

Dipole-Bound Anions of Glycine Based on the Zwitterion and Neutral Structures

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Abstract

The instability of the zwitterion structure of glycine is significantly reduced by the attachment of an excess electron and a local minimum develops on the anionic potential energy surface for the zwitterion structure. However, the global anionic minimum, that is lower by 9 kcal/mol, corresponds to a singly hydrogen-bonded non-zwitterion structure. The vertical electron detachment energies for these two dipole-bound zwitterion and non-zwitterion structures are 3175 and 668 cm^{-1} , respectively.

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In aqueous solutions, the ionic form of amino acids predominates at pH 7, with the α -amino group protonated and the carboxyl deprotonated. Therefore, most amino acids at neutral pH have no net charge, but they exist as zwitterions $\text{NH}_3^+\text{-CHR-COO}^-$ which clearly have large dipole moments¹. In contrast, in the gas phase the zwitterionic charge separation is not stabilized by the environment and a non-charge-separated configuration is likely to be more stable.

It was demonstrated in millimeter wave spectroscopy experiments² and by measurements of substituent effects on gas-phase basicity³ that glycine is not a zwitterion in the gas phase. These results are consistent with ab initio calculations that indicate the non-ionic tautomer is lower in energy⁴⁻⁸. On the basis of kinetic experiments, it was suggested that arginine, with its extremely basic guanidine group, might be stable as a zwitterion in the gas phase⁹. However, this result was not confirmed in later spectroscopic measurements¹⁰, although it was pointed out that there may be a significant barrier that separates the neutral and zwitterion forms of arginine and the thermodynamically unstable form may have a sufficiently long lifetime to be observed experimentally.

With no experimental or theoretical proof of the thermodynamic stability of the zwitterion of an amino acid in the gas phase, newer efforts concentrated on protonated⁹, alkali cationized¹¹, and hydrated⁸ amino acids. For instance, it was found that two water molecules can stabilize the zwitterion of glycine sufficiently to render it geometrically stable⁷. In the present contribution, we study the effect of attaching an excess electron on the relative stabilities of the zwitterion and non-ionic structures of the simplest amino acid, glycine. We demonstrate that the instability of the zwitterion structure of the neutral glycine is significantly reduced by the attachment of an excess electron and a local minimum develops on the anionic potential energy surface. These effects are related to the fact that the anionic state is dipole-bound and the dipole moment for the zwitterion structure is larger than that of the non-ionic structure.

In agreement with earlier studies^{4–8}, we find that the zwitterion structure of the neutral glycine **A** (see Fig. 1) is not even a minimum on the electronic ground state potential energy surface. Rather, geometry optimization based on ab initio calculated forces moves downhill in energy from **A** and collapses to the non-ionic structure **B_n** (see Fig. 2). The stationary point **B_n** is separated from a symmetry-equivalent **B_n** structure by a small barrier (19 cm⁻¹) at the top of which is a C_s-symmetry structure **B_p**. The **B_n** minimum is only 1 kcal/mol higher in energy than the neutral global minimum, **C**, which is geometrically quite distinct¹². Moreover, there is a significant difference in the polarity of **B_n** and **C**; the MP2 dipole moment of **B_n** is 5.52 D, whereas that of **C** is only 1.18 D.

To the best of our knowledge, the glycine molecule does not form a valence type anion in the gas phase because it has no vacant or half-filled valence orbital available. However, the dipole moment of **B_{n,p}** is more than sufficient to support a dipole-bound anionic state and the dipole moment of the zwitterion structure **A** is expected to be even larger than that of **B_{n,p}**. On the other hand, structure **C** has such a small dipole moment that it can not bind an electron. Let us therefore turn to our study of the stability of dipole-bound anions of glycine derived from the non-ionic (**B_p** or **B_n**) and zwitterion (**A**) structures.

As demonstrated by others, the calculated relative energetics of different isomers of the neutral glycine is sensitive to the level of theory¹². Moreover, electron correlation effects proved to be important for dipole-bound anions¹³. Therefore, the results reported in this study were obtained at the coupled cluster level of theory with single, double and non-iterative triple excitations¹⁴. We have used aug-cc-pVDZ basis sets¹⁵ supplemented with additional even-tempered five s and five p symmetry functions centered on the N atom. The geometric progression ratio for this extra diffuse set was equal to 3.2, and we started to build up the exponents from the lowest s and p exponents included in the aug-cc-pVDZ basis set designed for N. Stationary points on the

potential energy surfaces of the neutral and the anion as well as harmonic vibrational frequencies were determined at the MP2 level. In calculations for the doublet anion, the value of $\langle S^2 \rangle$ never exceeded 0.7501 for the SCF wavefunction.

