JOURNAL OF CHEMICAL & ENGINEERING DATA

ARTICLE

pubs.acs.org/jced

Thermophysical Study of Several α- and β-Amino Acid Derivatives by Differential Scanning Calorimetry (DSC)

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ABSTRACT: The present study reports a differential scanning calorimetry (DSC) study of the amino acids sarcosine [CAS Registry No. 107-97-1], α-alanine (DL) [CAS Registry No. 302-72-7], β-alanine [CAS Registry No. 107-95-9], *N*-benzyl-α-alanine (DL) [CAS Registry No. 40297-69-6], and *N*-benzyl-β-alanine [CAS Registry No. 5426-62-0] in the temperature interval from $T = 268$ K to their respective melting/decomposition temperatures. Temperatures and heat capacities as a function of temperature of all solids and the enthalpies and entropies of fusion of two of the amino acids, sarcosine and *N*-benzyl-β-alanine, are reported.

INTRODUCTION

Amino acids are among the most important building blocks of life and are also believed to play key roles in interstellar chemistry as well as in the origin of life on Earth.[1,2] They are the building blocks of peptides and the backbone of proteins, and for this reason, they have been extensively studied.

In addition to their fundamental biological importance, amino acids present rather interesting physical properties; for example, in solution or in the crystalline state they exist as zwitterions[3] that are stabilized by intermolecular electrostatic polarization, as well as hydrogen-bonding interactions with their environment.[4,5] By contrast, in the gaseous state, or when isolated in a noble gas matrix at low temperature, the neutral forms are more stable.[4,5]

The knowledge of heat capacity as a function of temperature is an essential property for the calculation of thermodynamic properties such as ΔH, ΔS, and ΔG at different temperatures, and this property plays an important role in identifying and understanding transitions occurring in the solid state of crystals and in liquid crystals. Heat capacities at $T = 298.15$ K have proven quite useful in adjusting vaporization, sublimation, and fusion enthalpies with temperature. Equations for doing this have recently been reported by Chickos and co-workers.[6−8] There are several compilations of critically evaluated calorimetrically measured heat capacities,[9−13] but new and reliable data on the heat capacity of important families of compounds are still needed,[14,15] particularly for crystalline solids. There has been an effort to develop reliable and accurate group contribution schemes to improve the estimation and compensate for the scarcity of this data. The simplest schemes are based on first-order additivity and only consider the constituent groups of the molecule.[16,17] Other methods use a second-order additivity scheme that takes into account nearest-neighbor interactions in the definition of the structural units of molecules.[18−20] These schemes normally neglect all next-to-nearest neighbor interactions because of the limited accuracy of the available experimental heat capacity data. Although current improvements in instrumentation and protocol allow the experimental determination of heat capacities by differential scanning calorimetry (DSC) within an error of 0.15 %,[21] the actual experimental uncertainty of the measured heat capacity is often larger due to the presence of impurities in the samples under investigation. Special care must be taken to remove or reduce the water content, especially for liquid samples, since the heat capacity of water departs considerably from that of the majority of organic compounds. Estimations of heat capacity of solids are more problematic than their liquid counterparts. This is due in part to the lack of data but also due to the anisotropic nature of the solid state. Phase transitions in solids can affect their heat capacities near these transitions. Solids that form liquid crystals, for example, appear to have larger heat capacities in certain temperature regions, and total phase change entropies seem to be attenuated in comparison to systems that melt directly to isotropic liquids.[22] Group values for estimating the heat capacity of crystalline solids have been reported, but the estimations in many cases have been hampered by the lack of sufficient reference data.

During the past few years, we have been involved in the experimental determination of enthalpies of fusion and heat capacities, as well as the study of polymorphism of pure crystalline organic compounds.[23−31] Nevertheless, despite the importance of amino acids, reliable experimental thermochemical studies are scarce. Very recently we have carried out[32,33] a thermochemical study of α-alanine (DL), β-alanine, *N*-benzyl-α-alanine (DL), and *N*-benzyl-β-alanine,

