
“ULTRASONIC VELOCITY, DENSITY AND VISCOSITY STUDIES OF MOLECULAR INTERACTIONS IN AQUEOUS AMINO ACID SOLUTIONS: A COMPREHENSIVE REVIEW”

***Sakshi Sushant Munde**

M.Sc. (Chemistry), Organic Chemistry Specialization, Shree Shivaji Science College, Amravati.

Article Received: 17 September 2026

Article Revised: 07 October 2026

Published on: 27 October 2026

***Corresponding Author: Sakshi Sushant Munde**

M.Sc. (Chemistry), Organic Chemistry Specialization, Shree Shivaji Science College, Amravati.

DOI: <https://doi-doi.org/101555/ijrpa.9977>

ABSTRACT

Dilute aqueous solutions of α -amino acids are among the simplest laboratory models for the charged, polar and nonpolar groups of proteins. Measurements of ultrasonic velocity, density and viscosity, used together, offer a sensitive, non-destructive picture of solute–solvent and solute–solute interactions in such systems. This review describes the zwitterionic chemistry of amino acids in water, the principles and practice of the three techniques, and the equations that yield adiabatic compressibility, intermolecular free length, acoustic impedance, hydration number, partial molar volume and compressibility, and Jones–Dole viscosity coefficients. A stepwise worked example based on an illustrative glycine data set at 298.15 K demonstrates the calculations and the meaning of each parameter. Representative literature on standard partial molar volumes, temperature effects, electrolyte effects and structure-making or structure-breaking behavior is then examined. A consistent picture emerges: charged end groups electrostrict water and give a negative partial molar compressibility, while nonpolar side chains add positive volume increments and raise the viscosity B coefficient. Remaining problems and future directions are noted.

INDEX TERMS: Amino Acids, Ultrasonic Velocity, Partial Molar Volume, Adiabatic Compressibility, Viscosity B-Coefficient, Solute–Solvent Interactions, Hydration.

I. INTRODUCTION

Each α -amino acid contains an amino group and a carboxyl group bonded to one carbon (the α -carbon) and carries a variable side chain R, which may be as small as a hydrogen atom

(glycine) or may be an aliphatic, aromatic, hydroxylic or ionizable group. Dissolved in water, these compounds are present mostly as zwitterions; a single small molecule thus has a positive and a negative site, a hydrogen-bonding backbone and, in many cases, a nonpolar surface [1]. Since proteins are assembled from these building blocks, how amino acids behave towards water, ions and additives serves as a thermodynamic model for protein hydration, folding and stability [2], [3], [4].

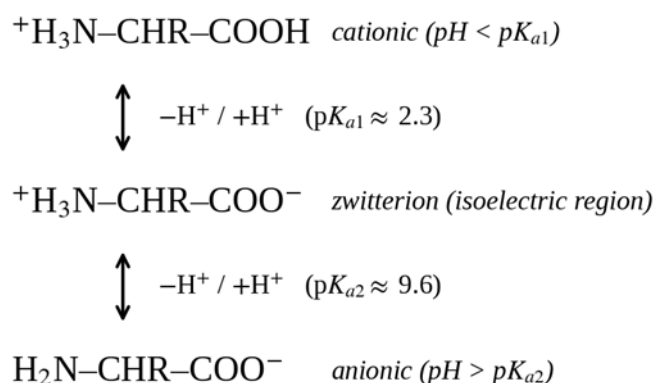
Calorimetric and spectroscopic probing of such interactions is difficult at the modest concentrations allowed by amino acid solubility and stability. Measurements of density, sound velocity and viscosity, by contrast, are straightforward and complement one another well. Density reveals the volume taken up by the solute and hence the degree to which water shrinks around it (electrostriction). Sound velocity depends on both density and adiabatic compressibility, so it reports on the hydration layer. Viscosity reflects solute size and shape and the ordering or disordering effect that the solute exerts on the surrounding water [5], [6].

After the pioneering determinations of apparent molal volumes and adiabatic compressibility's of amino acids [7], extensive data were gathered for pure water at various temperatures [8], [9], for salt solutions [10], [11] and for other additive media [12], [13]. The present review examines this work from an organic-chemistry viewpoint: the functional groups behind each interaction are identified, the equilibria are written explicitly, and the working equations are brought together and applied in a worked example. Its objectives are to (i) outline the behavior of amino acids in water, (ii) set out the principles and methods of ultrasonic, density and viscosity measurements, (iii) demonstrate the calculations stepwise, and (iv) assess the principal results and unresolved questions.

II. AMINO ACIDS IN AQUEOUS SOLUTION

A. Acid–base speciation

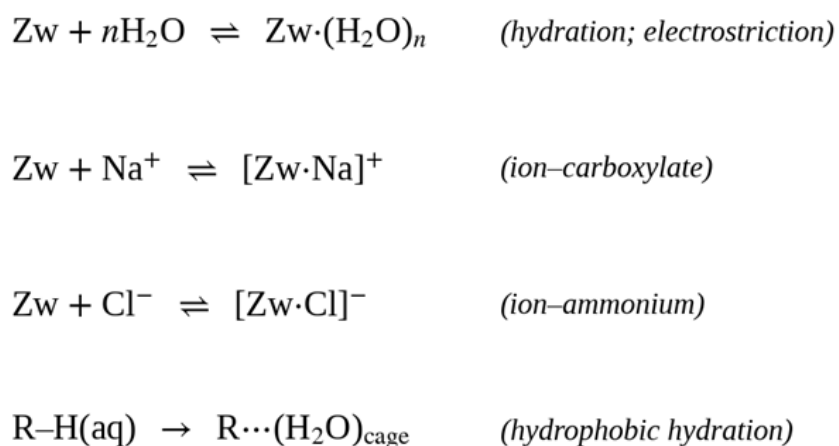
In water an α -amino acid undergoes the proton-transfer equilibria depicted in Scheme 1. Around neutral pH the zwitterion is the dominant form; its large dipole moment (roughly 10–15 D) accounts for good water solubility and strong interaction with polar media [1]. In glycine the two dissociation constants are $pK_{a1} \approx 2.3$ for the carboxyl group and $pK_{a2} \approx 9.6$ for the ammonium group. Because most volumetric and acoustic work uses unbuffered water at 0.01–1 mol kg⁻¹, only the zwitterion is considered significant. Residues with ionizable side chains (Asp, Glu, Lys, Arg, His) require pH control; otherwise the measured quantity is a mixture of contributions from several species.



