0.1800	0.1800	0.0902	0.0884	0.97 (0.01)	−10.61 (0.10)	18.56 (0.19)	28.21
0.2000	0.2000	0.1001	0.0981	1.07 (0.01)	−12.70 (0.13)	21.12 (0.21)	32.75
0.2200	0.2200	0.1100	0.1078	1.28 (0.01)	−15.77 (0.16)	22.54 (0.23)	37.03
0.2500	0.2500	0.1248	0.1224	1.50 (0.02)	−19.73 (0.20)	25.44 (0.25)	43.67
0.2800	0.2800	0.1396	0.1369	1.97 (0.02)	−25.43 (0.25)	27.53 (0.28)	50.99
0.3000	0.3000	0.1493	0.1466	2.07 (0.02)	−28.93 (0.29)	29.19 (0.29)	56.05
0.3200	0.3200	0.1591	0.1562	2.40 (0.02)	−33.13 (0.33)	31.40 (0.31)	62.14
0.3500	0.3500	0.1737	0.1707	2.57 (0.03)	−39.62 (0.40)	33.60 (0.34)	70.64
0.3800	0.3800	0.1883	0.1851	3.11 (0.03)	−46.18 (0.46)	36.15 (0.36)	79.22
0.4000	0.4000	0.1980	0.1947	3.35 (0.03)	−51.78 (0.52)	37.21 (0.37)	85.64
0.4200	0.4200	0.2076	0.2043	3.62 (0.04)	−55.12 (0.55)	39.40 (0.39)	90.90
0.4500	0.4500	0.2221	0.2186	4.05 (0.04)	−64.75 (0.65)	41.85 (0.42)	102.56
0.5000	0.5000	0.2461	0.2424	4.53 (0.05)	−81.50 (0.82)	44.20 (0.44)	121.17

Table 2 (Continued)