Received: May 11, 2011
Accepted: September 8, 2011
Published: September 26, 2011

dx.doi.org/10.1021/je200292z | J. Chem. Eng. Data 2011, 56, 3807–3812

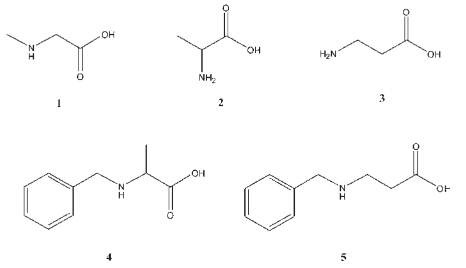

Figure 1. Molecular structures of the amino acids studied in the present work: sarcosine (**1**), α-alanine (**2**), β-alanine (**3**), *N*-benzyl-α-alanine (**4**), and *N*-benzyl-β-alanine (**5**).

reporting their molar enthalpies of formation in the condensed and gas states.

To our knowledge, since 1937, there are four data points in the literature for heat capacity at T = 298.15 K for α-alanine (DL): (121.7, 121.6, 113.8, and 114.0) $\text{J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$, according to Huffman and Ellis,[34] Spink and Wadsö,[35] Kulikov et al.,[36] and Badelin et al.,[37] respectively. It can be appreciated that these values are spread over a range of ca. 8 $\text{J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$.

For β-alanine, there are four published values for the heat capacity at T = 298.15 K: (116.4, 109.3, 109.0, and 116.2) $\text{J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$, reported by Skoulika and Sabbah,[38] Kulikov et al.,[36] Badelin et al.,[37] and most recently by Paukov et al.,[39] respectively. These values are also spread over a range of ca. 8 $\text{J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$.

For sarcosine we have found a single report from Sabbah and Laffitte[40] disclosing its heat capacity, $C_{p,\text{m}}$(cr, 298.15 K) = 128.9 $\text{J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$. There are no data in the literature for the heat capacities of *N*-benzyl-α-alanine (DL) and *N*-benzyl-β-alanine.

The present report discloses the temperature, enthalpy and entropy of fusion, and heat capacities of several amino acids measured by DSC. The target compounds (see Figure 1) are sarcosine (**1**), α-alanine (DL) (**2**), β-alanine (**3**), *N*-benzyl-α-alanine (DL) (**4**), and *N*-benzyl-β-alanine (**5**). An objective of this work was to expand the database of available experimental heat capacities of amino acids and to provide data to adjust and refine group contribution schemes for the estimation of this property for compounds that have not yet been investigated.

■ EXPERIMENTAL PROCEDURES

Materials. A commercial sample of sarcosine (Aldrich, cat. no. 131776, mp 481 K, decomp.) was used without further purification.

Commercial samples of α-alanine (DL) [CAS Registry No. 302-72-7] (15.0 g, 168.4 mmol, Aldrich, cat. no. 13,522-4, mp 562 K, decomp.) and β-alanine [CAS Registry No. 107-95-9] (15.0 g, 168.4 mmol, Aldrich, cat. no. 14,606-4, mp 475 K, decomp.) were placed in sublimators, which were evacuated to 0.5 mmHg and heated in an oil bath to (483 to 493) K and (433 to 443) K, respectively, to afford 11.8 g (79 % yield) of the sublimed α-alanine (DL), mp (563 to 564) K (decomp.), and 6.0 g (40 % yield) of the sublimed β-alanine, mp (477 to 478) K (decomp.). The purity of the samples was checked by NMR and C, H, and N microanalysis: NMR analysis suggested at least 99.5 % purity.

N-Benzyl-α-alanine (DL) [CAS Registry No. 40297-69-6] was obtained as follows: In a 300 mL hydrogenation flask was placed 3.0 g (33.7 mmol) of DL-alanine in 150 mL of $\text{MeOH/H}_2\text{O}$ (60:40), and to this was added 3.42 mL (33.7 mmol) of benzaldehyde and 0.30 g of 10 % Pd/C catalyst. The resulting mixture was pressurized to 200 psi with hydrogen and shaken for 24 h at 313 K before removal of the catalyst by filtration over Celite. The solvent was removed at reduced pressure in a rotary evaporator, and the crude product was purified by flash column chromatography (gradient EtOAc to EtOAc−MeOH, 70:30). The expected product (3.0 g, 50 % yield) was obtained as a white solid, mp (528 to 529) K (lit.[41] mp 526 K). ^{1}H NMR (D_2O, 270 MHz) δ: 1.46 (d, 3H, J = 7.2 Hz), 3.66 (q, 1H, J = 7.2 Hz), 4.17 (AB, 2H, J = 12.8 Hz), 7.44 (s, 5H). ^{13}C NMR (D_2O, 67.5 MHz) δ: 15.4, 49.9, 57.5, 129.4, 129.7, 130.0, 131.0, 174.9.

