Acta Chemica Scandinavica, 1997: 51: 439–441
Printed in UK – all rights reserved

ACTA
CHEMICA SCANDINAVICA
ISSN 0904-213X

Conformations of Glycolic Acid

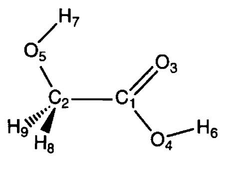
Frank Jensen†

Research School of Chemistry, Australian National University, Canberra, ACT 0200, Australia

Jensen, F., 1997. Conformations of Glycolic Acid. – Acta Chem. Scand. 51: 439–441. © Acta Chemica Scandinavica 1997.

Eight different conformations have been determined by *ab initio* calculations at the MP2/6-31G(d,p) level, although two of these are so close in terms of structure and energy that it is unlikely that they experimentally exist as separate species. Relative energies have been obtained at the CCSD(T)/6-31G(d,p), MP2/6-311++G(2d,2p) and MP2/cc-pVQZ levels. The experimental results are consistent with the observation of the three lowest-energy isomers, although the experimental energy difference for the two lowest species appears to be in error.

Glycolic acid (hydroxyacetic acid) belongs to the class of small molecules in which a number of different conformations involving intramolecular hydrogen bonding are possible. The lowest-energy structure is experimentally found to involve hydrogen bonding between the hydroxy proton and the carbonyl oxygen.[1–5] Based on electron diffraction the second lowest rotamer has been assigned to an isomer with a hydrogen bond between the alcohol hydrogen and a lone pair of the acid hydroxy group.[4] The energy difference between these isomers was calculated as 4.2 kcal mol^{-1} based on fitting to the diffraction data. Another isomer has been generated by infrared absorption from the lowest-energy conformation in a matrix-isolation study; this was assigned a structure involving hydrogen bonding between the acid hydroxy group and a lone pair of the alcohol oxygen.[5]



Theoretical calculations of possible conformations have previously been carried out by geometry optimizations at the HF/4-21G level[5,6] and HF/6-31G(d) single-point energies;[5] however, only geometries involving a planar arrangement of the heavy atoms were considered. The most recent study[5] found eight different structures, although these were not proven to be minima on the energy surface. The calculated energy difference between the two lowest isomers was 1.81 kcal mol^{-1} (4-21G) and 3.21 kcal mol^{-1} [6-31G(d)], significantly lower than the experimental estimate.

The present paper attempts to resolve the divergence between the two experimental studies as to the nature of the higher energy isomer(s), and the disagreement between theory and experiments on the relative stability.

Results and discussion

The initial survey included optimization[7] of all starting structures generated by values of the torsional angles $H_7O_5C_2C_1 = (0°, \pm 60°, \pm 120°, 180°)$, $H_6O_4C_1O_3 = (0°, 180°)$, and $O_3C_1C_2O_5 = (0°, \pm 60°, \pm 120°, 180°)$ at the HF/6-31G(d,p) level. The eight unique conformations obtained were confirmed to be minima by frequency calculations, and reoptimized at the MP2/6-31G(d,p) level. Improved estimates of the relative energies were obtained at the CCSD(T)/6-31G(d,p) and MP2/6-311++G(2d,2p) levels, using the MP2/6-31G(d,p) optimized geometries. Zero point energies were obtained from MP2/6-31G(d,p) harmonic frequencies, scaled by a factor of 0.97.[8] Table 1 shows that the effect of including electron correlation beyond MP2 for the four lowest-energy conformations is small, 0.01 kcal mol^{-1} or less. Enlarging the basis to 6-311++G(2d,2p) has a slightly larger effect, reversing the stability of **3** and **4** and of **6** and **7**.

As basis set incompleteness clearly is more important than electron correlation beyond MP2, the four lowest-energy species were further refined by optimization at the MP2/cc-pVDZ and MP2/cc-pVTZ levels, and the latter geometries used for single point MP2/cc-pVQZ energies. These results are shown in Table 2. The energy difference between the two lowest conformations converges to a value of 2.7 kcal mol^{-1}, which is lowered to 2.6 kcal mol^{-1} when the zero-point energies difference is included. This is substantially smaller than the experimental value of 4.2 kcal mol^{-1}. Given the data in Tables 1 and 2 it appears unlikely that the theoretical estimate can change by more than a few tenths of a kcal mol^{-1}

---

† Permanent address: Department of Chemistry, Odense University, DK-5230 Odense M, Denmark.

Table 1. Relative energies (in kcal mol^{-1}) of gylcolic acid conformations shown in Fig. 1.

