Ab Initio Studies of Solvent Effects on Molecular Conformation and Vibrational Spectra of Diglycine Zwitterion

G. Nandini and D. N. Sathyanarayana*

Department of Inorganic and Physical Chemistry, Indian Institute of Science, Bangalore-560012, India

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The molecular conformation of diglycine zwitterion and neutral diglycine is determined by the ab initio calculations at the Hartree−Fock level using the basis sets 6-31+g(d), 6-31++g(d,p), and 6-31+g(d,p). The infrared and Raman spectra of the diglycine zwitterion are assigned using the ab initio force field and the vibrational spectra of its nine selectively C-, N,C-, and N-deuterated and ^{15}N isotopic species. The effect of solvation on the conformation and vibrational spectra of diglycine zwitterion in solvents of dielectric constant 2.2 and 78 has been investigated by the self-consistent reaction field theory. The inclusion of a solvent reaction field has a strong influence on the total energies, conformation, and vibrational spectra. The frequency shifts in the solvents support stabilization of the nondipolar amide structure in polar solvents, unlike in neutral amide molecules where the dipolar structure is stabilized in polar solvents. Ab initio calculations have also been made on neutral diglycine in the gas phase and in a solvent medium ($\epsilon = 78.0$) at the Hartree−Fock and B3LYP level using the basis sets 6-31+g(d) and 6-31++g(d,p) and for the zwitterion in the solvent medium ($\epsilon = 78.0$) at B3LYP level using the latter basis set.

Introduction

Glycylglycine (Gly-Gly) and other dipeptides serve as important model systems for the theoretical and experimental studies of amide linkages in proteins and polypeptides. Studies on dipeptides have been motivated by the expectation that a fundamental understanding of the structural constraints in proteins and their role in controlling biological functions require a deep understanding of the structure and dynamics of the individual amide linkages in peptides. Proteins are linear polymer chains composed of amino acid residues linked by amide bonds. These linear polymer chains fold into specific three-dimensional structures; the steric and electrostatic constraints involve the limited flexibility of the amide bond, due to the planarity of the double bonded amide linkage and the preference of secondary amides for trans configuration. Glycylglycine (Gly-Gly) zwitterion is the smallest dipeptide and can be considered as a model biomolecule.

The ground-state structure of Gly-Gly has been experimentally characterized by a variety of techniques.[1−10] The X-ray and neutron diffraction studies of the structure of α, β, and γ conformers of diglycine zwitterion have been reported.[2−6] The α form of diglycine zwitterion is the most stable one among the α, β, and γ forms and in the α form, the dihedral angle between the plane of the amide group and that of the carboxylate COO[−] group is 22.4°, whereas the β and γ forms have coplanar amide and COO[−] groups. Nonplanarity of diglycine zwitterion permits better molecular packing with stronger hydrogen bonds and van der Waals interactions. The ^{13}C NMR spectra of the α form showed that diglycine zwitterion crystallized from aqueous solution possesses the δ form and on dehydration it changes over to the α form.[6] Infrared, Raman, and INS spectra of diglycine zwitterion and its N-deuterated analogue have been reported.[7,9,10] The infrared spectra of α-glycylglycine zwitterion

and its nine differently labeled N, C-, C- and N-deuterated and ^{15}N isotopic species have been investigated by Destrade et al.,[9] and the assignments for α-glycylglycine zwitterion have been made on the basis of a normal coordinate analysis employing a valence force field. The Raman and infrared spectra of glycylglycine zwitterion and its N-deuterated analogue have also been investigated by Lagant et al.[7] They have carried out a normal coordinate analysis for the α-crystalline form using a modified Urey−Bradley force field.

Ab initio self-consistent field calculations have been performed both on neutral diglycine and its zwitterion using a 2s1p Gaussian basis set, and the barrier to rotation about the peptide bond was found to be 22.9 and 23.9 kcal/mol, respectively.[11] For the neutral molecule as well as the zwitterion, the trans isomer was found to be more stable than the cis, and the latter conformer was predicted to be present only to a smaller extent.[11] From molecular dynamics studies too, the minimum-energy conformer of diglycine zwitterion was identified as the trans conformer.[12] From ^{1}H and ^{13}C NMR spectral studies of the zwitterion, hydrogen bonding between NH and COO[−] groups was inferred.[13]

The determination of the structure of biomolecules in solution as well as the calculation of their spectral properties is a problem of current interest. Solvation plays an important role in determining conformations and other quantities of chemical and biochemical interest.[14,15] In the present work, our endeavor is to determine the minimum-energy conformation of α-diglycine zwitterion and its force field that will reproduce experimental vibrational frequencies of the zwitterion and its nine selectively [15]N- and deuterium-labeled species. We show that the choice of an appropriate basis set at the Hartree−Fock level can stabilize the diglycine zwitterion. This is of interest since the structural and spectroscopic studies are available only for the diglycine zwitterion, and in aqueous solution, at biological pHs, it exists predominantly in this form. Since the intrinsic features of an empirical force field used in the earlier normal coordinate

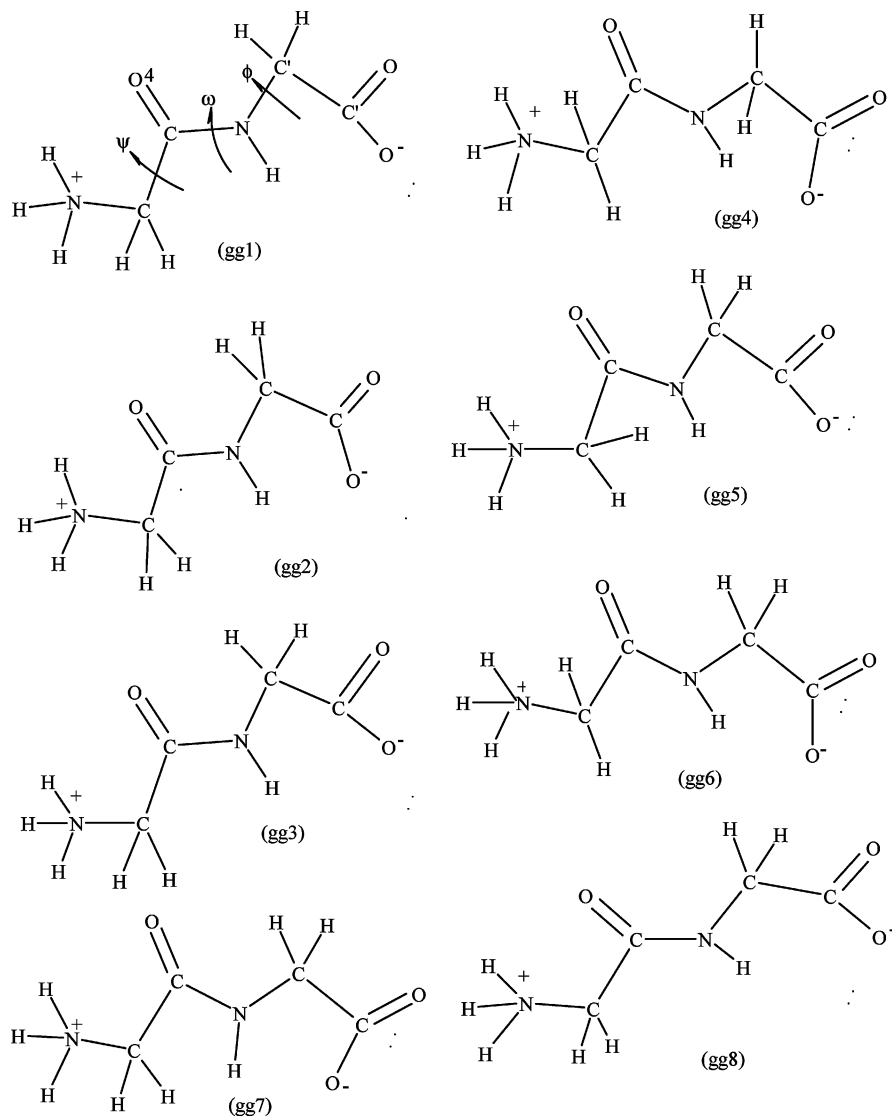* Corresponding author. E-mail:dns@ipc.iisc.ernet.in. Telephone: (91) 80 293 2827 (Office). Fax: (91) 80 360 1552.