Scheme 1. Proton-transfer equilibria of an α -amino acid in water.

B. Types of solute–solvent interaction

The interactions of the zwitterion with water and with added ions are collected in Scheme 2 and Table I, where Zw stands for the zwitterion. The charged NH_3^+ and COO^- ends bind water through ion–dipole forces and hydrogen bonds, ordering the neighboring water molecules (electrostriction). Alkyl and aryl side chains are nonpolar and are surrounded by a more ordered, cage-like water structure [14], [2]; the transfer free energies of these side chains out of water underlie the common hydrophobicity scales [15]. Polar side chains ($-\text{OH}$, $-\text{CONH}_2$) provide extra hydrogen-bonding sites. Added electrolytes can pair cations with carboxylate and anions with ammonium, and this competes with the hydration of those groups.



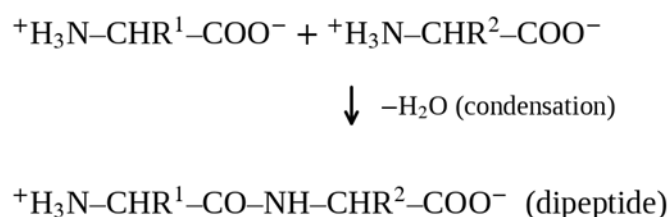
Scheme 2. Hydration and ion–zwitterion interactions of an amino acid zwitterion (Zw) in water and in aqueous electrolyte.

TABLE I: PRINCIPAL SOLUTE–SOLVENT INTERACTIONS OF AMINO ACIDS AND THEIR TYPICAL SIGNATURES.

Interaction	Chemical origin	Typical effect on measured properties
Ion–dipole hydration	NH_3^+ and COO^- bound to water by charge–dipole and H-bonds	Volume contraction (electrostriction); negative K_2^0 ; higher u ; positive B
Hydrophobic hydration	Alkyl or aryl side chain R	Positive volume increment per CH_2 ; B grows with chain length
Polar H-bonding	$-\text{OH}$, $-\text{CONH}_2$, peptide $\text{C}=\text{O}$ and $\text{N}-\text{H}$	Moderate volume contraction; moderate rise in B
Ion–zwitterion association	$\text{Na}^+ \cdots \text{COO}^-$, $\text{Cl}^- \cdots \text{NH}_3^+$ in salt solution	Release of electrostricted water; positive volume of transfer
Zwitterion–zwitterion	Dipole–dipole, H-bonding between solutes	Sign and size of S_v and S_k

Note: Compiled from the general picture in [4], [16].

Amino acids also condense into peptides (Scheme 3). For this reason, glycyl peptides and other small peptides are examined together with amino acids as models of the polar amide backbone of proteins [10]; comparing an amino acid with its peptide separates the contribution of the $-\text{CONH}-$ group from that of the charged termini.

**Scheme 3. Peptide-bond formation by condensation of two amino acid zwitterions.**

III. THEORETICAL BASIS OF THE MEASUREMENTS

A. Ultrasonic velocity and derived acoustic parameters

Ultrasonic waves (generally 1–5 MHz in laboratory interferometers) alternately compress and expand the liquid so quickly that heat has no time to flow, which makes the process adiabatic [17]. The velocity u is linked to the adiabatic compressibility β_s and the density ρ through the Newton–Laplace relation:

$$\beta_s = 1 / (u^2 \rho) \quad (1)$$

Since u cannot be interpreted without knowing how ρ varies, a set of derived quantities is employed. The specific acoustic impedance is

$$Z = u\rho \quad (2)$$

and the intermolecular free length, introduced by Eyring and Kincaid and put in practical form by Jacobson [18], [19], is

$$L_f = K_J (\beta_s)^{1/2}, K_J = (93.875 + 0.375 T) \times 10^{-8} \quad (3)$$

where T is the temperature in kelvin. A decrease of L_f with concentration indicates that the molecules are packed more tightly, as happens when the solute orders the surrounding solvent. The relative association is

$$R_A = (\rho/\rho_0)(u_0/u)^{1/3} \quad (4)$$

and the apparent hydration number, following the treatment of Ptaszynski and Shio [20], [21], is

$$n_h = (n_1/n_2)(1 - \beta_s/\beta_{s0}) \quad (5)$$

Here the subscript 0 denotes pure water, and n_1 and n_2 are the moles of water and solute in a given volume of solution. The model assumes that water in the hydration layer cannot be compressed further, so any fall in the compressibility of the solution relative to water is ascribed to bound water.