The vertical electron detachment energy (\mathcal{D}) for the excess electron was first determined at the Koopmans' theorem level (\mathcal{D}^{KT}) and then supplemented with orbital relaxation $\Delta\mathcal{D}_{ind}^{SCF}$ and electron correlation effects estimated at the CCSD(T) level¹⁶. The second-order dispersion interaction between the excess electron and the neutral molecule ($\Delta\mathcal{D}_{disp}^{MP2}$) was extracted from the latter term¹⁶ and the remaining higher-order correlation contribution to \mathcal{D} , denoted $\Delta\mathcal{D}^{HO}$, is defined as

$$\Delta\mathcal{D}^{HO} = \mathcal{D}^{CCSD(T)} - \mathcal{D}^{KT} - \Delta\mathcal{D}_{ind}^{SCF} - \Delta\mathcal{D}_{disp}^{MP2} \quad (1)$$

The energy profile for the transition between the zwitterion (**A**) and neutral (**B**) structures of the glycine anion is also displayed in Fig. 2 as a function of the distance between the nitrogen atom and the H₁ hydrogen atom that is displaced as tautomerization occurs. A broad plateau develops for R_{NH₁} in the 1.0-1.3 Å range. Specifically, a local MP2 minimum is present at R_{NH₁}=1.12 Å, but the depth of this minimum with respect to the barrier at R_{NH₁}=1.13 Å is only 1 cm⁻¹. Higher order CCSD(T) single point calculations performed at the stationary points on the MP2 potential energy surface led to a deeper minimum (27 cm⁻¹), but this stability is so weak that we do not expect this zwitterion form of the anionic glycine to exist in the gas phase at any but the lowest temperatures.

The relative energies of the neutral and anionic glycine structures calculated at the CCSD(T) level of theory and corrected for the MP2 zero-point vibrational energies are collected in Table 1. In agreement with previous studies for the neutral glycine¹², the low-dipole-moment **C** structure is lower in energy than the high-dipole-moment structure **B_n**, but the difference is only 394 cm⁻¹. Geometry optimization for the *anion* starting from the **B_n** structure of the neutral converged to a structure with C_s symmetry

denoted \mathbf{B}_p^- , which is the lowest energy stationary point that we found on the potential energy surface of the anion. It is even lower than the \mathbf{C} structure of the neutral, by 279 cm^{-1} . In addition to the \mathbf{B}_p^- species, we found, as noted above, a shallow local minimum structure \mathbf{A}^- having zwitterionic type bonding. The \mathbf{A}^- structure is 2888 cm^{-1} higher than the \mathbf{B}_p^- structure.

The vertical electron detachment energies for the anion of glycine at the \mathbf{B}_n^- and \mathbf{A}^- stationary points are collected in Table 2. The values of the MP2 dipole moments of the neutral at the anionic \mathbf{B}_p^- and \mathbf{A}^- stationary points are 5.7 and 9.3 D, respectively. As expected, the larger the dipole moment of the neutral, the larger the value of \mathcal{D}^{KT} and the more compact the charge distribution of the excess electron is (see Fig. 3). The SCF orbital polarization term, $\Delta\mathcal{D}_{ind}^{SCF}$, does not exceed 15% of \mathcal{D}^{KT} . The $\Delta\mathcal{D}_{disp}^{MP2}$ contribution describes dynamical correlation between the excess electron and the electrons of the neutral molecule. This stabilizing effect is as large as \mathcal{D}^{KT} for \mathbf{B}_p^- and it represents 62% of \mathcal{D}^{KT} for \mathbf{A}^- . The higher-order correlation term, $\Delta\mathcal{D}^{HO}$, contributes less than 9% to $\mathcal{D}^{CCSD(T)}$, but this relatively small contribution results from a cancellation of different electron correlation components. The values of $\mathcal{D}^{CCSD(T)}$ for the \mathbf{B}_p^- and \mathbf{A}^- structures are 668 and 3175 cm^{-1} , respectively.

We conclude that the instability of the zwitterion structure of glycine is significantly reduced by the attachment of an excess electron but not sufficiently to render this the lowest energy structure of the anion. The issue of whether electron attachment can offset the instability of the zwitterion form of amino acids with more significant proton affinities (such as arginine) will be explored in a future study. The lowest energy \mathbf{B}_p^- anion of glycine is vertically stable with respect to the neutral by 668 cm^{-1} and is adiabatically stable with respect to the global minimum \mathbf{C} of the neutral by 279 cm^{-1} .

Acknowledgments

M.G. acknowledges support of this work by the Division of Chemical Sciences

of the Office of Basic Energy Sciences of the Office of Science of the US Department of Energy. This work was performed in part under auspices of the U.S. Department of Energy, under Contract No. DE-AC06-76RLO 1830, with Battelle Memorial Institute, which operates the Pacific Northwest National Laboratory. This work was also supported by NSF Grant CHE-9618904, the Polish State Committee for Scientific Research (KBN) Grant No. 3 T09A 049 15 (Contract No. 0337/T09/98/15) to P.S. and M.G., and an allocation of computer time grant from the Center for High Performance Computing at the University of Utah. CHPC's SGI Origin 2000 system is funded in part by the SGI Supercomputing Visualization Center Grant.