Figure 1. Selected conformers of diglycine zwitterion in the gas phase and in aqueous medium. For abbreviations, see Table 1.

treatments lie in their uncertainty, particularly with respect to the interaction force constants, it is desirable to obtain a good quality force field by the ab initio method. In this context, an ab initio study of glycylglycine zwitterion $H_3N^+CH_2CONH$-CH_2COO^- (d_o) at the Hartree−Fock (HF) level using the three basis sets, 6-31+g(d), 6-31++g(d,p), and 6-31+g(d,p), is presented. The binding energy of the peptide bond of diglycine zwitterion has been calculated. The effect of solvation on the conformational equilibria and vibrational spectra of glycylglycine zwitterion is also examined by the ab initio method using the self-consistent reaction field (SCRF) theory for solvents of dielectric constant 2.2 and 78 corresponding to carbon tetrachloride and water, respectively, employing the dipole (Onsager) methods.[16] The present work should be of value to the fundamental understanding of polypeptides.

Ab initio calculations have also been made for neutral diglycine both in the gas phase and in a solvent medium of dielectric constant 78.0 both at the Hartree−Fock and B3LYP level using the basis sets 6-31+g(d) and 6-31++g(d,p). Comparison of the geometrical parameters and the total energy of neutral diglycine with the zwitterion is made.

Attempts to study a gas-phase zwitterionic species of diglycine using the density functional theory (DFT) B3LYP/6-31g(d) and the MP2 level of theory have not been successful; the calculations converged to a neutral structure or to an unstable

geometry with imaginary frequencies. Similar finding have been made for L-alanyl-L-alanine zwitterion using B3LYP/6-31g(d) and MP2 methods.[17] That is, on the B3LYP/6-31g(d) potential energy surface, there is no barrier to proton transfer from the positively charged NH_3^+ group to the negatively charged carboxylate group or from the NH_3^+ group to the adjacent carbonyl oxygen and from the amide nitrogen to the carboxylate group. Ab initio calculations carried out on diglycine zwitterion in a solvent of dielectric constant 78.0 using the B3LYP/6-31++g(d,p) method showed the zwitterion to be stable. The results are presented and discussed.

Computational Details

The ab initio calculations at the Hartree−Fock and B3LYP levels have been performed by employing the Gaussian 98 program.[18] The fully optimized geometry of neutral diglycine and its zwitterion was obtained by the analytical gradient methods. The Hartree−Fock Cartesian force constants, vibrational frequencies, and infrared and Raman band intensities were obtained for the optimized geometry of diglycine zwitterion and neutral diglycine. The atoms in Figures 1 and 2 for diglycine zwitterion and neutral diglycine, respectively, have been numbered for one structure in each to define the bond lengths, bond angles, and dihedral angles and to specify the internal
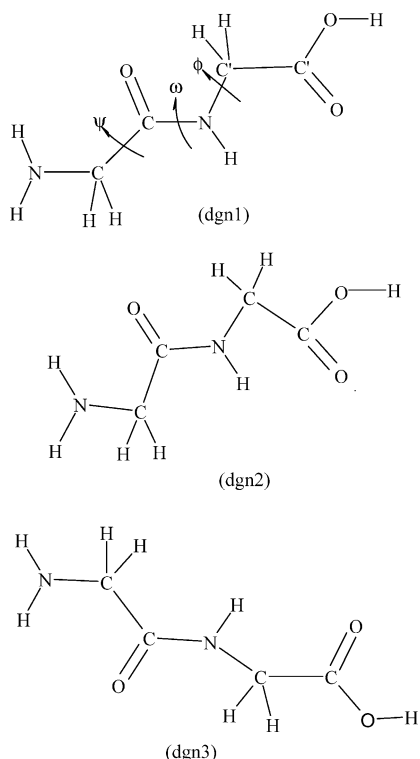
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Figure 2. Selected conformers of neutral diglycine in gas phase and in aqueous medium. For abbreviations, see Table 1.

coordinates used in the calculation of vibrational spectra. The full geometry optimization was carried out for diglycine zwitterion at the Hartree−Fock (HF) level using the basis sets 6-31+g(d), 6-31++g(d,p), and 6-31+g(d,p). The input for diglycine zwitterion was taken from the X-ray and neutron diffraction studies.[2−6] The ab initio vibrational frequencies and their assignments were calculated for diglycine zwitterion and its N-deuterated $D_3N^+CH_2CONDCH_2COO^-$ (d_4), C-deuterated $H_3N^+CD_2CONHCH_2COO^-$ ($d_{2\alpha}$), $H_3N^+CH_2CONHCD_2COO^-$ ($d_{2\beta}$), and $H_3N^+CD_2CONHCD_2COO^-$ ($d_{4\alpha\beta}$), C,N-deuterated $D_3N^+CD_2CONDCH_2COO^-$ ($d_{6\alpha}$), $D_3N^+CH_2CONDCD_2COO^-$ ($d_{6\beta}$), and $D_3N^+CD_2CONDCD_2COO^-$ (d_8), and ^{15}N-labeled $H_3{}^{15}N^+CH_2CO^{15}NHCH_2COO^-$ and $D_3{}^{15}N^+CH_2CO^{15}NDCH_2COO^-$ isotopic forms. The input for neutral diglycine was taken from the ab initio studies.[11] The full geometry optimization was carried out for neutral diglycine at the Hartree−Fock (HF) and B3LYP levels using the basis sets 6-31+g(d) and 6-31++g(d,p).

The effect of solute−solvent interaction was taken into account within the framework of the ab initio self-consistent reaction field (SCRF) theory.[16] This method is based on Onsager's reaction field theory of the electrostatic solvation model.[16] In the SCRF theory, the solvent is considered as a uniform field of dielectric constant ϵ. The solute is assumed to occupy a spherical cavity of radius a_o in the solvent. The permanent dipole of the solute will induce a dipole (reaction field) in the surrounding medium, which will interact with the molecular dipole leading to stabilization. In the SCRF MO formalism, the solute−solvent interaction is treated as a perturbation of the Hamiltonian of the isolated molecule. The reaction field is updated iteratively until self-consistency is achieved for the intramolecular electric field. The solvation energy calculated by the SCRF method corresponds to the electrostatic contribution to the free energy of solvation. At the Hartree−Fock level, the cavity radii a_o of 3.88, 4.12, and 4.08 Å were obtained for the basis sets 6-31+g(d), 6-31++g(d,p), and 6-31+g(d,p), respectively. At the B3LYP level, for the basis

set 6-31++g(d,p), the cavity radius a_o of 4.21 Å was obtained for the zwitterion. Both at the Hartree−Fock and B3LYP levels, the cavity radius a_o obtained for neutral diglycine was 4.10 Å for the basis set 6-31++g(d,p). The geometry optimizations and vibrational frequencies were obtained by analytical methods by fixing the cavity in the presence of the reaction field in solvents of dielectric constant 2.2 and 78 corresponding to carbon tetrachloride and water, respectively.

