

Theory versus Experiment in Jet Spectroscopy: Glycolic Acid

Peter D. Godfrey,* Fiona M. Rodgers, and Ronald D. Brown

Contribution from the Centre for High-Resolution Spectroscopy & Opto-electronic Technology, Chemistry Department, Monash University, Clayton, Victoria 3168, Australia

Received May 20, 1996[⊗]

Abstract: *Ab initio* MP2/6-31G(d,p) methods have been used to examine in detail the structures and relative energies of the conformers of glycolic acid and to investigate the pathways and energy barriers involved in possible conformational interconversions. From the results of these calculations it has been shown that if an adequate volatilization temperature is used then two glycolic acid species, not necessarily the two of lowest energy, should be detectable via free jet expansion microwave spectroscopy. We tested this prediction experimentally. The spectrum of a new species (**y**) was detected and shown via comparison of the predicted with observed rotational constants, planar moments of inertia, and isotopic substitution coordinates to be most consistent with the *trans*-carboxyl theoretical conformer {**13,18**} (see Figure 2). Previous microwave spectroscopy studies had found only one glycolic acid conformer (**x**). The detection of both (**x**) and (**y**) is fully consistent with the relative energy and conformer relaxation predictions from the *ab initio* calculations. Conformer (**y**) is similar to a species previously reported from matrix isolation infrared spectroscopy.

Introduction

Glycolic acid or hydroxyacetic acid (CH₂OHCOOH) is the simplest member of the α -hydroxycarboxylic acid series. It has an important role in photosynthesis and plant respiration¹ and as a precursor for oxalate in humans.² In its polymeric forms it has found extensive application for biodegradable sutures,³ drug delivery systems, and prostheses.

In the gas phase glycolic acid might be anticipated to have a structure analogous to that of the simplest α -amino acid glycine. In the case of glycine vapor several conformers appear to be involved^{4a–f} and in the present study we have undertaken to investigate the structure of gas-phase glycolic acid in the light of the results for glycine.

Both neutron diffraction⁵ and X-ray analysis⁶ have been used to determine the structure of crystalline glycolic acid. By neutron diffraction the structure was found to consist of a loose three-dimensional hydrogen-bonded network of two closely similar but crystallographically distinct types of molecules. The heavy atom frames in these molecules were found to be nearly planar and are closely similar in dimensions and conformation. In both of these conformers the alcoholic OH group appears to be involved in an internal hydrogen bond with the carbonyl oxygen of the carboxyl group in addition to participating in the network of intermolecular hydrogen bonds within the crystal structure. The crystal structure as determined by X-ray analysis was consistent with the neutron diffraction study in also

containing two distinct molecular species with nearly planar heavy atom frames and similar conformations.

The structure of gas-phase glycolic acid has been determined by microwave spectroscopy.^{7a–c} The molecule was concluded to be of *C_s* symmetry with the alcoholic hydroxyl group pointing toward the carbonyl oxygen of the carboxyl group. With the exception of the methylene hydrogens all the atoms in the molecule were found to be coplanar. It was concluded that this difference from the crystal structure arises since in the gas phase the conformation is no longer dominated by intermolecular hydrogen bonds with neighboring molecules.

An elegant infrared-induced rotamerization study of glycolic acid in an argon matrix at liquid helium temperature⁸ revealed a new conformer—“*trans*-glycolic acid”—based on characteristic frequencies of H-bonded hydroxyl groups. This differs from the form originally trapped, which was believed to be identical with the gas phase form previously identified by microwave spectroscopy. In the new conformer the carboxyl group has the *trans* conformation with its hydroxyl group pointing toward the oxygen in the alcoholic hydroxyl group.