$m_{x,i}$,[a] mol· kg^{-1}	$m_{y,i}$, mol· kg^{-1}	$m_{x,f}$, mol· kg^{-1}	$m_{y,f}$, mol·kg^{-1}	$\Delta H_{dil(x)}/w_1$, J·kg^{-1}	$\Delta H_{dil(y)}/w_1$, J·kg^{-1}	$\Delta H_{mix}/w_1$, J·kg^{-1}	$\Delta H^*/w_1$, J·kg^{-1}
			L-Threonine + 2-Methylpyridine				
0.1000	0.1000	0.0990	0.0453	0.25 (0.01)	−0.47 (0.01)	21.99 (0.22)	22.21
0.1500	0.1500	0.1478	0.0677	0.82 (0.01)	−1.92 (0.02)	34.77 (0.35)	35.87
0.1800	0.1800	0.1768	0.0811	1.05 (0.01)	−3.32 (0.03)	42.67 (0.43)	44.95
0.2000	0.2000	0.1961	0.0901	1.65 (0.02)	−4.83 (0.05)	48.25 (0.48)	51.44
0.2200	0.2200	0.2153	0.0990	1.71 (0.02)	−5.72 (0.06)	54.64 (0.55)	58.64
0.2500	0.2500	0.2439	0.1123	1.95 (0.02)	−8.30 (0.08)	62.53 (0.63)	68.87
0.2800	0.2800	0.2724	0.1256	2.13 (0.02)	−11.80 (0.12)	71.39 (0.71)	81.06
0.3000	0.3000	0.2912	0.1344	2.53 (0.03)	−13.04 (0.13)	78.52 (0.79)	89.04
0.3200	0.3200	0.3101	0.1432	3.01 (0.03)	−15.17 (0.15)	82.47 (0.82)	94.64
0.3500	0.3500	0.3381	0.1564	2.35 (0.02)	−19.69 (0.20)	90.19 (0.90)	107.52
0.3800	0.3800	0.3661	0.1696	3.19 (0.03)	−23.91 (0.24)	98.60 (0.99)	119.32
0.4000	0.4000	0.3846	0.1783	3.35 (0.03)	−27.30 (0.27)	105.08 (0.11)	129.02
0.4200	0.4200	0.4030	0.1871	3.62 (0.04)	−31.04 (0.31)	110.07 (0.11)	137.49
			L-Threonine + 3-Methylpyridine				
0.1000	0.1000	0.0540	0.0453	0.25 (0.01)	−3.22 (0.03)	14.11 (0.14)	17.08
0.1500	0.1500	0.0808	0.0677	0.82 (0.01)	−7.50 (0.08)	21.62 (0.22)	28.30
0.1800	0.1800	0.0968	0.0811	1.05 (0.01)	−13.09 (0.13)	25.20 (0.25)	37.24
0.2000	0.2000	0.1075	0.0901	1.65 (0.02)	−16.66 (0.17)	27.50 (0.28)	42.51
0.2200	0.2200	0.1181	0.0990	1.71 (0.02)	−19.57 (0.20)	30.38 (0.30)	48.24
0.2500	0.2500	0.1340	0.1123	1.95 (0.02)	−25.38 (0.25)	33.74 (0.34)	57.17
0.2800	0.2800	0.1498	0.1256	2.13 (0.02)	−32.18 (0.32)	38.04 (0.38)	68.08
0.3000	0.3000	0.1604	0.1344	2.53 (0.03)	−36.82 (0.37)	39.83 (0.40)	74.12
0.3200	0.3200	0.1709	0.1432	3.01 (0.03)	−41.40 (0.41)	42.41 (0.42)	80.80
0.3500	0.3500	0.1866	0.1564	2.35 (0.02)	−49.78 (0.50)	44.70 (0.45)	92.13
0.3800	0.3800	0.2022	0.1696	3.19 (0.03)	−57.91 (0.58)	47.94 (0.48)	102.66
0.4000	0.4000	0.2127	0.1783	3.35 (0.03)	−61.89 (0.62)	49.70 (0.50)	108.23
0.4200	0.4200	0.2231	0.1871	3.62 (0.04)	−68.19 (0.68)	52.84 (0.53)	117.41
0.4500	0.4500	0.2386	0.2001	4.50 (0.05)	−78.90 (0.79)	56.63 (0.57)	131.03
0.5000	0.5000	0.2644	0.2218	4.70 (0.05)	−96.26 (0.96)	62.48 (0.62)	154.04
			L-Threonine + 4-Methylpyridine				
0.1000	0.1000	0.0540	0.0453	0.25 (0.01)	−3.96 (0.04)	18.97 (0.19)	22.68
0.1500	0.1500	0.0808	0.0677	0.82 (0.08)	−8.75 (0.09)	27.49 (0.27)	35.42
0.1800	0.1800	0.0968	0.0811	1.05 (0.01)	−16.18 (0.16)	32.43 (0.32)	47.56
0.2000	0.2000	0.1075	0.0901	1.65 (0.02)	−20.56 (0.21)	35.94 (0.36)	54.86
0.2200	0.2200	0.1181	0.0990	1.71 (0.02)	−24.02 (0.24)	38.70 (0.39)	61.02
0.2500	0.2500	0.1340	0.1123	1.95 (0.02)	−31.09 (0.31)	42.51 (0.43)	71.65
0.2800	0.2800	0.1498	0.1256	2.13 (0.02)	−39.02 (0.39)	46.55 (0.47)	83.44
0.3000	0.3000	0.1604	0.1344	2.53 (0.03)	−44.30 (0.44))	49.50 (0.50)	91.27
0.3200	0.3200	0.1709	0.1432	3.01 (0.03)	−50.63 (0.51)	52.11 (0.52)	99.73
0.3500	0.3500	0.1866	0.1564	2.35 (0.02)	−59.65 (0.60)	54.57 (0.55)	111.87
0.3800	0.3800	0.2022	0.1696	3.19 (0.03)	−70.60 (0.71)	57.62 (0.58)	125.03
0.4000	0.4000	0.2127	0.1783	3.35 (0.03)	−73.54 (0.74)	60.27 (0.60)	130.45
0.4200	0.4200	0.2231	0.1871	3.62 (0.04)	−82.10 (0.82)	63.00 (0.63)	141.48
0.4500	0.4500	0.2386	0.2001	4.50 (0.05)	−93.88 (0.94)	70.73 (0.71)	160.11
0.5000	0.5000	0.2644	0.2218	4.70 (0.05)	−114.02 (0.11)	74.19 (0.74)	183.51