The binding energy of the peptide bond of diglycine zwitterion was calculated at the Hartree−Fock level using the basis set 6-31++g(d,p) following the procedure of Chaduri and Camuto.[19] The binding energy of the peptide bond of neutral diglycine has already been reported by them.

Results and Discussion

The equilibrium geometry of diglycine zwitterion obtained from the ab initio calculations is discussed first, and later a brief discussion of the vibrational spectra and solvent effects is presented. The equilibrium geometry of neutral diglycine is also discussed.

Conformation. In the case of peptides and proteins, the torsional angles $\phi(C'_{i-1}-N_i-C^\alpha_i-C'_i)$ and $\psi(N_i-C^\alpha_i-C'-N_{i+1})$ represent the rotation about the $(N-C^\alpha)$ and $(C^\alpha-C)$ bonds, respectively. A set of torsional angles (ϕ,ψ) thus represents the conformation at the α-carbon atom. The torsional angle $\omega(C^\alpha-C-N-C^\alpha)$ provides an estimate of the nonplanarity of the peptide group. Thus, the torsional angles (ϕ,ψ,ω) specify the conformation in the case of simple dipeptides.[20]

Diglycine zwitterion has many conformers which are relatively low in energy and are present at room temperature. The values of ϕ, ψ, ω, and total energy for the conformers of diglycine zwitterion lying in the local and global minima both in the gas phase and in the solvent media as obtained by all the three basis sets 6-31+g(d), 6-31++g(d,p), and 6-31+g(d,p) are given in Table 1. Similar results for neutral diglycine, obtained by the basis sets 6-31+g(d) and 6-31++g(d,p) both at the Hartree−Fock and B3LYP levels are also included in Table 1. The conformers of diglycine zwitterion and neutral diglycine which lie in the local and global minima of the potential energy scan calculated at HF/6-31++g(d,p) are shown in Figures 1 and 2, respectively. From the total energy of each of the conformers shown in Figure 1, it was found that for the zwitterion the conformer with (ϕ, ψ) of nearly (180.0, 180.0) is more stable than all the other conformers. It corresponds to the α form of diglycine zwitterion. The orientation of NH_3^+ and COO^- groups of diglycine zwitterion may also influence the stability of the conformer besides its ϕ and ψ values. In the gaseous phase, in order keep the charges separated, the zwitterion has NH_3^+ in a staggered conformation with respect to the NCC plane. The COO^- group is coplanar with the $NC'C'$ plane.

The planarity of the peptide group of diglycine zwitterion is determined by the torsional angle ω and the calculated value of ω is 178.49, −179.99, and −179.99 for the basis sets 6-31+g(d), 6-31++g(d,p), and 6-31+g(d,p), respectively. The experimental values of (ϕ, ψ, ω) for diglycine zwitterion are (177.7, 156.2, 178.7), (154.6, 152.3, 174.5), (157.1, 151.0, 176.1) and (157.1, 151.0, 176.1) as noted from the X-ray,[2] X-ray,[3] neutron,[4] and electron diffraction studies,[5] respectively. The X-ray structure of the α-form of diglycine zwitterion[3] has shown the peptide group to be planar, and the carboxylate and amide groups inclined at an angle of 22° to each other. Although the experimental values of (ϕ, ψ) show a nonplanar skeleton, the ab initio calculations of ϕ and ψ always converged to (180.0,

TABLE 1: Conformers of Diglycine Zwitterion and Neutral Diglycine and Their Total Energies in the Gas Phase and in Solvent Media

conformers	basis set	ϵ	dihedral angles			total energy[a,b]	rel energy[a]
			ϕ	ψ	ω		
				Diglycine Zwitterion			
	6-31+g(d)	1	177.85	167.43	178.49	−485.579 85[c]	
		2.2	−177.54	170.20	176.89	−489.645 90[c]	
		78.0	177.45	−179.61	176.44	−489.745 28[c]	
(gg1)	6-31++g(d,p)	1	179.97	179.98	−179.99	−489.601 43[c]	0.0
(gg2)		1	−150.0	−180.0	−192.0	−489.600 79[c]	1.68
(gg3)		1	−180.0	150.0	−181.7	−489.600 0[c]	3.75
(gg4)		1	−150.0	150.0	−193.4	−489.599 04[c]	6.27
(gg5)		1	−180.0	120.0	−177.4	−489.594 77[c]	17.49
(gg6)		1	−150.0	120.0	−188.96	−489.593 33[c]	21.27
(gg7)		1	−180.0	90.0	−174.19	−489.589 66[c]	30.90
(gg8)		1	−150.0	90.0	−186.6	−489.587 59[c]	36.30
	6-31++g(d,p)	2.2	177.99	−172.08	−177.33	−489.644 97[c]	
(gg1)	6-31++g(d,p)	78.0	179.98	−179.99	179.98	−492.518 89[d]	
(gg1)	6-31++g(d,p)	78.0	179.97	−179.98	179.99	−489.725 71[c]	0.0
(gg2)		78.0	−150.0	−180.0		[−489.696 69[c]]	76.2
(gg3)		78.0	−180.0	150.0		[−489.658 86[c]]	175.5
(gg4)		78.0	−150.0	150.0		[−489.633 53[c]]	242.0
(gg5)		78.0	−180.0	120.0		[−489.417 97[c]]	808.0
(gg6)		78.0	−150.0	120.0		[−489.396 87[c]]	863.4
(gg7)		78.0	−180.0	90.0		[−488.851 61[c]]	2295.0
(gg8)		78.0	−150.0	90.0		[−488.836 28[c]]	2335.2
	6-31+g(d,p)	1	179.95	179.99	−179.99	−489.600 85[c]	
		2.2	−179.99	179.94	179.99	−489.645 18[c]	
		78.0	−179.98	179.93	179.97	−489.726 91[c]	
				Neutral Diglycine			
(dgn1)	6-31++g(d,p)	1	179.20	146.61	177.19	−489.684 89[c]	
(dgn2)		1	180.0	180.0	180.0	[−489.591 02[c]]	246.4
		1	150.0	150.0	180.0	[−489.654 78[c]]	79.1
		1	180.0	120.0	180.0	[−489.643 44[c]]	108.8
(dgn3)		78.0	−179.52	153.36	174.18	−489.686 41[c]	
	6-31++g(d,p)	1	178.83	147.53	176.88	−492.481 25[d]	
		78.0	−177.82	156.34	173.73	−492.483 11[d]	

[a] Energy in Hartrees and relative energy in kJ/mol and the values of ϕ, ψ, ω are in degrees. [b] Conformers (gg1) to (gg8) are shown in Figures 1 and 2, values in the brackets are single point energies. [c] Hartree−Fock level. [d] By B3LYP method.

180.0), representing a planar skeleton for diglycine zwitterion. This deviation between the experiment and the ab initio results may be traced to the fact that in the solid state the zwitterion forms a network of intermolecular hydrogen bonds which is absent in the gas phase and to which the results of the ab initio study refer to.

The atoms involved in the peptide linkage −C(=O)N(H)− are coplanar as a consequence of the delocalization of the C, O, and N π electrons to form a three-centered π system. The occurrence of such coplanarity is often assumed to be of general importance in determining the secondary structure of proteins. This interpretation is reinforced by the marked shortening of the C−N bond.