Conf.	HF 6-31G(d,p)	MP2 6-31G(d,p)	CCSD(T) 6-31G(d,p)[a]	MP2 6-311++G(2d,2p)[a]	ΔZPE MP2/6-31G(d,p)
1	0.00	0.00	0.00	0.00	0.00
2	2.18	1.98	1.99	2.52	−0.13
3	4.38	3.78	3.79	3.05	0.00
4	4.75	3.42	3.43	3.22	−0.36
5	4.76	4.66	4.67	4.48	0.17
6	6.92	6.11	6.00	4.86	0.20
7	5.03	5.81	5.12	4.95	0.09
8	13.09	12.24	12.06	10.58	0.51
TS(3–4)	4.80	3.80	3.81	3.07	0.09

[a] On MP2/6-31G(d,p) optimized geometries.

Table 2. Relative energies (in kcal mol^{-1}) of the four lowest conformations.

Conf.	MP2 cc-pVDZ	MP2 cc-pVTZ	MP2 cc-pVQZ[a]
1	0.00	0.00	0.00
2	2.22	2.71	2.71
3	3.60	3.37	3.20
4	3.26	3.32	3.28
TS(**3–4**)	3.65	3.37	

[a] On MP2/cc-pVTZ optimized geometries.

upon improving the computational level, suggesting that the experimental value is in error.

The MP2 optimized geometries are shown in Fig. 1, using the cc-pVTZ basis for **1**–**4** and 6-31G(d,p) for **5**–**8**. The lowest-energy minimum has C_s symmetry, although the 6-31G(d,p) basis produces a slightly asymmetric geometry. The second lowest conformation is found to have a hydrogen bond between the alcohol hydrogen and a lone pair of the acid hydroxy group, in agreement with the electron diffraction data. Structures **3** and **4** involve the same type of hydrogen bonding, differing mainly in the $H_7O_5C_2C_1$ torsional angle, being 168° for **3** and 98° for **4**, and they are essentially isoenergetic. The barrier for interconversion between these two conformations is very small (Tables 1 and 2), at the highest level of optimization (MP2/cc-pVTZ) the TS is only a few cm^{-1} above **3**. Nevertheless, the structural difference persists, the TS corresponds to a rotation of the OH group by 45° from **3**. Additional optimizations at the QCISD/6-31G(d,p) level suggest that the electronic surface has two separate minima, but the rotational energy profile is extremely flat. When vibrational zero point energies are considered, it is possible that **3** and **4** will merge and experimentally behave as a single conformation.

Previous theoretical results also obtained eight different conformations by optimizations at the HF/4-21G level.[5] However, only species with a planar arrangement of the heavy atoms were considered, and the optimized structures where not checked to see whether they are minima on the energy surface. The previous located structures correspond approximately to isomers **1**–**3** and **5**–**8** in Fig. 1. An additional geometry considered in the previous work is a second-order saddle point. Furthermore, only four of the present isomers (**1**, **5**, **6** and **8**) have in fact a planar skeleton. As a consequence, relative energies are somewhat different.

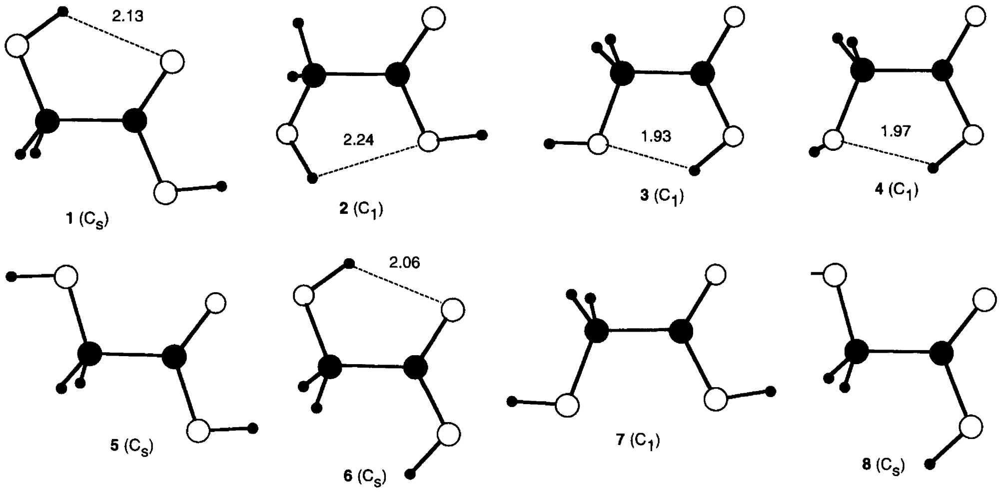


Fig. 1. MP2 optimized conformations of glycolic acid with the cc-pVTZ basis for **1**–**4** and 6-31G(d,p) for **5**–**8**. Hydrogen bonds are indicated by a dashed line (distance in Å).