N-Benzyl-β-alanine [CAS Registry No. 5426-62-0] was prepared in a 500 mL hydrogenation flask in which was placed 10.0 g (112.2 mmol) of β-alanine in 150 mL of $\text{MeOH/H}_2\text{O}$ (80:20), and to this was added 11.4 mL (133.7 mmol) of benzaldehyde and 1.0 g of 10 % Pd/C catalyst. The resulting mixture was pressurized to 60 psi with hydrogen and shaken for 24 h before removal of the catalyst by filtration over Celite. The solvent was removed at reduced pressure in a rotary evaporator, and the crude product was purified by flash column chromatography (gradient EtOAc to EtOAc−MeOH, 70:30). The expected product (13.0 g, 65 % yield) was obtained as a white solid, mp (466 to 467) K (lit.[42] mp 469 K). ^{1}H NMR (D_2O, 270 MHz) δ: 2.43 (t, 2H, J = 20.0 Hz), 3.08 (t, 2H, J = 18.9 Hz), 4.10 (s, 2H), 7.37 (s, 5H). ^{13}C NMR (D_2O, 67.5 MHz) δ: 32.5, 43.8, 50.8, 129.4, 129.7, 129.8, 130.9, 178.0.

The standards used for DSC calibration were hexafluorobenzene, 99.9 % purity, supplied by Aldrich; benzoic acid, National Institute of Standards and Technology (NIST) standard reference sample 39j; and high-purity indium (mass fraction: > 0.99999), tin (mass fraction: > 0.99999), and synthetic sapphire, supplied by Perkin-Elmer.

Purity Control. All samples were carefully dried under vacuum. The purity and composition of the samples were checked by DSC and C, H, and N microanalysis. Calculated for $\text{C}_3\text{H}_7\text{NO}_2$, $10^2\,w(\text{C}) = 0.4044$, $10^2\,w(\text{H}) = 0.0792$, $10^2\,w(\text{N}) = 0.1572$; found $10^2\,w(\text{C}) = 0.4052 \pm 0.012$, $10^2\,w(\text{H}) = 0.0843 \pm 0.0041$, $10^2\,w(\text{N}) = 0.1596 \pm 0.0036$; $10^2\,w(\text{C}) = 0.4051 \pm 0.0026$, $10^2\,w(\text{H}) = 0.0797 \pm 0.0023$, $10^2\,w(\text{N}) = 0.1552 \pm 0.0023$; $10^2\,w(\text{C}) = 0.4054 \pm 0.0019$, $10^2\,w(\text{H}) = 0.0775 \pm 0.0006$, $10^2\,w(\text{N}) = 0.1575 \pm 0.0007$; for sarcosine, α-alanine (DL), and β-alanine, respectively. Calculated for $\text{C}_{12}\text{H}_{13}\text{NO}_2$, $10^2\,w(\text{C}) = 0.6702$, $10^2\,w(\text{H}) = 0.0731$, $10^2\,w(\text{N}) = 0.0782$; found $10^2\,w(\text{C}) = 0.6537 \pm 0.0001$, $10^2\,w(\text{H}) = 0.0723 \pm 0.0004$, $10^2\,w(\text{N}) = 0.0761 \pm 0.0006$ and $10^2\,w(\text{C}) = 0.6644 \pm 0.0011$, $10^2\,w(\text{H}) = 0.0710 \pm 0.0001$, $10^2\,w(\text{N}) = 0.0791 \pm 0.0003$ for *N*-benzyl-α-alanine (DL) and *N*-benzyl-β-alanine, respectively. For the determination of purity by DSC a heating rate of 0.04 $\text{K}\cdot\text{s}^{-1}$ was used, and five to eight samples weighing (1 to 2) mg were recorded. A fresh sample was used for each run. The determination of purities, using the fractional fusion technique,[43] indicated that the purities of sarcosine and *N*-benzyl-β-alanine were 99.0 ± 0.03 and 98.4 ± 0.02, respectively. It was not possible to determine the purity of α-alanine (DL), β-alanine, and *N*-benzyl-α-alanine because of decomposition of the compounds during the fusion process. No solid−solid phase transitions were observed in the compounds over the temperature interval where the heat capacity measurements were measured.