The observed geometrical parameters of diglycine zwitterion from the X-ray and neutron diffraction studies[2−5] are compared in Table 2 with those calculated at the HF level using the basis set 6-31++g(d,p). The calculated geometrical parameters of diglycine zwitterion were nearly the same in all the three basis sets, and hence only the values derived at HF/6-31++g(d,p) are given. The calculated bond lengths and bond angles are in good agreement with the experiment. The calculated bond lengths of C=O and C′=O are smaller by 0.071 and 0.022 Å, respectively, than the experiment. This may be expected since the two C=O groups are involved in intermolecular hydrogen bonding in the solid state. The calculated bond angles of N+−C−C, C−C=O, and C−N−C′ are lower than the experimental values by nearly 5°, while the calculated value of C−N−C′ is higher by about 8° than that observed. The experimental values of the dihedral angles N−C−C=O, N−C′−C′=O, and C−C−

N−H suggest nonplanarity of the molecular skeleton.[3] However, the calculated values demonstrate nearly planar skeletal structure for diglycine zwitterion as discussed above.

Neutral diglycine is not planar but its peptide group is planar. The conformation of neutral diglycine defined by (ϕ, ψ, ω) is 180.0°, 150.0°, 180.0°, respectively, as derived both at the Hartree−Fock and B3LYP level using the basis set 6-31++g(d,p). For neutral diglycine, a potential energy scan was made by varying (ϕ, ψ) values in the gas phase as well as in the solvent medium of dielectric constant 78.0 at HF/6-31++g(d,p). Selected conformations obtained with single point energies are listed in Table 1 and shown in Figure 2. The optimized conformation of neutral diglycine, which lies in the global minima, has (ϕ, ψ, ω) of (179.2, 146.6, 177.2), showing deviation from planarity. The energy differences between the various conformations of neutral diglycine are considerable as given in Table 1.

The energy difference between the conformers lying in the global minima of the zwitterion and neutral diglycine is higher, −219 kJ/mol, showing that the neutral form is more stable than the zwitterion. However, the zwitterionic form of glycine and other amino acids is 20−60 kcal/mol more stable than the corresponding neutral form. Inclusion of electron correlation is essential in evaluating the stability of the zwitterion over the neutral form.

The geometrical parameters of diglycine zwitterion are compared with those of the neutral molecule in Table 2. A comparison of the geometrical parameters of neutral diglycine obtained at the HF level in the gas phase with those of the

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TABLE 2: Experimental and Calculated Geometrical Parameters of Diglycine Zwitterion and Neutral Diglycine

parameters[a]	diglycine zwitterion			calculated (6-31++g(d,p))					
	experiment			diglycine zwitterion			neutral diglycine		
	X-ray[3]	neutron[5]	gas	$\epsilon = 2.2$	$\epsilon = 78.0^b$	$\epsilon = 78.0^c$	gas[b]	$\epsilon = 78.0^b$	$\epsilon = 78.0^c$
N^+-C	1.491	1.484	1.496	1.496	1.496	1.512	1.445	1.446	1.460
$C-C$	1.519	1.518	1.543	1.539	1.541	1.553	1.518	1.519	1.530
$C=O$	1.249	1.240	1.226	1.214	1.220	1.227	1.204	1.206	1.232
$C-N$	1.319	1.333	1.291	1.314	1.362	1.373	1.347	1.344	1.355
$N-C'$	1.451	1.453	1.461	1.459	1.462	1.473	1.437	1.438	1.447
$C'-C'$	1.514	1.524	1.560	1.549	1.551	1.564	1.505	1.507	1.515
$C=O$	1.230	1.235	1.244	1.260	1.260	1.254	1.19	1.19	1.213
$C'-O^-$	1.232	1.251	1.217	1.234	1.263	1.284	1.32	1.321	1.344
N^+-H^a	1.001	1.037	1.005	1.009	1.021	1.036	1.0	1.00	1.019
N^+-H^b	1.035	1.040	1.042	1.022	1.013	1.029	0.999	0.999	1.015
$C-H$	1.094	1.101	1.080	1.080	1.082	1.094	1.093	1.092	1.104
$N-H$	1.023	1.020	1.015	1.002	0.996	1.013	0.995	0.996	1.014
$C'-H$	1.103	1.103	1.082	1.083	1.084	1.096	1.085	1.084	1.097
$O-H$							0.949	0.950	0.974
N^+-C-C	109.5	109.3	104.5	106.73	111.52	111.10	109.62	110.05	109.71
$C-C=O$	120.4	119.9	115.4	116.88	119.72	119.48	121.59	121.71	121.64
$C-C-N$	116.3	116.6	115.4	116.79		118.33	116.09	115.61	115.56
$C-N-C'$	121.2	120.6	128.4	123.80	119.69	120.12	121.02	121.67	122.23
$C-N-H$	120.7	120.6	123.7	123.17	121.97				
$N-C'-C'$	112.4	112.5	106.2	110.21		117.12	109.64	109.28	108.95
$C'-C'=O$	117.9	118.4	113.9	115.89	120.05	119.50	125.03	124.60	124.41
$C'-C'-O^-$	115.5	116.6	114.7	114.37	114.21	114.33	111.7	111.71	111.53
$N-C-C=O$	−30.9	−32.2	−0.016	9.1	0.02	0.04	−36.21	−29.43	−26.1
$C-C-N-C'$	174.5	176.1	−179.99	−177.33	179.99	−179.98		174.18	173.73
$C-C-N-H$	−4.6	−11.3	−0.01	1.062		0.0	−6.6	−3.9	−3.3
$N-C'-C'-O^-$	−169.7	−169.1	180.0	−179.99	−179.99	−180.0	179.29	179.03	178.93
$N-C'-C'=O$	11.5	10.7	0.003	0.23	0.02	0.0	−0.8	−1.07	−1.2

[a] Bond lengths are in Å, bond angles and dihedral angles in degrees; a: in plane, b: out of plane. [b] Hartree−Fock level. [c] By B3LYP method.

zwitterion shows that N−C, C−C, N−H, and amide C=O bond lengths decrease by 0.05 Å or less as we go from the zwitterion to the neutral molecule, while the amide C−N bond length increases, showing increased contribution of the covalent resonance form in neutral diglycine for the amide group. The carboxylate group of the zwitterion shows a small decrease for the C=O bond length and a similar increase for the C−OH group as expected for the neutral diglycine. The N−C−C=O and C−C−N−H dihedral angles in neutral diglycine show nonplanarity of the molecular skeleton.

Binding Energy. The binding energy of diglycine zwitterion was obtained as the difference in energies for the formation of diglycine zwitterion from two glycine zwitterions with the release of a molecule of water. The total energies were calculated for glycine zwitterion, diglycine zwitterion, and water molecule using the same basis set. The binding energy for diglycine zwitterion neglecting zero point energy corrections was found to be −172.12 and −199.5 kJ/mol respectively, as calculated using the basis sets 6-31++g(d,p) and 6-31+g(d). The method of Chauduri and Camuto,[19] who have calculated the binding energy for neutral diglycine, was followed.