References

- [1] Cantor, C.R.; Schimmel, P.R. *Biophysical Chemistry*; Part I, W.H. Freeman and Company: New York, 1980; pp 41-53.
- [2] Suenram, R.D.; Lovas, F.J. *J. Mol. Spectrosc.* **1980**, *72*, 372-382.
- [3] Locke, M.J.; McIver, R.T., Jr. *J. Am. Chem. Soc.* **1983**, *105*, 4226-4232.
- [4] Jensen, J.H.; Gordon, M.S. *J. Am. Chem. Soc.* **1991**, *113*, 7917-7924.
- [5] Csaszar, A.G. *J. Am. Chem. Soc.* **1992**, *114*, 9568-9575.
- [6] Hu, C.H.; Shen, M.; Schaefer, H.F., III *J. Am. Chem. Soc.* **1993**, *115*, 2923-2928.
- [7] Jensen, J.H.; Gordon, M.S. *J. Am. Chem. Soc.* **1995**, *117*, 8159-8170.
- [8] Gordon, M.S.; Jensen, J.H. *Acc. Chem. Res.* **1996**, *29*, 536-543.
- [9] Price, W.D.; Jockusch, R.A.; Williams, E.R. *J. Am. Chem. Soc.* **1997**, *119*, 11988-11989.

- [10] Chapo, C.J.; Paul, J.B.; Provencal, R.A.; Roth, K.; Saykally, R.J. *J. Am. Chem. Soc.* **1998**, *120*, 12956-12957.
- [11] Wyttenbach, T.; Matthias, W.; Bowers, M.T. *J. Am. Chem. Soc.* **2000**, *122*, 3458-3464.
- [12] Nguyen, D.T.; Scheimer, A.C.; Andzelm, J.W.; Sirois, S.; Salahub, D.R.; Hagler, A.T. *J. Comp. Chem.* **1997**, *18*, 1609-1631.
- [13] Gutowski, M.; Skurski, P. *Recent Res. Devel. Physical Chem.* **1999**, *3*, 245-260.
- [14] Bartlett, R.J.; Stanton, J.F. in *Reviews in Computational Chemistry* Vol. V, Lipkowitz, K.B; Boyd, D.B. Editors, VCH Publishers Inc.: New York, 1994; pp 65-169.
- [15] Kendall, R.A.; Dunning, T.H.; Jr., Harrison, R.J. *J. Chem. Phys.* **1992**, *96*, 6796-6806.
- [16] Gutowski, M.; Skurski, P. *J. Phys. Chem. B* **1997**, *101*, 9143-9146.

Captions for Figures

Figure 1. The equilibrium structures, relative CCSD(T) energies without zero-point vibrational energies (in parentheses, given in cm^{-1}), and MP2 dipole moments of the neutral glycine (in Debyes). For the neutral **A**, the geometry of **A**⁻ is used and the energy level is indicated by a dashed line since it does not correspond to a stationary point on the potential energy surface of the neutral.

Figure 2. The energy profile for the neutral (circles) and anionic (squares) glycine for proton transfer.

Figure 3. Singly occupied molecular orbital of the anionic glycine at the **A**⁻ (contour spacing 0.021) and **B**_p⁻ (contour spacing 0.0087) stationary points.

Table 1: The CCSD(T) energies (E in cm^{-1}) of the neutral and anionic species calculated with respect to the **C** tautomer of the neutral. The energies, also in cm^{-1} , corrected for the MP2 zero-point vibrational energies are denoted $E + E_{vib}^o$.

System	E	$E + E_{vib}^o$
Neutral(C) ^{a,b}	0	0
Neutral(B_p)	304	368
Neutral(B_n)	285	394
Anion(B_p⁻)	-321	-279
Anion(A⁻)	3238	2888

^aThe CCSD(T) energy is -283.79681153

^aThe MP2 value of E_{vib}^o is 50.051 kcal/mol

Table 2: The components of the vertical electron detachment energy (in cm^{-1}) calculated for the anion of glycine at its **B_p⁻** and **A⁻** structures.

Structure	B_p⁻	A⁻
\mathcal{D}^{KT}	290	1920
$\Delta\mathcal{D}_{ind}^{SCF}$	33	284
$\Delta\mathcal{D}_{disp}^{MP2}$	287	1199
$\Delta\mathcal{D}^{HO}$	58	-229
$\mathcal{D}^{CCSD(T)}$	668	3175