B. Density and volumetric parameters

For a solute of molar mass M at molarity c , the apparent molar volume is

$$V_\phi = M/\rho_0 - 1000(\rho - \rho_0)/(c\rho_0) \quad (6)$$

where V_ϕ is in $\text{cm}^3 \text{mol}^{-1}$, densities are in g cm^{-3} , and c is in mol dm^{-3} . The concentration dependence at low concentration is described by the Masson equation [22], [23]:

$$V_\phi = V_2^0 + S_v c \quad (7)$$

The intercept V_2^0 , the standard partial molar volume at infinite dilution, expresses solute–solvent interaction without any solute–solute contribution, whereas the slope S_v expresses solute–solute interaction [24]. The volume can be split physically as

$$V_2^0 = V_M + V_T + V_I \quad (8)$$

where V_M is the intrinsic volume of the molecule, V_T the thermal (void) volume, and V_I the interaction volume, which is negative when water is contracted around charged or polar groups [4]. For an amino acid with side chain of n_C carbon atoms, group additivity gives

$$V_2^0 \approx V^0(\text{NH}_3^+, \text{COO}^-) + n_C V^0(\text{CH}_2) \quad (9)$$

The effect of a co-solute (salt or another additive) is expressed by the standard volume of transfer:

$$\Delta_{\text{tr}}V^0 = V_2^0(\text{aqueous co-solute}) - V_2^0(\text{water}) \quad (10)$$

C. Apparent molar adiabatic compressibility

The apparent molar adiabatic compressibility, obtained from the sound velocity and density data, is

$$K_{\phi} = 1000(\beta_s - \beta_{s0})/c + \beta_{s0}V_{\phi} \quad (11)$$

and, like V_{ϕ} , it is extrapolated linearly to infinite dilution:

$$K_{\phi} = K_2^0 + S_k c \quad (12)$$

For the small, polar amino acids K_2^0 is negative: water in the electro-stricted hydration layer resists compression more than bulk water, so solute addition lowers the compressibility of the solution [7], [8].

D. Viscosity

The relative viscosity $\eta_r = \eta/\eta_0$ of dilute solutions is described by the Jones–Dole equation [25]:

$$\eta_r = 1 + Ac^{1/2} + Bc \quad (13)$$

which is used in the linear form

$$(\eta_r - 1)/c^{1/2} = A + Bc^{1/2} \quad (14)$$

The Falkenhagen coefficient A measures ion–ion (solute–solute) interaction and is small for zwitterions. The B coefficient ($\text{dm}^3 \text{mol}^{-1}$) measures solute–solvent interaction together with solute size and shape: large positive values go with strongly hydrated, structure-making solutes, and negative values with structure breakers [26], [16]. The transition-state treatment of Feakins *et al.* [27] provides the activation free energies for viscous flow of solvent and solute:

$$\Delta\mu_1^{0\ddagger} = RT \ln(\eta_0 V_1^0 / h N_A) \quad (15)$$

$$\Delta\mu_2^{0\ddagger} = \Delta\mu_1^{0\ddagger} + (RT/V_1^0)[1000B - (V_1^0 - V_2^0)] \quad (16)$$

In these expressions V_1^0 is the molar volume of water, h is Planck's constant and N_A is Avogadro's constant. When $\Delta\mu_2^{0\ddagger}$ is considerably greater than $\Delta\mu_1^{0\ddagger}$, the solute hinders formation of the flow transition state, which indicates strong solute–solvent interaction.

IV. EXPERIMENTAL PRACTICE

The measurements normally combined in such work are listed in Table II. Solutions are made up by weight with low-conductivity water, and the amino acid is dried (and recrystallized if

required) beforehand. The temperature must be steady and known to ± 0.01 K or better, since the density, velocity and viscosity of water all vary markedly with temperature. Pure water serves as reference and calibrant, with ρ_0 and u_0 taken from standard tables [28], [29].

TABLE II: MEASUREMENT TECHNIQUES COMMONLY USED

Property	Typical instrument	Practical points
Sound velocity u	Fixed- or variable-path ultrasonic interferometer (about 1–5 MHz); pulse-echo cells	Calibrate with pure water; thermostat the cell; use the same frequency throughout
Density ρ	Vibrating-tube densimeter; pycnometer or bicarpellary pycnometer	Calibrate with dry air and degassed water; degas solutions; avoid bubbles
Viscosity η	Suspended-level Unbehoden or Ostwald capillary viscometer	Measure flow time repeatedly; apply kinetic-energy correction when needed; use ρ to convert to η

Note: General laboratory practice; instrument precision should be taken from the specific instrument used.

For every solution, ρ and u are recorded at one and the same temperature, and the viscosity follows from the efflux time t as $\eta = \eta_0(\rho t)/(\rho_0 t_0)$. Molal concentrations are normally converted to molarity (or vice versa) with the measured density.

V. CALCULATION PROCEDURES AND WORKED EXAMPLE

Important note: the values in Table IV form an *illustrative* data set for glycine in water at 298.15 K. They were constructed to be consistent with magnitudes seen in the literature and serve only to show how each equation is applied. They are *not* experimental results and should not be cited as such; in a research article they must be replaced by measured data.

TABLE III: REFERENCE PROPERTIES OF PURE WATER AT 298.15 K USED IN THE CALCULATIONS

Property	Symbol	Value
Density	ρ_0	997.047 kg m ⁻³
Sound velocity	u_0	1496.7 m s ⁻¹
Viscosity	η_0	0.8903 mPa s
Adiabatic compressibility	β_{s0}	4.4773×10^{-10} Pa ⁻¹
Molar volume of water	V_1^0	18.069 cm ³ mol ⁻¹
Molar mass of glycine	M	75.07 g mol ⁻¹

Note: ρ_0 and u_0 after [28], [29]; β_{s0} from Eq. (1).