glycine zwitterion   glycine zwitterion   diglycine zwitterion
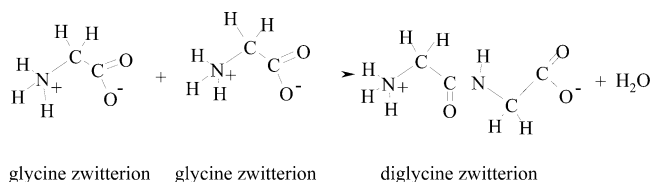
Vibrational Spectra. The lowest energy conformer of α-diglycine zwitterion (gg1) possessing the point group symmetry C_1 yielded all real frequencies at the HF level for all the three basis sets mentioned earlier. Harmonic frequencies and their assignments were calculated by utilizing the force constants

derived at the HF/6-31++g(d,p) level; the calculated total energy for the lowest energy conformer (gg1) was a minimum in this basis set as compared to that obtained from the other two basis sets as noted from Table 1. The ab initio force constants were not modified using the scale factors to bring the calculated frequencies nearer to the observed frequencies, which is generally the practice.[21] However, as discussed below, the calculated frequencies were scaled according to Scott and Radom[22] to obtain a better agreement between the calculated and experimental frequencies. The calculated scaled frequencies under harmonic approximation are compared with the observed infrared and Raman bands of the α-diglycine zwitterion[7,9,10] in Table 3, wherein the assignments from the potential energy distributions (PED) are also given. Similar results for the N-deuterated zwitterion (d₄) are presented in Table 4. It is satisfying to note that the Raman bands have been observed corresponding to each of the infrared bands of the diglycine zwitterion in most cases. The observed and calculated frequency shifts for ^{15}N isotopic molecule of α-diglycine zwitterion (dₒ) and its N-deuterated species (d₄) are listed in Tables 3 and 4, respectively. The predicted ^{15}N shifts are in satisfactory agreement with the experiment.

It is well-known that the ab initio harmonic frequencies are typically by about 10% overestimated from the experimentally observed fundamentals. Errors arise because of the neglect of anharmonicity and electron correlation and due to the use of a finite basis set. Scaling factors are usually applied to the ab initio force constants to obtain a good overall agreement between the calculated and observed frequencies,[21] as mentioned before. However, Scott and Radom[22] have proposed from a comprehensive study scaling factors for the theoretical harmonic frequencies themselves rather than for the force constants. They have recommended a scale factor of 0.9054 for the harmonic

TABLE 3: Observed and Calculated ^{15}N Shifts and Scaled Harmonic Frequencies (cm^{-1}) of Diglycine Zwitterion and Their Assignment

exptl[a]			N^{15} shifts		calcd	
IR[7]	IR[9]	Raman[7]	obsd[9]	calcd	scaled[a]	PED
				11	3431	$NH_3as(100)$
3282	3282	3285	7.5	6	3364	$NH_3ss(61)$, $NH_3as(39)$
	3288	3285	7.5	9	3234	$NHs(99)$
3055	3055[b]	3062		0	3024	$CH_2as(100)$
3015	3020[b]	3013		0	2982	$C'H_2as(100)$
3015	3014[b]	2960		0	2964	$CH_2s(99)$
2925	2965[b]	2927		0	2934	$C'H_2s(99)$
2925	2920[b]	2874		6	2854	$NH_3as(57)$, $NH_3ss(42)$
1676	1674	1682	0	1	1724	$COs(31)$, $CNs(29)$, $COOas(16)$
1658	1668	1647	4	8	1722	$COOas(42)$, $COOs(21)$, $CNs(13)$, $COs(11)$
1627	1629	1629	0	2	1636	$NH_3ab(97)$
1598	1605	1611	0	4	1607	$NH_3ab(74)$, $NH_3sb(15)$
1554, 1533	1532	1531, 1503	12	17	1523	$NHb(28)$, $COs(21)$, $CNs(19)$
1478	1482	1481	0	0	1463	$CH_2b(78)$
1441	1441	1447		0	1457	$C'H_2b(85)$
1408	1406	1408	0	6	1404	$NH_3sb(57)$
1388	1385	1399	0	0	1361	$COOs(44)$, $C'C's(18)$, $COOas(15)$, $C'H_2b(15)$
1333	1337	1338	0.6	3	1340	$CH_2t(46)$, $CCs(10)$
1310	1311	1315	0.4	2	1300	$C'H_2t(45)$, $CH_2t(18)$
1251	1252	1249	1.2	5	1284	$CH_2r(67)$, $NH_3w(22)$
1231	1233	1242	1.9	2	1195	$C'H_2t(91)$
1157	1157	1158	0.9	0	1191	$NHb(43)$, $C'H_2t(26)$
1129	1134	1136	4.4	2	1074	$NH_3w(36)$, $CH_2r(34)$, $CH_2w(19)$
1094	1097	1100	8.1	9	1073	$NH_3r(53)$, $NCCb(10)$
1037	1040	1046	3	12	1037	$NC's(51)$, $NH_3r(11)$
1001	1001	1007	0.9	1	996	$C'H_2w(62)$, $\Pi_{COO}(28)$
965	964	968	3.2	12	960	$NCs(42)$, $CCs(16)$, $COb(16)$
918	918	918	1.8	7	911	$NCs(36)$, $CCs(13)$
895	900	910	2.2	1	902	$CH_2w(45)$, $NH_3w(35)$, $\Pi_{CO}(15)$
				2	863	$C'C's(41)$, $COOb(31)$
				2	846	$\Pi_{NH}(46)$, $\tau_{CN}(37)$ $\tau_{NC'}(14)$
735	734	730	2	2	704	$CCs(23)$, $COb(22)$, $NCCb(21)$, $COOb(12)$
711	710	718	0.9			
664	663	665	1.2	2	654	$COOb(33)$, $C'C's(20)$, $COb(19)$
588	592	598	3	1	587	$\Pi_{COO}(37)$, $C'H_2w(19)$, $\Pi_{CO}(12)$
580	585	588	0.8	1	556	$\Pi_{CO}(38)$, $CH_2w(19)$, $\Pi_{COO}(12)$, $C'H_2w(10)$
522	532	535	1.6	5	542	$CC'Ob(40)$, $CCNb(16)$
440	402	396		4	391	$NCCb(29)$, $C'C'Ob(25)$
400						
310	314	317		2	321	$CCNb(26)$, $C'C'Ob(11)$, $NC's(10)$ $NCCb(10)$
		298		2	268	$NC'C'b(34)$, $NCCb(14)$
231	232	221		0	243	$\tau_{NH_3}(61)$, $NH_3ab(30)$
207	207	182		1	181	$\tau_{CC'}(29)$, $\tau_{CN}(24)$, $\Pi_{NH}(17)$, $\tau_{NH_3}(11)$
	(118)[c]	167		1	165	$CNC'b(42)$, $CCNb(27)$, $NC'C'b(16)$
	(79)[c]			0	84	$\tau_{CC'}(47)$, $\Pi_{NH}(22)$, $\tau_{CN}(14)$
	(56)[c]			1	48	$\tau_{NH_3}(35)$, $\tau_{CC}(24)$, $\tau_{NC'}(18)$, $\Pi_{NH}(11)$
	(36)[c]			0	14	$\tau_{NH_3}(51)$, $\tau_{CC}(35)$

[a] cm^{-1}. [b] ss = symmetric stretching, as = asymmetric stretching, sb = symmetric bending, ab = asymmetric bending, τ = torsion, Π = out of plane bend, t = twisting, w = wag, r = rocking. [c] Values in the parenthesis are calculated values from ref 9.

frequencies calculated at HF/6-31++g(d,p). Accordingly in the present work the ab initio harmonic frequencies have been scaled down by using a scale factor of 0.9054. The agreement between the calculated scaled harmonic frequencies and the observed frequencies is satisfactory. However, the NH$_3^+$ stretching frequencies show comparatively larger deviation from the experimental frequencies, which may be due to hydrogen bonding and larger anharmonicities involving hydrogen stretching vibrations. The COO$^-$ stretching modes also show a somewhat larger deviation, possibly since the COO$^-$ group is involved in hydrogen bonding.