[a] $m_{x,i}$ and $m_{y,i}$ are the initial molalities of solutes x and y; $m_{x,f}$ and $m_{y,f}$ are the final molalities of solutes x and y. [b] The values in parentheses are the experimental errors.

there exists h_{xy}(L-valine) > h_{xy}(L-threonine), which indicates that the former effect is relatively stronger. But in pyridine aqueous solution, the case is reversed.

b. Enthalpic Pairwise Interactions of the Same Amino Acid with Pyridine and Methylpyridine Isomers in Aqueous Solution. In this continuing series of investigations,[7,8] the rules of the interactions of L-valine and L-threonine with pyridine and methylpyridine isomers have been found to be different from those of glycine, L-alanine, and L-serine.

Compared to the cases of glycine, L-alanine, and L-serine, the hydrophobic group of L-valine has the biggest volume. And the steric effect is the most notable for 2-methylpyridine among pyridine and the methylpyridine isomers. Consequently, the interactions between L-valine and 2-methylpyridine are weakened. Thus, the rule of L-valine, different from that of glycine, L-alanine, and L-serine,[7,8] has been observed as follows: h_{xy}(4-methylpyridine) > h_{xy}(3-methylpyridine) > h_{xy}(2-methylpyridine).

There is one hydroxyl on the side chain of L-threonine, correspondent to one methyl on the isopropyl of L-valine replaced by one hydroxyl. Because the solvation volume of hydroxyl is larger than that of methyl, the steric effect becomes more remarkable for the interaction between L-threonine and 2-methylpyridine, compared to L-valine. For L-threonine, there exists the following rule: h_{xy}(pyridine) > h_{xy}(2-methylpyridine), which shows that the influence brought about by the steric effect has surpassed that brought about by the introduction of methyl to the pyridine ring.

2. SWAG Analysis of the Enthalpic Pairwise Interaction Coefficients of Amino Acids with Pyridine and Methylpyridine Isomers. The simplest way currently available to address the data set of heterotactic pairwise interaction coefficients is to use the Savage and Wood additivity of groups (SWAG) approach,[10] which has been used with varying degrees of success in a considerable number of investigations.[15−19] The principle assumes that when two solute molecules interact, every functional group in molecule x interacts with every functional group in molecule y and that each interaction has a characteristic enthalpy, which is independent of the position of each group within their respective molecules. The total pairwise molecular interaction enthalpy is then the sum of all of

Table 3. Experimental Heterotactic Enthalpic Interaction Coefficients and Calculated Values of Heterotactic Enthalpic Pairwise Interaction Coefficients (h_{xy}) for Various α-Amino Acids with Pyridine and Methylpyridine in Aqueous Solutions at 298.15 K

solutes $x + y$	h_{xy}(expt)/ J·kg·mol^{-2}	$10^{-4}h_{xxy}$/ J·kg^2·mol^{-3}	$10^{-4}h_{xyy}$/ J·kg^2·mol^{-3}	SD[d]	Cr[e]/mol·kg^{-1}	h_{xy}(calc)/ J·kg·mol^{-2}	δ[f]
glycine + pyridine[a]	1147	105	−106	0.69	0.10−0.50	1122	−2.2
L-alanine + pyridine[a]	1268	−80	82	0.54	0.10−0.50	1312	3.5
L-serine + pyridine[b]	1769	73	82	0.98	0.10−0.50	1692	−1.1
L-valine + pyridine[c]	1711	−13	13	0.92	0.10−0.50	1798	−0.7
L-threonine + pyridine[c]	1975	25	25	0.43	0.10−0.50	1988	0.7
glycine + 2-methylpyridine[a]	2150	−40	48	0.50	0.10−0.42	2237	4.1
L-alanine + 2-methylpyridine[a]	2176	−47	56	1.39	0.10−0.42	2423	11.3
L-serine + 2-methylpyridine[b]	3192	264	317	1.27	0.10−0.42	2794	−10.8
L-valine + 2-methylpyridine[c]	3134	−237	282	1.07	0.10−0.42	2431	−23.8
L-threonine + 2-methylpyridine[c]	1857	−5	11	0.64	0.10−0.42	2617	40.9
glycine + 3-methylpyridine[a]	1869	34	−41	0.85	0.10−0.50	1741	−6.9
L-alanine + 3-methylpyridine[a]	1956	46	−55	0.99	0.10−0.50	2346	19.9
L-serine + 3-methylpyridine[b]	3128	383	−458	1.19	0.10−0.50	3557	−6.9
L-valine + 3-methylpyridine[c]	3820	−498	594	1.76	0.10−0.45	2733	−12.6
L-threonine + 3-methylpyridine[c]	2943.1	−197.4	234.8	0.69	0.10−0.50	3338	13.4
glycine + 4-methylpyridine[a]	2270.0	39.9	−48.5	1.64	0.10−0.50	2146	−5.5
L-alanine + 4-methylpyridine[a]	2412.9	59.7	−72.0	1.54	0.10−0.50	2790	15.6
L-serine + 4-methylpyridine[b]	3770.9	418.3	−501.0	1.38	0.10−0.50	4079	−5.9
L-valine + 4-methlpyridine[c]	4335.6	−562.8	670.4	1.88	0.10−0.45	3385	−10.2
L-threonine + 4-methylpyridine[c]	3646.2	−247.6	294.6	1.46	0.10−0.50	4030	10.5