TABLE IV: ILLUSTRATIVE MEASURED DATA FOR GLYCINE IN WATER AT 298.15 K.

c (mol dm ⁻³)	ρ (kg m ⁻³)	u (m s ⁻¹)	η (mPa s)
0.10	1000.243	1502.4	0.9111
0.20	1003.433	1507.8	0.9310
0.30	1006.615	1513.0	0.9507
0.40	1009.790	1517.8	0.9702
0.50	1012.959	1522.3	0.9898
0.60	1016.120	1526.4	1.0093

Note: Illustrative data for demonstration of the calculations only.

Worked calculation for $c = 0.30$ mol dm⁻³. From Table IV: $\rho = 1006.615$ kg m⁻³, $u = 1513.0$ m s⁻¹, $\eta = 0.9507$ mPa s.

Step 1. Adiabatic compressibility, Eq. (1): $\beta_s = 1/[(1513.0)^2 \times 1006.615] = 1/(2.3043 \times 10^9) = 4.340 \times 10^{-10}$ Pa⁻¹.

Step 2. Acoustic impedance, Eq. (2): $Z = 1513.0 \times 1006.615 = 1.523 \times 10^6$ kg m⁻² s⁻¹.

Step 3. Free length, Eq. (3): $K_I = (93.875 + 0.375 \times 298.15) \times 10^{-8} = 2.0568 \times 10^{-6}$, so $L_f = 2.0568 \times 10^{-6} \times (4.340 \times 10^{-10})^{1/2} = 4.285 \times 10^{-11}$ m = 0.4285 Å.

Step 4. Apparent molar volume, Eq. (6): $V_\phi = 75.07/0.997047 - 1000(1.006615 - 0.997047)/(0.30 \times 0.997047) = 75.293 - 31.988 = 43.30$ cm³ mol⁻¹.

Step 5. Apparent molar compressibility, Eq. (11): $K_\phi = 1000(4.340 - 4.477) \times 10^{-10}/0.30 + 4.477 \times 10^{-10} \times 43.30 = -4.59 \times 10^{-8} + 1.94 \times 10^{-8} = -2.65 \times 10^{-8}$ cm³ mol⁻¹ Pa⁻¹ (-2.65×10^{-14} m³ mol⁻¹ Pa⁻¹).

Step 6. Relative viscosity, Eq. (13): $\eta_r = 0.9507/0.8903 = 1.0678$, so $(\eta_r - 1)/c^{1/2} = 0.0678/0.5477 = 0.1239$ dm^{3/2} mol^{-1/2}.

The same steps applied to all six concentrations give Table V and Table VI. Linear least-squares fits of Eqs. (7), (12) and (14) then give the parameters in Table VII.

TABLE V: CALCULATED ACOUSTIC PARAMETERS (ILLUSTRATIVE DATA)

c	β_s (10 ⁻¹⁰ Pa ⁻¹)	Z (10 ⁶ kg m ⁻² s ⁻¹)	L_f (Å)	R_A	n_h
0.10	4.4292	1.5028	0.4329	1.0019	5.92
0.20	4.3835	1.5130	0.4306	1.0039	5.74
0.30	4.3397	1.5230	0.4285	1.0060	5.60
0.40	4.2987	1.5327	0.4264	1.0081	5.42
0.50	4.2600	1.5420	0.4245	1.0102	5.26
0.60	4.2239	1.5510	0.4227	1.0125	5.08

Note: c in mol dm⁻³; β_s from Eq. (1), Z from (2), L_f from (3), R_A from (4), n_h from (5).

TABLE VI: CALCULATED VOLUMETRIC, COMPRESSIBILITY AND VISCOSITY PARAMETERS (ILLUSTRATIVE DATA)

c	V_ϕ (cm ³ mol ⁻¹)	K_ϕ (10 ⁻¹⁴ m ³ mol ⁻¹ Pa ⁻¹)	η_r	$(\eta_r-1)/c^{1/2}$
0.10	43.238	-2.875	1.0234	0.0739
0.20	43.268	-2.751	1.0457	0.1022
0.30	43.305	-2.648	1.0678	0.1239
0.40	43.340	-2.524	1.0897	0.1419
0.50	43.374	-2.404	1.1118	0.1581
0.60	43.410	-2.279	1.1337	0.1726

Note: V_ϕ from Eq. (6), K_ϕ from (11), $\eta_r = \eta/\eta_0$.

TABLE VII: PARAMETERS OBTAINED BY LINEAR REGRESSION OF THE ILLUSTRATIVE DATA.

Parameter	Value	Unit	R^2
V_2^0	43.20	cm ³ mol ⁻¹	0.9994
S_v	0.35	cm ³ dm ³ mol ⁻²	
K_2^0	-2.99	10 ⁻¹⁴ m ³ mol ⁻¹ Pa ⁻¹	0.9993
S_k	1.18	10 ⁻¹⁴ m ³ dm ³ mol ⁻² Pa ⁻¹	
A	0.0059	dm ^{3/2} mol ^{-1/2}	1.00000
B	0.215	dm ³ mol ⁻¹	
$\Delta\mu_1^{0\ddagger}$	9.16	kJ mol ⁻¹	
$\Delta\mu_2^{0\ddagger}$	42.13	kJ mol ⁻¹	

Note: $\Delta\mu_1^{0\ddagger}$ and $\Delta\mu_2^{0\ddagger}$ from Eqs. (15) and (16).

VI. RESULTS AND DISCUSSION

A. Standard partial molar volumes from the literature

Table VIII gives representative standard partial molar volumes of simple amino acids at 298.15 K, rounded to 0.1 cm³ mol⁻¹, taken from the established compilations [7], [8], [16]; the increments relative to glycine were computed here. Volume grows with side-chain size. In Fig. 1 the slope is about 16 cm³ mol⁻¹ per carbon atom, close to the CH₂ increment found for the homologous α,ω -amino carboxylic acids [9]; this is the basis of Eq. (9).