The assignment of the observed infrared and Raman bands of diglycine zwitterion is accomplished by noting the agreement between the observed and calculated frequencies for the parent molecule and its isotopomers. Two intense infrared bands at about 1675 and 1660 cm^{-1} found for diglycine zwitterion are assigned to the amide I band and asymmetric COO$^-$ stretching

mode, respectively. The present assignment differs from that of Destrade et al.[9] who have assigned the latter band to NH$_3^+$ deformation and a band at 1605 cm^{-1} to COO$^-$ stretching. According to the present results, their assignments for the 1660 and 1605 cm^{-1} bands need to be reversed. However, there is broad agreement regarding the assignment of the other frequencies considering the inherent limitations of the earlier normal coordinate analysis with empirical force fields. Chakraborty and Manogaran[23] have calculated the vibrational frequencies of glycylglycine hydrochloride from the ab initio force field obtained at the HF/6-31g(d) level for the lowest energy conformer. They have also assigned a few of the experimental frequencies. The present assignments are in good agreement with them. In particular, the assignments of asymmetric NH$_3^+$ bending modes at 1630 and 1605 cm^{-1} and the symmetric NH$_3^+$ bending at 1406 cm^{-1} are compatible with those in diglycine hydrochloride.[23] Similarly the assignment of NH$_3^+$ rocking and

TABLE 4: Observed and Calculated ^{15}N Shifts and Scaled Harmonic Frequencies (cm^{-1}) of N-Deuterated Diglycine Zwitterion and Their Assignment

exptl[a]			N^{15} shifts		calcd	
IR[7]	IR[9]	Raman[7]	obsd[9]	calcd	scaled freq	PED[b]
3020		3012		0	3024	CH$_2$as(100)
2960		2958		0	2982	C′H$_2$as(100)
2925		2923		0	2964	CH$_2$s(99)
		2870		0	2934	C′H$_2$s(99)
	2434	2463	14	16	2533	ND$_3$as(99)
2418	2434	2431		11	2445	ND$_3$ss(49), ND$_3$as(49)
2290		2408		13	2376	NDs(97)
		2154		8	2083	ND$_3$ss(49), ND$_3$as(48)
1660	1659	1673	2	0	1718	COOas(59), COOs(30)
1645	1640	1633	2	9	1708	COs(43), CNs(43)
1485	1488	1480	14	14	1485	COs(28), CNs(19), CCs(12)
1442	1443	1445	0	14	1459	CH$_2$b(76)
1402	1407	1403		1	1456	C′H$_2$b(81)
1367	1358	1358	4.5	0	1359	COOs(44), C′C′s(18), COOb(15), COOas(14)
1345		1348		3	1330	CH$_2$t(74)
1307	1311	1310	1.0	0	1284	C′H$_2$t(75)
1280	1280	1280				
1240	1243	1242	0.25	3	1248	CH$_2$r(84)
1165	1170	1168	1.0	2	1195	C′H$_2$r(91)
1165	1170	1168	1.0	6	1182	ND$_3$ab(47), ND$_3$sb(39), NCs(11)
	1150	1154		6	1178	ND$_3$ab(97)
	1107	1108	10	10	1069	ND$_3$ab(36), ND$_3$sb(31), NCs(18)
1042	1047	1044	1	11	1030	NC′s(55)
1020	1027	1020	3	2	1016	CH$_2$w(53), τ_{CO}(17), CH$_2$r(13), ND$_3$w(11)
1000	994	995	0.5	0	995	C′H$_2$w(61), τ_{COO}(28)
992	989	982	3.5	6	983	NDb(24), CCs(23), COb(18)
935	935	924	0.6	4	930	ND$_3$r(23), NCCb(21), NDb(11)
			3.5	3	892	NCs(36), NDb(23)
850	858	864	1.0	0	863	C′C′s(42), COOb(31)
	843					
782	786	787	1	7	809	ND$_3$r(40), NCs(15), COb(11)
710	704	696	0	2	742	ND$_3$w(74)
658	654	656	1.4	1	673	CCs(22), COOb(20), COb(11)
658	654	656	1.4	2	648	COb(29), COOb(24), C′C′s(17)
				2	628	Π_{ND}(40), τ_{CN}(28), Π_{COO}(11)
582	593	586	1.1	0	584	Π_{COO}(33), C′H$_2$w(17), ΠCO(14)
	584					
537	532	534	2.7	2	547	Π_{CO}(32), CH$_2$w(18), Π_{ND}(13), Π_{COO}(11)
495	492	504	1.0	5	529	C′C′Ob(43), CCNb(14)
403	387	382		2	368	C′C′Ob(27), NCCb(21)
	310	304		1	311	CCNb(20), COb(12), CNC′b(12), NCCb(11), NC′s(10)
	300					
		287		2	255	NC′C′b(29), NCCb(20)
214	214			1	188	τ_{ND_3}(27), ND$_3$ab(22), Π_{ND}(14), $\tau_{CC'}$(13), τ_{CC}(12)
	(182)[c]			1	177	τ_{ND_3}(31), τ_{CN}(19), $\tau_{CC'}$(19)
	(114)[c]			1	99	CNC′b(41), CCNb(27), NC′C′b(16)
	(76)[c]			1	83	$\tau_{CC'}$(54), Π_{ND}(19), τ_{CN}(16)
	(55)[c]			1	43	τ_{ND_3}(34), τ_{CC}(22), $\tau_{NC'}$(20), Π_{ND}(13)
	(34)[c]			0	13	τ_{ND_3}(51), τ_{CC}(35)

^{a} cm^{-1}. ^{b} ss = symmetric stretching, as = asymmetric stretching, sb = symmetric bending, ab = asymmetric bending, τ = torsion, Π = out of plane bend, t = twisting, w = wag, r = rocking. ^{c} Values in the parenthesis are calculated values from ref 9.

wagging modes respectively near 1100 and 1134 cm^{-1} in the infrared spectrum are in accord with those in diglycine hydrochloride.[23] The observed stretching frequencies of NH$_3$+, CO, and COO$^-$ groups are considerably lower than their respective calculated frequencies. This is expected since these groups are involved in intra- and intermolecular hydrogen bonding. The calculated frequencies refer to the isolated zwitterion in the gas phase.

The symmetric COO$^-$ stretching is assigned to a fairly intense band observed in the infrared and Raman spectra near 1385 cm^{-1}. The assignment of the amide II band to an infrared band at 1532 cm^{-1} is consistent with that in diglycine hydrochloride[23] as well as with the experimental assignment of Lagant et al.[7] The assignment of the characteristic amide III band (due to C−N stretching) is rendered difficult because of its highly coupled nature. However, the amide IV and VI bands due to in plane

and out of plane C=O bending modes, respectively, may be attributed to the infrared bands observed near 665 and 585 cm^{-1}, respectively.