There have been several previous *ab initio* theoretical studies on the various rotamers of glycolic acid. Initially only six of the eight possible *C_s* rotamers of glycolic acid were studied⁹ at the HF/4-21G level. This study was further extended to all eight *C_s* rotamers at both the HF/4-21G and HF/6-31G* levels.⁸ These authors reported that rotamer **2** lost its *C_s* symmetry at the higher HF/6-31G* level. An augmented version of the conformer numbering scheme introduced in that paper has been adopted in the present study. Due to the identification of several non-*C_s* conformers of glycolic acid we have extended this numbering scheme. An extra numeral, 1 or 2, has been placed before the number of the related *C_s* structure to identify the non-*C_s* structures. For example, conformer **13** is a non-*C_s* form similar to *C_s* conformer **3**.

[⊗] Abstract published in *Advance ACS Abstracts*, February 1, 1997.

(1) Zelitch, I. *McGraw-Hill Encyclopedia of Science and Technology*, 7th ed; McGraw-Hill, Inc: New York, 1992; Vol. 13, p 709.

(2) Petrarulo, M.; Marangella, M.; Linari, F. *Clin. Chim. Acta* **1991**, *196*, 17.

(3) Frazza, E. J.; Schmitt, E. E. *J. Biomed. Mater. Res. Symp.* **1971**, *1*, 43.

(4) (a) Brown, R. D.; Godfrey, P. D.; Storey, J. W. V.; Bassez, M. P. *J. Chem. Soc., Chem. Commun.* **1978**, 547–548. (b) Suenram, R. D.; Lovas, F. J. *J. Mol. Spectrosc.* **1978**, *72*, 372–382. (c) Schäfer, L.; Sellers, H. L.; Lovas, F. J.; Suenram, R. D. *J. Am. Chem. Soc.* **1980**, *102*, 6566–6568. (d) Suenram, R. D.; Lovas, F. J. *J. Am. Chem. Soc.* **1980**, *102*, 7180–7184. (e) Godfrey, P. D.; Brown, R. D. *J. Am. Chem. Soc.* **1995**, *117*, 2019–2023. (f) Godfrey, P. D.; Brown, R. D.; Rodgers, F. M. *J. Mol. Struct.* **1996**, *376*, 65–81.

(5) Ellison, R. D.; Johnson, C. K.; Levy, H. A. *Acta Crystallogr.* **1971**, *B27*, 333–344.

(6) Pijper, W. P. *Acta Crystallogr.* **1971**, *B27*, 344–348.

(7) (a) Blom, C. E.; Bauder A. *Chem. Phys. Lett.* **1981**, *82*, 492–495. (b) Blom, C. E.; Bauder A. *J. Am. Chem. Soc.* **1982**, *104*, 2993–2996. (c) Hasegawa, H.; Ohashi, O.; Yamaguchi, I. *J. Mol. Struct.* **1982**, *82*, 205–211.

(8) Hollenstein, H.; Ha, T.-K.; Günthard, H. H. *J. Mol. Struct.* **1986**, *146*, 289–307.

(9) Ha, T.-K.; Blom, C. E.; Günthard, H. H. *J. Mol. Struct.* **1981**, *85*, 285–292.

A more recent study¹⁰ used *ab initio* HF/4-31G calculations to determine the geometries, energies, and reaction paths for rotational isomerization and barriers of seven conformers. In all the past *ab initio* studies the lowest energy conformer has been found to be the same C_s species with the alcoholic hydroxyl group pointing toward the carbonyl oxygen of the carboxyl group.

In comparing the results from microwave spectroscopy structural studies of glycolic acid and glycine it is notable that only a single conformer of glycolic acid has been identified in contrast with two for glycine. This observation prompted us to examine more closely via *ab initio* methods the relative energies of conformers of glycolic acid in the context of the analogous conformers of glycine. Further, in the light of the recently noted significance of conformational interconversion in the case of glycine and related molecules,^{4f} it was decided to extend the *ab initio* calculations to investigate the pathways and energy barriers involved in conformational interconversion in glycolic acid.