Apparatus and Procedure. The behavior of the samples as a function of temperature was studied by DSC. A Pyris 1 instrument from Perkin-Elmer equipped with an intracooler unit was used to monitor purity, to study the fusion process, to establish or rule out the possible existence of phase transitions in the solid samples, and to determine heat capacities as a function of temperature. The apparatus was previously calibrated in temperature and energy with reference materials. Temperature and power scales were calibrated[44−46] at heating rates of (0.04 and 0.17) K·s^{-1}. The temperature scales were calibrated by the melting temperature of the high-purity reference materials, hexafluorobenzene, tin, and indium.[47] The power scales were calibrated with high-purity indium.[47]

Thermograms of samples hermetically sealed in aluminum pans were recorded in a nitrogen atmosphere. All of the pans with the samples were weighed on a Mettler AT21 microbalance with a detection limit of $1 \cdot 10^{-6}$ g before and after the experiments to confirm that no product had volatilized.

Table 1. Group Values Used to Estimate $C_{p,\mathrm{m}}(\mathrm{cr})(298\ \mathrm{K})$ and $\Delta_{\mathrm{tpce}}S(T_{\mathrm{fus}})$

	$C_{p,\mathrm{m}}(\mathrm{cr})$ (298 K)	$\Delta_{\mathrm{tpce}}S(T_{\mathrm{fus}})$
	$\mathrm{J \cdot mol^{-1} \cdot K^{-1}}$	
groups (R)	Γ_R	Γ_R
CH_3-	36.6	17.6
$-CH_2-$	26.9	7.1
$-CH(C_2)$	9	−16.4
$-CH=$ aromatic	17.5	7.4
$-C=$ aromatic adj to an sp^3 C	8.5	−9.6
$-CO_2H$	53.1	16.2
$-NH_2$ (acyclic)	21.6	21.4
$-NH-$ (acyclic)	−0.3	−5.3

After calibration, several runs with high-purity benzoic acid and indium were performed under the same conditions as the experimental determinations. The accuracies associated with measurements of temperature and enthalpy of fusion were calculated as the percentage deviation of the experimental data with respect to the values given in the literature;[47] in all cases the deviations were lower than 0.2 % and 2.0 % for temperature and enthalpy determinations, respectively.[27]

For determinations of purity, temperature, and enthalpy of fusion, a heating rate of 0.04 K·s^{-1} was used, and five to eight samples weighing (1 to 2) mg were recorded. A fresh sample was used for each run. All compounds for which fusion enthalpies are reported showed thermal stability during the fusion process.

Different scans at heating rates of (0.04 and 0.17) K·s^{-1} were performed to determine the possible existence of phase transitions in the samples over the temperature range from T = 268 K to their melting or decomposition temperature.

Heat capacities were determined by the "scanning method" following the experimental methodology previously described[48−50] with synthetic sapphire (α-aluminum oxide) as reference material.[47−50] DSC is a commonly accepted method for the quantitative determination of heat capacities, and it has been proven as a suitable technique for obtaining reliable and accurate thermochemical data.[51,52] As a check of the reliability of the experimental method, control heat capacity experiments were performed with benzoic acid in the temperature interval T = (268 to 360) K.[27]

Table 2. Mean Experimental $C_{p,\mathrm{m}}(\mathrm{cr})$ Values (in $\mathrm{J \cdot mol^{-1} \cdot K^{-1}}$)