Spectra of Isotopic Molecules. Vibrational frequencies for selectively N-, C-, and C,N-deuterated diglycine zwitterions have been calculated using the force constants derived employing the basis set 6-31++g(d,p) and the calculated frequencies are scaled down according to Scott and Radom[22] and compared with the observed ones in Table 5. For all the fundamentals of the nine isotopomers of diglycine zwitterion the agreement between the observed frequencies and the calculated scaled harmonic frequencies is good. Thus the ab initio force field successfully reproduces the experimentally observed fundamentals for all the isotopic species including ^{15}N isotopic shifts of diglycine zwitterion. Some deviations between the observed and calculated frequencies (or the shifts) may be attributed to the larger

TABLE 5: Observed and Calculated Scaled Harmonic Frequencies (cm⁻¹) of Variously Deuterated Diglycine Zwitterion[a]

$d_{2\alpha}$		$d_{2\beta}$		$d_{4\alpha\beta}$	
obsd[9]	calcd	obsd[9]	calcd	obsd[9]	calcd
3288	3234	3288	3233	3288	3233
	2982	3228	3024		2855
1673	1723	1674	1722	1670	1721
1650	1721	1653	1721	1650	1720
1629	1636	1626	1636	1627	1636
1599	1606	1606	1607	1598	1606
1543	1522	1539	1522	1539	1521
1481	1457	1442	1463	1409	1400
1445					
1404	1400	1409	1405	1328	1359
1334	1361	1388	1359	1228	1255
1298	1312	1336	1335	1208	1155
1227	1208	1263	1284	1151	1135
1207	1195	1263	1234	1115	1101
1136	1152	1127	1100	1078	1084
1136	1135	1076	1074	1053	1057
1086	1089	1076	1071		1017
1051	1047	1049	1055	947	978
1000	996	1017	998	921	913
961	989	949	953	921	906
925	903	928	913	895	885
910	877	909	903	878	878
887	854	887	889	868	863
837	844	867	887	835	836
837	819		838	804	823
804	793		823	804	792
703	682	720, 704	698	701	673
657	648	649	631	642	628
589	581	573	564	544	512
562	537	536	518	526	510
496	493	499	491	481	477
399	389	400	389	397	388
309	316	310	320	306	314
	267		266		265
226	243	226	243	228	243
	177		161		157
	100		100		100
	83		84		83
	43		44		43
	14		14		13

$d_{6\alpha}$		$d_{6\beta}$		d_8	
obsd	calcd	obsd	calcd	obsd	calcd
	2982		3024	2434	2533
2434	2376	2434	2376		2216
1655	1718	1657	1716	1620	1716
1638	1706	1636	1707	1590	1704
1482	1482	1487	1484	1477	1481
1447	1456	1442	1459	1410	1359
1405	1362	1410	1359	1220	1186
1313	1285	1357	1330	1171	1181
1202	1195	1282	1248	1150	1157
1170	1186	1173	1182	1118	1093
1170	1181	1173	1178	1118	1090
1142	1146	1149	1111	1077	1077
1077	1081	1080	1089	1034	1045
1036	1052	1080	1068	957	982
1009	1018	1003	1016	957	981
	996		987	938	920
975	981	936	943	938	912
948	953	898	912	915	905
908	898	898	890	904	881
908	888	868	886	904	878
882	869		824	868	854
	853	786	805	858	823
	781		750		780
727	692		742	725	691
695	665	695	665	678	650
638	638	644	627	630	625
638	626	644	623	630	618
587	574	587	558	544	
524	525	514	507	514	503
486	486	485	487	468	471
385	367	387	367	379	365
311	308	304	310	295	306
	254	220	253		253
215	186		186	210	185
	175		159		156
	97		98		97
	81		83		81
	43		43		43
	12		13		12

[a] For abbreviations $d_{2\alpha}$ $d_{2\beta}$, $d_{4\alpha\beta}$, $d_{6\alpha}$, $d_{6\beta}$, and d_8, see text.

anharmonicity associated with hydrogen involving vibrations and the effect of hydrogen bonding.

Solvent Effects. Amino acids and peptides exist in aqueous solutions as zwitterions rather than in their neutral form as supported by the ab initio calculations carried out, for example, for glycine.[17] Zwitterion formation in solution occurs by means of an intramolecular proton transfer from oxygen to amine nitrogen. Solvent effects on the conformation of diglycine zwitterion were investigated by the ab initio method using the basis sets 6-31+g(d), 6-31++g(d,p), and 6-31+g(d,p) for solvents of dielectric constant (ϵ) 2.2 and 78, corresponding to carbon tetrachloride and water, respectively, using the dipole method.

The Onsager continuum model is a method to predict the solvation effects on the properties of the solute without considering explicit solvent molecules. This model has been used to predict the spectral and structural changes occurring due to the solvent in good agreement with the experiment.[16,24] The results have shown that the success of the Onsager reaction field model is largely due to the cancellation of errors. The unrealistic cavity shape cancels errors due to the neglect of higher order electrostatic terms. Other cavity shapes such as an ellipsoid or an approximation to the van der Waals surface[21] have been used; the effect of higher moments has also been examined.[25-27] However, the simple model remains the only one for which analytical gradients and second derivatives are available. They are needed for efficient geometry optimization and the calculation of vibrational frequencies in the presence of the reaction field. The more general Onsager reaction field approach with judicious choice of the basis set and the radius of the molecular volume in a particular dielectric medium appears to give a more appropriate description of the amino acid zwitterions.

The structures obtained in the gas-phase geometry optimizations were used as initial structures for the optimizations within the Onsager model using the HF and B3LYP methods employing the 6-31++g(d,p) basis set. All the structures optimized to stable structures.

The calculated total energies for the conformers of diglycine zwitterion lying in the global minima of the potential energy scan at the HF level made using the three basis sets 6-31+g(d), 6-31++g(d,p) and 6-31+g(d,p) in solvents of dielectric constant 2.2 and 78.0 are given in Table 1. The conformers lying in the local minima of the potential energy scan calculated at HF/6-31++g(d,p) in solvent of dielectric constant 78 are shown in Figure 1. The potential energy scans were made by varying both ϕ and ψ from 180.0 to 0.0 and the minimum energy was again found to correspond to ϕ, ψ values of 180.0, 180.0 in the aqueous medium. A study of the rotation of the COO⁻ group in aqueous medium showed that the COO⁻ group coplanar with the diglycine skeleton represents the minimum energy conformation. In the solvent of dielectric constant 2.2, diglycine zwitterion tends to be slightly nonplanar with ϕ and ψ values of 177.99 and −172.08, respectively. Table 1 shows that the total energy of diglycine zwitterion decreases with increase in the dielectric constant of the solvent due to solvation effect. The extra stability of the zwitterion in the solution (or solid state) over that in the gas phase seems to come from the intermolecular interactions and the interactions with the solvent. Thus the effect of the solvent environment and intermolecular hydrogen bonding cannot be ignored in the theoretical studies of the dipeptide zwitterion.

Ab initio calculations on diglycine zwitterion in a solvent of dielectric constant 78.0 were also carried out using the B3LYP/

TABLE 6: Calculated Scaled Frequencies (cm^{-1}) of Diglycine Zwitterion in Solvents of $\epsilon = 2.2$ and 78