TABLE VIII: REPRESENTATIVE STANDARD PARTIAL MOLAR VOLUMES OF AMINO ACIDS IN WATER AT 298.15 K.

Amino acid	n_C	Side chain	V_2^0 (cm ³ mol ⁻¹)	ΔV vs. Gly
Glycine	2	-H	43.2	0.0
L-Alanine	3	-CH ₃	60.4	+17.2
L-Serine	3	-CH ₂ OH	60.6	+17.4
L-Proline	5	cyclic	82.8	+39.6
L-Valine	5	-CH(CH ₃) ₂	90.8	+47.6
L-Leucine	6	-CH ₂ CH(CH ₃) ₂	107.8	+64.6

Note: Rounded literature values from [7], [8], [16]; check the original tables before citing precise values.

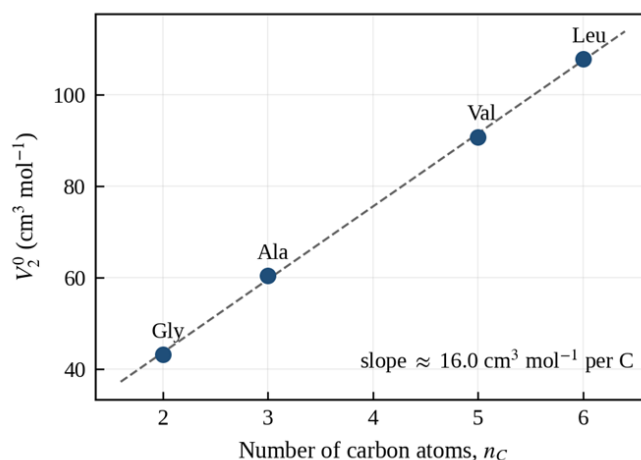


Fig. 1. Standard partial molar volume of Gly, Ala, Val and Leu versus number of carbon atoms (values from Table VIII); dashed line is the linear fit.

Two points deserve comment. Firstly, serine and alanine have nearly equal volumes even though serine bears an additional -OH ; the hydroxyl group is generally considered to contract the water around it, offsetting its own intrinsic volume. Secondly, proline (82.8) is smaller than valine (90.8) with the same number of carbons, in keeping with the more compact packing of its ring-closed side chain.

B. Interpretation of the worked example

Velocity and density. As Fig. 2 shows, each mol dm⁻³ of glycine raises the density by about 32 kg m⁻³ and the velocity by about 48 m s⁻¹. The rise in velocity means the solution grows stiffer (less compressible) with added solute, as expected when water is drawn into the electro-stricted shells around the NH_3^+ and COO^- groups.

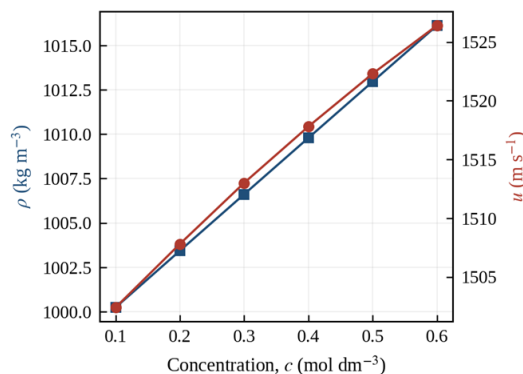


Fig. 2. Density and ultrasonic velocity versus concentration for the illustrative glycine data at 298.15 K.

Compressibility and free length. According to Fig. 3, β_s drops from $4.477 \times 10^{-10} \text{ Pa}^{-1}$ in pure water to $4.224 \times 10^{-10} \text{ Pa}^{-1}$ at 0.60 mol dm^{-3} , and L_f falls along with it, whereas the impedance and relative association both rise (Table V). Together these trends point to stronger solute–solvent association and closer packing of the medium [5].

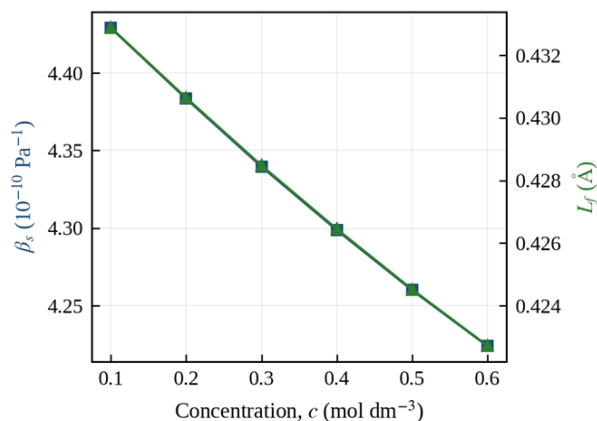


Fig. 3. Adiabatic compressibility and intermolecular free length versus concentration (illustrative data).

Hydration number. The apparent n_h declines from 5.9 to 5.1 as concentration increases (Table V). Such a decline is normally explained by overlap of the hydration co-spheres of neighbouring solute molecules, which leaves fewer water molecules per solute in the low-compressibility state.

Apparent molar properties. In Fig. 4, extrapolation gives $V_2^0 = 43.2 \text{ cm}^3 \text{ mol}^{-1}$, which recovers the value used to build the data (Table VIII); this verifies the calculation route and is not a finding. The small positive S_v and positive S_k suggest weak solute–solute interaction in this range. The negative K_2^0 ($-2.99 \times 10^{-14} \text{ m}^3 \text{ mol}^{-1} \text{ Pa}^{-1}$) reflects electrostriction, as discussed in Section III-C.