Table 3. MP2/6-31G(d,p) harmonic frequencies (in cm^{-1}) scaled by 0.9335 for the OH stretch region.

Conf.	ν_{OH}	ν_{COOH}
1	3570	3560
2	3633	3564
3	3661	3495
4	3634	3478
5	3644	3568
6	3539	3598
7	3642	3552
8	3640	3602
TS(3–4)	3667	3476

The dominant isomer in an argon matrix displays only one OH band at 3565 cm^{-1}.[5] Upon infrared irradiation two new bands emerge at 3660 and 3470 cm^{-1}, assigned to be the hydroxy and acid OH stretches, respectively, based on ^{18}O isotope shifts. This was taken as evidence of a free hydroxy OH stretch, while the acid hydrogen is involved in hydrogen bonding. Consequently it was assigned a structure corresponding to isomer **3**. The MP2/6-31G(d,p) harmonic frequencies for isomer **1** has OH bands at 3824 and 3814 cm^{-1}, i.e. it is quite plausible that they experimentally appear as one absorption. The experimental value of 3565 cm^{-1} for isomer **1** can be reproduced by scaling the calculated frequencies by 0.9335, these results are shown in Table 3. The experimental bands at 3660 and 3470 cm^{-1} for the second isomer are only consistent with the calculated spectrum of a conformation corresponding to **3**/**4**. It can be noted that the TS connecting **3** and **4** has calculated OH stretching frequencies of 3667 and 3476 cm^{-1}, in almost perfect agreement with the experimental values. This indicates that only a single 'average' structure **3**/**4** exists experimentally. Note also that the calculated bands of isomer **2** match corresponding bands of isomers **1** and **3**/**4**, i.e. is it possible that **2** is also present in the experiments, but not detected owing to overlapping absorptions. Considering that the transformation of **1** to **3**/**4** involves rotations around three bonds, it would appear logical that **2** is formed as well.

Conclusion

At the MP2/6-31G(d,p) level there are eight different conformations of glycolic acid, although two of these are likely to behave as a single conformation experimentally. The energy difference between the two lowest-energy conformations is calculated to be 2.6 kcal mol^{-1}, with an additional five isomers located within 5 kcal mol^{-1} of the global minimum. The electron diffraction data agree with the structure of the second lowest isomer, but appear to overestimate significantly the energy difference. The results from matrix-isolation studies indicate observation of the third lowest isomer, located ca. 3 kcal mol^{-1} above the global minimum.

Acknowledgment. This work was supported by grants from the Danish Natural Science Research Council. I thank RSC, ANU for a visiting fellowship.

References

1. Newton, M. D. and Jeffrey, G. A. *J. Am. Chem. Soc. 99* (1977) 2413.
2. Blom, C. E. and Bauder, A. *J. Am. Chem. Soc. 104* (1982) 2993.
3. Hasegawa, H., Ohashi, O. and Yamahuchi, I. *J. Mol. Struc. 82* (1982) 205.
4. Iijima, K., Kato, M. and Beagley, B. *J. Mol. Struct. 295* (1993) 289.
5. Hollenstein, H., Ha, T.-K. and Günthard, H. H. *J. Mol. Struct. 146* (1986) 289.
6. Ha, T.-K., Blom, C. E. and Günthard, H. H. *J. Mol. Struct. (Theochem) 85* (1981) 285.
7. Frisch, M. J., Trucks, G. W., Schlegel, H. B., Gill, P. M. W, Johnson, B. G, Robb, M. A., Cheeseman, J. R., Keith, T., Petersson, G. A., Montgomery, J. A, Raghavachari, K., Al-Laham, M. A., Zakrzewski, V. G., Ortiz, J. V., Foresman, J. B., Cioslowski, J., Stefanov, B. B., Nanayakkara, A., Challacombe, M., Peng, C. Y., Ayala, P. Y., Chen, W., Wong, M. W., Andres, J. L., Replogle, E. S., Gomperts, R., Martin, R. L., Fox, D. J., Binkley, J. S., Defrees, D. J., Baker, J., Stewart, J. J. P., Head-Gordon, M., Gonzalez, C. and Pople J. A. *Gaussian 94*, Gaussian, Inc., Pittsburgh, PA 1995.
8. Scott, A. P. and Radom, L. *J. Phys. Chem. 100* (1996) 16502.

Received June 4, 1996