T	$C_{p,\mathrm{m}}(\mathrm{cr})/\mathrm{J \cdot mol^{-1} \cdot K^{-1}}$ compound					T	$C_{p,\mathrm{m}}(\mathrm{cr})/\mathrm{J \cdot mol^{-1} \cdot K^{-1}}$ compound				
K	1	2	3	4	5	K	1	2	3	4	5
263.15	107.3	107.6	105.2	199.3	193.4	380.15	145.4	148.3	139.1	263.6	274.1
265.15	108.3	108.4	105.8	200.7	194.4	385.15	147.0	149.8	140.7	266.4	277.6
270.15	109.9	110.2	107.3	204.2	196.9	390.15	148.8	151.3	142.4	269.8	281.6
273.51	110.8	111.3	108.2	206.2	198.2	395.15	150.5	153.0	144.0	273.0	285.3
275.15	111.5	111.9	108.8	207.8	199.0	400.15	152.2	154.6	145.7	276.8	289.2
280.15	112.8	113.4	110.3	211.1	201.4	405.15	154.0	156.3	147.4	280.6	292.9
285.15	114.2	115.0	111.7	213.9	204.2	410.15	155.6	158.1	148.9	283.5	296.6
290.15	116.0	116.9	113.1	217.2	207.1	415.15		159.7	150.0	285.5	300.7
295.15	117.4	118.9	114.5	220.4	210.5	420.15		161.5	152.0	288.7	305.1
298.15	118.2	119.9	115.2	222.4	221.7	425.15		163.0	152.7	293.1	
300.15	119.0	120.8	115.9	224.0	214.3	430.15		164.9	154.4	295.7	
305.15	120.5	122.7	117.3	227.2	217.8	435.15		167.0	156.2		
310.15	122.1	124.7	118.8	233.2	221.7	440.15		168.0	158.0		
315.15	123.5	126.2	119.8	232.3	227.0	445.15		170.1	159.6		
320.15	125.1	127.9	121.3	235.6	230.7	450.15		172.0	161.4		
325.15	126.4	128.4	122.2	237.2	234.4	455.15		173.8			
330.15	128.1	130.6	123.8	240.5	237.6	460.15		175.4			
335.15	129.8	132.2	125.4	244.6	241.6	465.15		177.0			
340.15	131.4	134.3	126.9	248.2	245.2	470.15		178.7			
345.15	133.2	136.1	128.4	250.9	248.3	475.15		178.8			
350.15	134.9	138.2	130.0	253.6	251.0	480.15		180.7			
355.15	136.4	140.3	131.7	256.3	254.3	485.15		183.4			
360.15	138.5	142.4	133.5	258.4	257.8	490.15		184.9			
365.15	140.6	144.1	135.0	257.7	262.7	495.15		187.5			
370.15	142.3	145.9	136.6	261.6	266.3	500.15		190.1			
375.15	143.9	146.8	137.7	261.0	270.9						

Table 3. Coefficients of the Fitted Curves

	T	A	$B \cdot 10^2$	$C \cdot 10^4$	$D \cdot 10^6$		rmsd[a]
	K	$J \cdot mol^{-1} \cdot K^{-1}$	$J \cdot mol^{-1} \cdot K^{-1}$	$J \cdot mol^{-1} \cdot K^{-1}$	$J \cdot mol^{-1} \cdot K^{-1}$	R^2	$J \cdot mol^{-1} \cdot K^{-1}$
1	263−410	118.16 ± 0.03	30.81 ± 0.09	4.2 ± 0.3	-1.6 ± 0.3	0.9998	0.20
2	263−500	119.00 ± 0.06	35.8 ± 0.2	-2.2 ± 0.3	0.69 ± 0.13	0.9995	0.52
3	263−450	115.09 ± 0.04	27.91 ± 0.13	2.2 ± 0.3	-0.41 ± 0.17	0.9997	0.30
4	263−430	223.41 ± 0.17	62.7 ± 0.6	-25.1 ± 1.6	14.5 ± 1.0	0.9978	1.31
5	263−420	214.02 ± 0.14	68.1 ± 0.5	10.3 ± 1.4	-4.5 ± 1.0	0.9992	0.99

[a] Root mean square deviation.