HF/6-31+g(d)			HF/6-31++g(d,p)			B3LYP/6-31++g(d,p)
gas	$\epsilon = 2.2$	$\epsilon = 78.0$	gas	$\epsilon = 2.2$	$\epsilon = 78.0$	$\epsilon = 78.0^a$
3422	3435	3505	3431	3417	3506	3590
3359	3371	3324	3364	3386	3342	3458
3263	3331	3278	3234	3334	3307	3424
3041	3234	3161	3024	3108	3217	3328
3020	3029	3006	2982	3016	2995	3145
2998	2982	2969	2964	2970	2950	3091
2980	2972	2956	2934	2959	2941	3089
2952	2943	2918	2854	2928	2916	3057
1727	1716	1757	1724	1709	1739	1750
1722	1662	1668	1722	1670	1624	1658
1664	1661	1649	1636	1634	1622	1654
1625	1630	1588	1607	1619	1612	1629
1533	1516	1580	1523	1513	1540	1549
1478	1502	1481	1463	1470	1466	1493
1472	1477	1473	1457	1462	1461	1482
1451	1473	1425	1404	1446	1441	1419
1366	1391	1395	1361	1383	1387	1370
1361	1368	1345	1340	1350	1346	1337
1316	1317	1330	1300	1304	1316	1327
1296	1306	1263	1284	1288	1283	1288
1215	1229	1250	1195	1213	1240	1242
1206	1199	1122	1191	1190	1155	1159
1083	1082	1076	1074	1074	1073	1079
1082	1077	1070	1073	1068	1065	1070
1036	1035	1025	1037	1038	1029	1032
1000	1000	992	996	996	992	974
964	970	949	960	968	963	970
911	916	906	911	916	913	916
896	890	875	902	906	872	882
863	865	828	863	866	845	845
843	700	687	846	710	686	681
702	685	631	704	694	626	629
653	640	620	654	645	619	626
591	603	597	587	597	602	599
563	552	506	556	547	516	526
537	529	415	542	535	471	492
397	359	323	391	368	334	338
328	303	254	321	307	264	263
276	234	250	268	238	198	196
213	178	189	243	189	195	183
184	111	155	181	165	150	135
105	110	129	165	108	119	117
84	92	118	84	83	111	106
68	82	86	48	70	75	63
30	57	65	14	−64	49	−90

^{a} Not scaled.

6-31++g(d,p) method. Diglycine zwitterion was found to be stable in the solvent medium at the B3LYP/6-31++g(d,p) level, unlike in the gas phase. At the Hartree−Fock and B3LYP level, the cavity radii a_o of 4.12 and 4.21 Å, respectively, were obtained for the basis set 6-31++g(d,p). The conformer (gg1), which lies in the global minima at HF/6-31++g(d,p), was considered for geometry optimization at B3LYP/6-31++g(d,p) for the solvent of dielectric constant 78.0. The total energy and geometrical parameters obtained for the ab initio calculations carried out at the B3LYP level are given in Tables 1 and 2, respectively. The values of (ϕ, ψ, ω) from the HF and B3LYP methods for the basis set 6-31++g(d,p) are (179.97, −179.98, 179.99) and (179.98, −179.99, 179.98), respectively. The total energy obtained at the B3LYP level of theory includes electron correlation too. The calculated bond lengths, bond angles, and dihedral angles for diglycine zwitterions at the B3LYP level in solvent of dielectric constant 78.0 are very nearly the same as those obtained at the HF level, confirming the presence of a dipolar structure in polar solvents. The geometrical parameters of diglycine zwitterion in the two solvents of dielectric constant
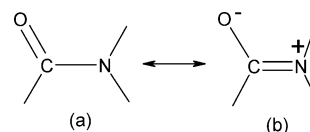

Figure 3. Resonance structures for the amide group.

2.2 and 78 calculated at HF level using the basis sets 6-31+g(d) and 6-31++g(d,p) are given in Table 2.

The geometrical parameters of diglycine zwitterion in the solvent of $\epsilon = 2.2$ do not show much variation from those in the gas phase. The variations are slightly higher for the solvent of $\epsilon = 78$. Interestingly, the calculated amide C=O and N−H bond lengths are slightly shorter and the amide C−N bond is slightly longer in the solvent of higher dielectric constant compared to their values in the gas phase. This suggests the stabilization of covalent resonance form (a) over the dipolar form (b) shown in Figure 3 in solvents of higher dielectric constant, unlike for the neutral amide molecules where the dipolar resonance structure is stabilized in polar solvents.[28] The bond length of C=O of the carboxylate group of the zwitterion

shows a decrease, while that of the $C-O^-$ group shows a slight increase in the aqueous medium. The bond angle of $C-C=O$ shows an increase, while the bond angle CNC' was found to decrease in the aqueous medium by about 8° from their calculated values in the gas phase. The dihedral angles do not register much variation in the two solvents from their values in the gas phase. The shifts in bond lengths and bond angles demonstrate considerable interaction of diglycine zwitterion with the surrounding solvent molecules.

Ab initio calculations were carried out for neutral diglycine both at the HF and B3LYP levels using the basis set 6-31++g(d,p) in solvent of dielectric constant 78.0. It was found by both the methods that the conformer lying in the global minimum possesses a nonplanar conformation in the solvent. The ϕ, ψ, ω values of the conformer of neutral diglycine lying in the global minima in the polar solvent at HF and B3LYP levels are (−179.52, 174.18, 153.36) and (−177.82, 173.73, 156.34), respectively, while diglycine zwitterion has a planar conformation. In Table 2, the bond lengths, bond angles, and dihedral angles of neutral diglycine for the gas phase obtained at both HF and B3LYP levels using the basis set 6-31++g(d,p) are given. It is observed that the bond lengths obtained at B3LYP/6-31++g(d,p) are longer than those obtained at the HF level for all amide and nonamide bonds. At the B3LYP level, the amide $C=O$ bond length is longer by 0.001 Å and the $C-N$ by 0.082 Å. The carboxylate $C'=O$ is longer by 0.01 and the $C'-O^-$ by 0.05 Å. The $N-H$ bond length is shorter by 0.02 Å. The bond angles and dihedral angles do not vary much compared to those obtained at the HF level. The geometrical parameters of neutral diglycine in a polar solvent are almost the same as those in the gas-phase values at HF/6-31++g(d,p).

The vibrational frequencies of diglycine zwitterion in the two solvents calculated at the HF level using the basis sets 6-31+g(d) and 6-31++g(d,p) are given in Table 6. Diglycine zwitterion yielded all positive vibrational frequencies in both the solvents. The calculated shifts in the frequencies are higher for the more polar solvent than those for the less polar solvent. The $N-H$ and $C=O$ stretching frequencies increase in the solvent of higher dielectric constant from that in the gas phase in accord with the observation made above regarding their decreasing bond lengths in more polar solvents. The shifts are generally in the same direction for both the solvents, although there are some exceptions. The lower frequency modes show larger shifts. Interestingly, the CH_2 group adjacent to the $C=O$ group shows larger frequency shifts, possibly owing to the change in the $C-N$ bond order. Similarly, the asymmetric COO^- stretching frequency records a larger downward shift. The out-of-plane NH bending, which is known to be sensitive to the environment, shows the largest downward shift.

The calculated vibrational frequencies for diglycine zwitterion in solvent of ϵ 78.0 by the B3LYP/6-31++g(d,p) method are tabulated in Table 6. The calculated frequencies by the DFT method were not scaled. One imaginary frequency corresponding to NH_3 torsion was obtained. There is very good agreement between the frequencies of the zwitterions calculated by the HF and B3LYP methods, particularly for frequencies below 1800 cm^{-1}. Only the hydrogen-involving stretching vibrations show larger shift. This may be due to larger anharmonicity associated hydrogen-involving stretching vibrations. Thus the results obtained by these two methods are consistent.

Conclusions

Diglycine zwitterion is stable both in the gas phase and in solvents, carbon tetrachloride and water, and it is more stabilized

in the latter. The minimum energy conformation in the gas phase and in aqueous medium possesses planar skeletal geometry. The vibrational spectra of diglycine zwitterion have been assigned using the theoretical ab initio frequencies and their assignments, and the spectra of nine selectively C-, N,C-, and N-deuterated and ^{15}N-labeled isotopic species.

Neutral diglycine is apparently more stable than the zwitterionic form in the gas phase. The zwitterionic form is stabilized at the B3LYP level in the solvent medium. The equilibrium geometry and the vibrational frequencies of diglycine zwitterion in the solvent medium calculated at the HF level are consistent with those obtained by the B3LYP method.

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