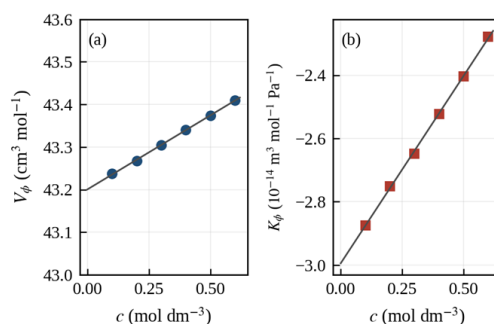


Fig. 4. Apparent molar volume (a) and apparent molar adiabatic compressibility (b) versus concentration, with linear extrapolation to infinite dilution (illustrative data).

Viscosity. The Jones–Dole plot in Fig. 5 is linear, with a small A (0.0059) and a large positive B ($0.215 \text{ dm}^3 \text{ mol}^{-1}$). A small A is to be expected for an uncharged zwitterion, while the positive B points to solute–solvent interaction that orders the solvent. In addition, $\Delta\mu_2^{0\dagger}$ (42.1 kJ mol^{-1}) is much larger than $\Delta\mu_1^{0\dagger}$ (9.2 kJ mol^{-1}); flow in the presence of the solute therefore demands more activation free energy than flow of pure water, which also indicates strong solvation [27].

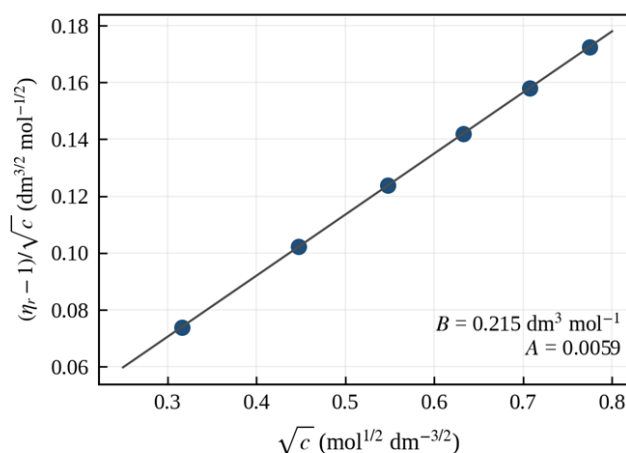


Fig. 5. Jones–Dole plot for the illustrative glycine data; the line is the linear fit, with slope B and intercept A .

TABLE IX: GUIDE TO INTERPRETING THE DERIVED PARAMETERS.

Parameter	Observation	Usual interpretation
β_s, L_f	Decrease with c	Tighter packing; strong solute–solvent interaction; hydration of charged or polar groups
Z	Increases with c	Stronger intermolecular forces; more rigid medium
V_2^0	Large and positive	Large intrinsic volume; magnitude reduced by electrostriction
$\Delta_{tr}V^0$	Positive in salt solution	Ion–hydrophilic (charged-group) interactions dominate
$\Delta_{tr}V^0$	Negative in co-solute	Hydrophobic–hydrophobic or ion–hydrophobic interactions dominate
K_2^0	Negative	Electro-stricted, less compressible water around charged groups
S_v	Positive	Solute–solute interaction
B	Positive and large	Structure-making, strongly hydrated solute
dB/dT	Negative	Structure-making (Kosmo tropic) behavior
$\Delta\mu_2^{0\dagger}$ vs. $\Delta\mu_1^{0\dagger}$	$\Delta\mu_2^{0\dagger}$ larger	Solute–solvent interaction strong; transition state less favorable

Note: Compiled from the general interpretation used in [16], [30], [31].

C. Effect of temperature

Standard partial molar volumes of amino acids usually grow with temperature because electrostriction around the charged groups weakens as the water structure loosens [8], [9]. For the smaller amino acids the partial molar adiabatic compressibility stays negative across the 5–45 °C range examined by Kikuchi *et al.* [8], although its magnitude shifts as the hydration shell changes. As regards viscosity, a fall of B with temperature ($dB/dT < 0$) is frequently reported for structure-making solutes [16], while a positive dB/dT signals structure breaking.

D. Effect of electrolytes and other co-solutes

In the presence of NaCl, the standard partial molar volumes, compressibilities and viscosity B coefficients of α,ω -amino acids were found to be higher, and this was attributed to strong interaction between the ions and the charged groups of the amino acid [11]. Positive transfer volumes of amino acids and peptides from water to aqueous NaCl lead to the same conclusion [10]. In terms of Scheme 2, pairing of Na^+ with COO^- and of Cl^- with NH_3^+ displaces electro-stricted water from the end groups, so the amino acid takes up more volume. This agrees with the co-sphere overlap model of Friedman and Krishnan [31], in which overlap of two hydrophilic co-spheres releases water and increases volume, whereas overlap of a hydrophilic and a hydrophobic co-sphere acts in the opposite sense.

Studies of α -amino acids in acetate salt solutions [12] and of homologous α -amino acids in aqueous semi carbazide hydrochloride [13] have likewise been discussed in terms of ion–hydrophilic, ion–hydrophobic and hydrophobic–hydrophobic interactions and of Kosmotropic or chaotropic character. Table X collects these and other key investigations.

TABLE X: SUMMARY OF SELECTED EXPERIMENTAL STUDIES.