The relative percentage error of our measurements in comparison with those reported in the literature was less than 2 %.[27]

The mass of sapphire used in each run was 0.030345 g. For heat capacity determinations, three to six fresh samples weighing (10 to 25) mg were scanned for each solid compound in the temperature range from $T = 268$ K to its melting or decomposition temperature at 0.17 $K \cdot s^{-1}$. The complete temperature range for determination of heat capacity was divided in intervals of approximately 40 K, overlapping by 15 K from one interval to another. For the calculations, an overlap of only 5 K was used. The initial 10 K allowed the instrument's electronics to establish a linear baseline. The molecular weights used to convert the specific heat capacities measured to their molar values were calculated from the atomic weights recommended by the International Union of Pure and Applied Chemistry (IUPAC) in 2009.[53]

Estimations of $C_{p,m}$(cr) and $\Delta_{tpce}S(T_{fus})$. The group values listed in column 2 of Table 1 were used to estimate heat capacities,[16] and those provided in the third column were used to estimate total phase change entropy, $\Delta_{tpce}S(T_{fus})$,[54] from $T = (0$ to $T_{fus}/T_{decom})$ K of the amino acids studied. The protocol used to estimate $C_{p,m}$(cr)(298 K) is a straightforward additive group method and requires little clarification. Since group values for carboxyl and ammonium salts are not currently available, the group values for a primary and secondary aliphatic amine and a carboxylic acid were used as substitutes. As an example, using the group values in Table 1, the heat capacity for N-benzyl-α-alanine would be evaluated as: $5 \cdot (17.5) + 8.5 + 26.9 - 0.3 + 9 + 36.6 + 53.1 = 221.3\ J \cdot mol^{-1} \cdot K^{-1}$.

A similar situation regarding the absence of appropriate group values for ammonium and carboxylate salts exists for the estimation of $\Delta_{tpce}S(T_{fus})$. Therefore, the same substitutions were employed for these estimations. In these cases, it should be pointed out that the group value for a carboxylic acid, 13.4 $J \cdot mol^{-1} \cdot K^{-1}$, depends on the number of functional groups present.[54] The value of 16.2 $J \cdot mol^{-1} \cdot K^{-1}$ listed in Table 1 reflects the contribution of a carboxylic acid in the presence of two functional groups $(13.4 \cdot 1.21)$. Finally, the contribution of a methylene group, whenever the number of consecutive $-CH_2-$ groups equals or exceeds the sum total of the remaining groups, is equal to the 1.31 times the value listed in column 3 of the table. With the amino acids of the present study, this condition applies only to β-alanine: $21.4 + 2 \cdot 7.1 \cdot 1.3 + 16.2 = 56.2\ J \cdot mol^{-1} \cdot K^{-1}$. For substances containing only aromatic and aliphatic groups, the protocol used in estimating $\Delta_{tpce}S(T_{fus})$ is otherwise similar to the estimation of $C_{p,m}$(cr) (298 K).

RESULTS AND DISCUSSION

The measured molar heat capacities as a function of temperature for all compounds are collected in Table 2. The values given in Table 2 are averages of three to six independent runs. The standard deviation of all of the data associated with multiple measurements is less than 2 $J \cdot mol^{-1} \cdot K^{-1}$.

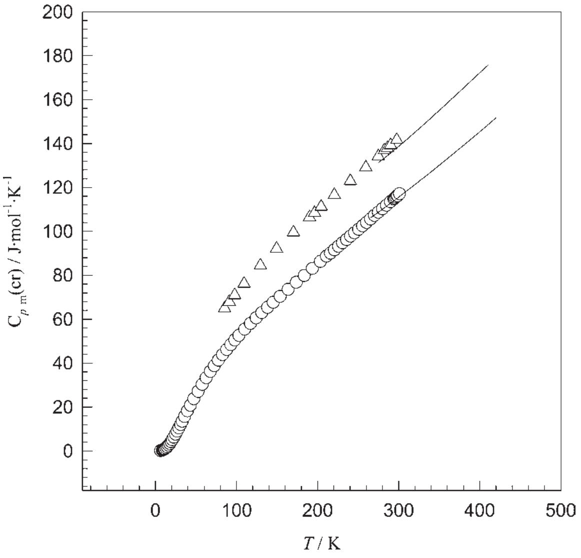

Figure 2. A comparison of the results of this work (lines) calculated using eq 1 with previous experimental literature values (symbols). Top curve: the heat capacity of DL-alanine[34] (for purposes of separating the two curves, a value of 20 was arbitrarily added to each experimental $C_{p,m}$ (cr) value). Bottom curve: the heat capacity of β-alanine.[39]

The experimental results for the compounds were fit to a third-order polynomial in temperature of the type:

$$C_{p,m}(cr) = A + B(T/K - 298.15) + C(T/K - 298.15)^2 + D(T/K - 298.15)^3 \qquad (1)$$

The range studied for each compound, the coefficients of the fitted third-order equation in temperature, and the root-mean-square deviation for all the compounds are collected in Table 3.