[a] Reference 7. [b] Reference 8. [c] This work. [d] SD = standard derivation. [e] Cr = concentration range. [f] Relative deviation, $\delta = 100\{[h_{xy}(\text{calc}) - h_{xy}(\text{expt})]/h_{xy}(\text{expt})\}$.

the various functional group interactions. The resulting equation is

$$h_{xy} = \sum_{i,j} n_i^x n_j^y H_{ij} \tag{7}$$

where n_i^x is the number of groups of type i on molecule x, n_j^y is the number of groups of type j on molecule y, H_{ij} is the characteristic contribution to the enthalpy of one i group interaction with one j group, and h_{xy} is the coefficient (reflecting pairwise interactions of x and y) in the molality expansion of excess enthalpy.

In the present work amino acids + pyridine and amino acids + methylpyridine systems are attempted to be treated using the SWAG principle. To apply this additivity approach, it is necessary to divide each molecule in the set into a number of functional groups. For α-amino acids and pyridine and methylpyridine molecules, the following division method has been conducted: the $^+NH_3$ and COO^- functional groups are treated as one unit, which has been symbolized E. The hydrocarbon functional group is based on the methylene unit. Following the literature,[3] a CH_3 group is equivalent to 1.5 CH_2 groups, a CH group is equivalent to 0.5 CH_2 groups, and H is also counted as 0.5 CH_2 group. The hydroxyl group (OH) of the α-amino acids and the pyridine ring of pyridine and methylpyridine are the next distinguished functional groups. The treatment method of the alkyl on the pyridine ring is the same as that of the alkyl on the α-carbon of the amino acids.

For the group contributions of the above five amino acids (x) and pyridine and methylpyridine (y), eq 7 can be expressed as

$$h_{xy} = H_{E-B} + n_{CH_2}(x)H_{CH_2-B} + H_{OH-B} + n_{CH_2}(y)H_{E-CH_2} + n_{CH_2}(x)\, n_{CH_2}(y)H_{CH_2-CH_2} + n_{CH_2}(y)H_{OH-CH_2} \tag{8}$$

The experimental results of amino acids + 4-methylpyridine, amino acids + 3-methylpyridine, and amino acids + 2-methylpyridine, along with the data of amino acids + pyridine, were treated using the SWAG approach, respectively. Multiple linear regression analysis applied to eq 8 yielded the following H_{ij} values, respectively:

$$H_{E-B} = 1027\ (133) \qquad H_{CH_2-B} = 189\ (58) \qquad H_{OH-B} = 581\ (122)$$

$$H_{E-CH_2} = 531\ (123) \qquad H_{CH_2-CH_2} = 303\ (55) \qquad H_{OH-CH_2} = 224\ (115) \tag{9}$$

$$H_{E-B} = 1027\ (137) \qquad H_{CH_2-B} = 190\ (60) \qquad H_{OH-B} = 581\ (126)$$