Ref.	System and conditions	Properties and principal inference
[7]	Aqueous amino acids, 25 °C	Apparent molal volume and adiabatic compressibility; group-contribution analysis of charged and side-chain groups
[8]	Amino acids in dilute water, 5–45 °C	Partial molar volume and adiabatic compressibility as functions of temperature; hydration of polar and nonpolar groups
[9]	α,ω -Amino carboxylic acids, 18–55 °C	Volumes, expansibilities and compressibility's; additive contributions of charged end groups and CH_2
[10]	Amino acids and peptides, water to aq. NaCl, 298.15 K	Heat capacities and volumes of transfer; ion–charged group interactions
[11]	α,ω -Amino acids, water and aq. NaCl, 293.2–333.2 K	Volumes, compressibility's and viscosities; NaCl raises all three, indicating strong ion–amino acid interaction

Ref.	System and conditions	Properties and principal inference
[12]	α -Amino acids in aq. acetate salts, 303.15–323.15 K	Viscosity A and B coefficients; ion effect on solvation
[13]	Homologous α -amino acids in aq. semi carbazide HCl, 293.15–318.15 K	Apparent molar properties, transfer volumes and group contributions; Kosmo tropic/chaotropic behavior
[16]	Review of amino-acid B and V^0 data	Relation of B and V^0 to protein stabilization

Note: Summaries are condensed from the cited papers.

E. Structure making and structure breaking

The labels structure maker (Kosmo trope) and structure breaker (chaotropic) originate in the ordering effects of ions on water [14], [30]. For amino acids the classification rests on several indicators taken together: a positive B , a negative dB/dT , a negative K_2^0 , a falling β_s and a large $\Delta\mu_2^{0\ddagger}$ all indicate structure making (Table IX). The indicators sometimes disagree, particularly for large hydrophobic side chains where charged-group and nonpolar contributions have opposite signs, so a conclusion should rest on several properties rather than one.

F. Relevance to protein stability

Amino acid hydration matters for protein stability because both are controlled by the balance of hydrophilic and hydrophobic hydration [2]. Cosolutes that are preferentially excluded from a protein surface favor the native state [3], [32], and Zhao has shown how the viscosity B coefficients and standard partial molar volumes of amino acids help to interpret such stabilization of proteins and enzymes [16]. Kirkwood–Buff theory [33] gives a rigorous route from volumetric and compressibility data to preferential interaction parameters and is being used more and more for this purpose.

VII. CHALLENGES AND FUTURE DIRECTIONS

Several factors hinder comparison of results between laboratories. (i) Different concentration scales (molality, molarity) alter S_v and S_k . (ii) The infinite-dilution extrapolation depends on the lowest concentration used and on measurement precision; small density errors are greatly amplified in V_ϕ at low c . (iii) Velocity is typically measured at one frequency, so relaxation effects go unnoticed. (iv) The speciation of ionizable amino acids is seldom controlled. (v) Hydration numbers from compressibility assume that bound water is incompressible and are therefore best used to compare members of a series.

Useful next steps include pairing volumetric and acoustic data with spectroscopy (FTIR, NMR) and molecular dynamics, applying Kirkwood–Buff analysis, studying multicomponent and biologically relevant media such as osmolyte mixtures, and extending the work systematically from amino acids to peptides and model proteins. Publishing complete data tables, uncertainty estimates and the concentration scale would make existing results easier to compare and reuse.

VIII. CONCLUSION

Density, ultrasonic velocity and viscosity data supply complementary views of how amino acids interact with water and with additives. The equations collected here convert the three measured quantities into adiabatic compressibility, free length, impedance, hydration number, partial molar volume and compressibility, viscosity B coefficients and activation parameters. The literature shows consistent patterns: each CH_2 group adds about $16 \text{ cm}^3 \text{ mol}^{-1}$; charged end groups produce electrostriction and a negative partial molar compressibility; added electrolytes weaken electrostriction and enlarge the apparent volume of the amino acid; and structure-making behavior appears as positive B coefficients. Future studies should stress standardized reporting, broader ranges of temperature and composition, and integration with spectroscopic and computational methods.

REFERENCES

1. E. J. Cohn and J. T. Edsall, *Proteins, Amino Acids and Peptides as Ions and Dipolar Ions*. New York, NY, USA: Reinhold, 1943.
2. W. Kauzmann, "Some factors in the interpretation of protein denaturation," *Adv. Protein Chem.*, vol. 14, pp. 1–63, 1959.
3. S. N. Timasheff, "Protein hydration, thermodynamic binding, and preferential hydration," *Biochemistry*, vol. 41, no. 46, pp. 13473–13482, 2002.
4. T. V. Chalikian, "Volumetric properties of proteins," *Annu. Rev. Biophys. Biomol. Struct.*, vol. 32, pp. 207–235, 2003.
5. A. P. Sarvazyan, "Ultrasonic velocimetry of biological compounds," *Annu. Rev. Biophys. Biophys. Chem.*, vol. 20, pp. 321–342, 1991.
6. T. V. Chalikian and K. J. Breslauer, "Thermodynamic analysis of biomolecules: A volumetric approach," *Curr. Opin. Struct. Biol.*, vol. 8, no. 5, pp. 657–664, 1998.