As noted previously, the heat capacity of DL-alanine was measured in 1937 by Huffman and Ellis[34] and β-alanine most recently in 2009 by Paukov et al.,[39] both by adiabatic calorimetry. Figure 2 illustrates the previous results with those obtained by DSC in this study. Over the temperature interval in which both previous studies overlap with the current results, the results appear in good agreement. The percent error for DL-alanine varies from (2.6 to 3.1) % and from (0.03 to 1.1) % for the most recent detailed study of β-alanine.

Table 4. Temperatures, Enthalpies, and Entropies of Fusion and Heat Capacities at $T = 298.15$ K for the Compounds Studied in This Work

	T_{fus}	$\Delta_{fus}H(T_{fus})$	$\Delta_{fus}S(T_{fus})/(J\cdot mol^{-1}\cdot K^{-1})$		$C_{p,m}(cr)(298.15\ K)/(J\cdot mol^{-1}\cdot K^{-1})$	
	K	$kJ\cdot mol^{-1}$	exp.	calcd[a]	exp.[b]	calcd[c]
sarcosine	481.6 ± 1.4	20.6 ± 0.7	42.8 ± 1.6	35.6	118.2	116.3
α-alanine				38.8	119.9	120.3
β-alanine				56.2	115.2	128.5
N-benzyl-α-alanine				46.6	222.4	221.3
N-benzyl-β-alanine	457.0 ± 0.5	42.7 ± 0.7	69.0 ± 0.5	59.6	221.7	229.5

[a] Values calculated according to ref 54; they represent the sum of all transition enthalpies from $T = (0 - T_{fus}/T_{decomp})$ K. [b] Experimental values at $T = 298.15$ K from Table 2. [c] Values calculated according to ref 16.

Experimental temperatures, enthalpies, and entropies of fusion of the compounds and heat capacities at $T = 298.15$ K measured and estimated in this work are summarized in Table 4. The uncertainties were taken as the standard deviation of the mean value. T_{fus} values are reported as DSC onset temperatures. No solid—solid phase transitions were observed over the temperature interval from $T = 268$ K to the corresponding melting or decomposition temperatures of any of the compounds.

Also included in column 5 of the Table 4 is the estimated total phase change entropy, $\Delta_{tpce}S(T_{fus})$, for all compounds.[54] This term includes the total phase change entropy associated in going from $T = 0$ K to the liquid at $T = T_{fus}$. For compounds without any other phase transitions, this entropy change is identical to the fusion entropy. The estimation of total phase change entropies, $\Delta_{tpce}S(T_{fus})$, and heat capacity, $C_{p,m}(cr)$ of the amino acids, because of their zwitterionic nature, would require group values for various ammonium (primary, secondary, etc.) and carboxylate ions. However, because of the paucity of such data, these particular group parameters are not available. Both sets of estimations were therefore conducted using the group values for the parent amino acids as found in their gas phase structures. The average error in the total phase change entropy estimation reported in Table 4 is about 8 $J\cdot mol^{-1}\cdot K^{-1}$. Similarly for the estimated heat capacities at $T = 298.15$ K, the use of existing group values for a carboxylic acid and primary and secondary amine appear to reproduce the experimental heat capacities within a standard deviation of $\pm$ 6.6 $J\cdot mol^{-1}\cdot K^{-1}$. Despite the limited statistics, both sets of estimation are well within the uncertainty associated with similar estimations on nonzwitterionic solids, reaffirming an earlier suggestion[16] that new group values for the ionic functional groups in amino acids may not be necessary.[8]

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Funding Sources

The support of the Spanish Ministry of Science and Innovation under Projects CTQ2007-60895/BQU and CTQ2010-16402 is gratefully acknowledged. E.J. is also indebted to CONACYT, Mexico, for financial support via Grant 60366.

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