$$H_{E-CH_2} = 274\ (127) \qquad H_{CH_2-CH_2} = 277\ (56) \qquad H_{OH-CH_2} = 72\ (118) \tag{10}$$

$$H_{E-B} = 1027\ (214) \qquad H_{CH_2-B} = 190\ (93) \qquad H_{OH-B} = 581\ (196)$$

$$H_{E-CH_2} = 745\ (198) \qquad H_{CH_2-CH_2} = -3\ (88) \qquad H_{OH-CH_2} = -320\ (184) \tag{11}$$

where the units of H_{ij} are J·kg·mol^{-2}, the correlation coefficients are 0.9952, 0.9932, and 0.9804, respectively, and the data in the parentheses are the estimated deviations.

Table 3 gives a comparison of the experimental enthalpies of interaction and the calculated ones obtained from eqs 9−11, on the basis of the contributions mentioned above. As can be seen from Table 3, despite the simplicity of the model of interactions, in most cases the two sets of data are in satisfactory agreement. The results obtained from the SWAG approach make the interactions between α-amino acids and pyridine and methylpyridine quantitative and can basically reflect the rules of the interactions processes. The resulting value of h_{xy} would be a consequence of the balance between the various interactions of the functional groups.

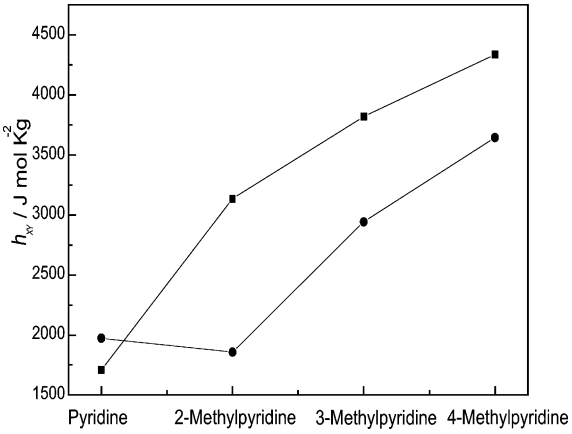

Figure 1. Comparison between the values of heterotactic enthalpic pairwise interaction coefficients for L-valine and L-threonine with pyridine and methylpyridine isomers in aqueous solutions at 298.15 K: (■) L-valine; (●) L-threonine.

As can be seen from eqs 9−11, the values of H_{E-B}, H_{CH_2-B}, and H_{OH-B} are nearly equal, but among those of H_{E-CH_2}, $H_{CH_2-CH_2}$, and H_{OH-CH_2}, there exist very large differences. The main interpretation is that for pyridine and methylpyridine molecules the former three group contributions only concern the pyridine ring; however, the latter ones relate to the methyl substituent group on the pyridine ring, from which results the obvious steric effect.

In addition, eq 11 displays that for amino acids + 2-methylpyridine systems some unreasonable H_{ij} values occur; for example, $H_{CH_2-CH_2} = -3$ J·kg·mol^{-2} and $H_{OH-CH_2} = -320$ J·kg·mol^{-2} are clearly of the wrong sign. Table 3 also shows that there exists a very large relative deviation for the L-threonine + 2-methylpyridine system. The primary reason is that the assumption of SWAG is too simple. Subtle but important effects were disregarded in the molecular interaction processes. Deviations from the correlation can be caused by specific effects such as the following: (1) steric effects when two groups are prevented from getting close to each other by the presence of other groups; (2) nearest-neighbor effects in which the presence of a close-by functional group changes the interactions of its neighbors; (3) cooperative effects in which a strong attraction (repulsion) between two groups brings two neighboring groups close together (keeps them apart more often and increases (decreases) their interaction).[3,20] Among the methylpyridine isomers, the introduction of a methyl group for 2-methylpyridine causes the strongest steric effect. When it interacts with L-threonine, whose volume is relatively big, the steric effect is exhibited more obviously. Thus, when such a system is treated by SWAG, the error is relative large, and even, an unreasonable H_{ij} value appears.

To sum up, although in this work there are some relatively large deviations arising from the results according to SWAG, this approach could still be of some value for amino acids + pyridine and amino acids + methylpyridine systems in aqueous solutions. It is just that a unique set of interaction parameters would have to be determined for these classes of compounds.

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