7. F. J. Millero, A. L. Surdo, and C. Shin, "The apparent molal volumes and adiabatic compressibilities of aqueous amino acids at 25 °C," *J. Phys. Chem.*, vol. 82, no. 7, pp. 784–792, 1978.
8. M. Kikuchi, M. Sakurai, and K. Nitta, "Partial molar volumes and adiabatic compressibilities of amino acids in dilute aqueous solutions at 5, 15, 25, 35, and 45 °C," *J. Chem. Eng. Data*, vol. 40, no. 4, pp. 935–942, 1995.
9. T. V. Chalikian, A. P. Sarvazyan, and K. J. Breslauer, "Partial molar volumes, expansibilities, and compressibilities of α,ω -aminocarboxylic acids in aqueous solutions between 18 and 55 °C," *J. Phys. Chem.*, vol. 97, no. 49, pp. 13017–13026, 1993.
10. R. Bhat and J. C. Ahluwalia, "Partial molar heat capacities and volumes of transfer of some amino acids and peptides from water to aqueous sodium chloride solutions at 298.15 K," *J. Phys. Chem.*, vol. 89, no. 6, pp. 1099–1105, 1985.
11. C. M. Romero, M. A. Estes, and G. P. Trujillo, "Partial molar volumes, partial molar compressibilities, and viscosities of α,ω -amino acids in water and in aqueous solutions of sodium chloride over a temperature range of 293.2–333.2 K," *J. Chem. Eng. Data*, vol. 63, no. 11, pp. 4012–4019, 2018.
12. J. A. Siddique and S. Naqvi, "Viscosity behavior of α -amino acids in acetate salt solutions at temperatures (303.15 to 323.15) K," *Int. J. Thermophys.*, vol. 33, pp. 47–57, 2012.
13. J. Gupta and A. K. Nain, "Effect of concentration and temperature on apparent molar properties of homologous α -amino acids in aqueous-semicarbazide hydrochloride solutions: A quest on the concept of kosmotropic/chaotropic behaviour of amino acids," *J. Chem. Thermodyn.*, vol. 135, pp. 9–26, 2019.
14. H. S. Frank and M. W. Evans, "Free volume and entropy in condensed systems III. Entropy in binary liquid mixtures; partial molal entropy in dilute solutions; structure and thermodynamics in aqueous electrolytes," *J. Chem. Phys.*, vol. 13, no. 11, pp. 507–532, 1945.
15. Y. Nozaki and C. Tanford, "The solubility of amino acids and two glycine peptides in aqueous ethanol and dioxane solutions," *J. Biol. Chem.*, vol. 246, no. 7, pp. 2211–2217, 1971.
16. H. Zhao, "Viscosity B-coefficients and standard partial molar volumes of amino acids, and their roles in interpreting the protein (enzyme) stabilization," *Biophys. Chem.*, vol. 122, no. 3, pp. 157–183, 2006.

17. T. J. Mason and J. P. Lorimer, *Sonochemistry: Theory, Applications and Uses of Ultrasound in Chemistry*. Chichester, U.K.: Ellis Horwood, 1988.
18. H. Eyring and J. F. Kincaid, "Free volumes and free angle ratios of molecules in liquids," *J. Chem. Phys.*, vol. 6, no. 10, pp. 620–629, 1938.
19. B. Jacobson, "Ultrasonic velocity in liquids and liquid mixtures," *J. Chem. Phys.*, vol. 20, no. 5, pp. 927–928, 1952.
20. A. Passynsky, "Compressibility and solvation of solutions of electrolytes," *Acta Physicochim. URSS*, vol. 8, pp. 385–418, 1938.
21. H. Shiio, "Ultrasonic interferometer measurements of the amount of bound water. Saccharides," *J. Am. Chem. Soc.*, vol. 80, no. 1, pp. 70–73, 1958.
22. D. O. Masson, "Solute molecular volumes in relation to solvation and ionization," *Philos. Mag.*, vol. 8, pp. 218–235, 1929.
23. F. T. Gucker, "The apparent molal heat capacity, volume, and compressibility of electrolytes," *Chem. Rev.*, vol. 13, no. 1, pp. 111–130, 1933.
24. F. J. Millero, "The molal volumes of electrolytes," *Chem. Rev.*, vol. 71, no. 2, pp. 147–176, 1971.
25. G. Jones and M. Dole, "The viscosity of aqueous solutions of strong electrolytes with special reference to barium chloride," *J. Am. Chem. Soc.*, vol. 51, no. 10, pp. 2950–2964, 1929.
26. J. E. Desnoyers and G. Perron, "The viscosity of aqueous solutions of alkali and tetraalkylammonium halides at 25 °C," *J. Solution Chem.*, vol. 1, no. 3, pp. 199–212, 1972.
27. D. Feakins, D. J. Freemantle, and K. G. Lawrence, "Transition state treatment of the relative viscosity of electrolytic solutions. Applications to aqueous, non-aqueous and methanol + water systems," *J. Chem. Soc., Faraday Trans. 1*, vol. 70, pp. 795–806, 1974.
28. G. S. Kell, "Density, thermal expansivity, and compressibility of liquid water from 0° to 150 °C: Correlations and tables for atmospheric pressure and saturation reviewed and expressed on 1968 temperature scale," *J. Chem. Eng. Data*, vol. 20, no. 1, pp. 97–105, 1975.
29. V. A. Del Grosso and C. W. Mader, "Speed of sound in pure water," *J. Acoust. Soc. Am.*, vol. 52, no. 5B, pp. 1442–1446, 1972.
30. Y. Marcus, "Effect of ions on the structure of water: Structure making and breaking," *Chem. Rev.*, vol. 109, no. 3, pp. 1346–1370, 2009.

31. H. L. Friedman and C. V. Krishnan, "Thermodynamics of ion hydration," in *Water: A Comprehensive Treatise*, vol. 3, F. Franks, Ed. New York, NY, USA: Plenum, 1973, ch. 1, pp. 1–118.
32. T. Arakawa and S. N. Timasheff, "The stabilization of proteins by osmolytes," *Biophys. J.*, vol. 47, no. 3, pp. 411–414, 1985.
33. J. G. Kirkwood and F. P. Buff, "The statistical mechanical theory of solutions. I," *J. Chem. Phys.*, vol. 19, no. 6, pp. 774–777, 1951.