The question always arises of accuracy of the theoretical predictions of energies of conformers and of predictions of shallow minima and other small features on potential energy surfaces. A recent assessment, based on studies of molecules similar in complexity to glycolic acid, indicated that calculated barriers were probably reliable to about 200 cm^{-1} (about 2 kJ mol^{-1}) for computations of the same quality as those reported here. The reliability of predictions of minor features on the potential energy surface is still harder to assess and perhaps will ultimately rely upon steady accumulation of case histories of the degree of compatibility with experiment. From our own studies of related molecular species we have the impression that features representing energy variations of 100 cm^{-1} or more are probably meaningful but that smaller features should be treated with caution.

Theoretical and Experimental Methodology

Ab Initio Calculations. *Ab initio* calculations were performed using the GAUSSIAN 92^{11a} and 94^{11b} suite of programs. Starting with the seven structures as presented by Flock and Ramek,¹⁰ full geometry optimizations were performed on each conformer at the same level of theory (RHF/4-31G) and then at successively higher levels of theory—RHF/6-31G(d,p) and MP2/6-31G(d,p). The remaining conformers with planar heavy-atom skeletons, as presented in Hollenstein *et al.*,⁸ were identified and optimized. In some cases it was necessary to constrain the structures to C_s . A search was also made for other possible conformers—in particular in the cases where we found that the conformers previously identified at lower levels of calculation were at the higher levels, according to frequency calculations, saddle points. The atom numbering system adopted is shown in Figure 1. There were three main torsional angles to vary— $\text{O}_4\text{C}_1\text{C}_2\text{O}_3$, $\text{H}_8\text{O}_3\text{C}_2\text{C}_1$, and $\text{H}_9\text{O}_5\text{C}_1\text{C}_2$.

The barriers to interconversion of the conformers were explored. A torsional angle that varied between the two conformers of interest

(10) Flock, M.; Ramek, M. *International journal of quantum chemistry. Quantum chemistry symposium*; Wiley: New York, 1992; Vol. 26, pp 505–515.

(11) (a) Gaussian 92/DFT, Revision G.3, Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Gill, P. M. W.; Johnson, B. G.; Wong, M. W.; Foresman, J. B.; Robb, M.; Head-Gordon, M. A.; Replogle, E. S.; Gomperts, R.; Andres, J. L.; Raghavachari, K.; Binkley, J. S.; Gonzalez, C.; Martin, R. L.; Fox, D. J.; Defrees, D. J.; Baker, J.; Stewart, J. J. P.; Pople, J. A.; Gaussian, Inc.: Pittsburgh, PA, 1993. (b) Gaussian 94, Revision B.1, Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Gill, P. M. W.; Johnson, B. G.; Robb, M.; 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.; Pople, J. A.; Gaussian, Inc.: Pittsburgh, PA, 1995.

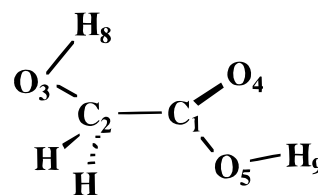


Figure 1. The adopted atom numbering system for glycolic acid. The methylene hydrogens are numbered 6 and 7.

was selected. A series of constrained optimizations was performed varying this angle in steps of between 15 and 30° . In some cases in order to guarantee that the correct conformer was produced it was necessary to vary several constrained parameters simultaneously. These results from constrained optimizations allowed the transition state to be approximately located. The transition state was then located more precisely by a localized series of constrained optimizations of step size $1-2^\circ$. This allowed the saddle point to be identified with sufficient accuracy to serve as a starting point for the automatic transition state optimization method available in GAUSSIAN 92^{11a} and 94.^{11b} The optimized transition state was in turn used as the starting point for an intrinsic reaction path¹² calculation to determine the minimum energy pathways to the adjacent conformers. All these IRC calculations were performed using either the tight or very tight optimization criteria and the step size was adjusted to allow the calculated pathway to extend to the adjacent conformer energy minima.

The conformational potential energy surface of glycolic acid exhibited some regions of unusual complexity which did not yield to the methodology described above or to the more sophisticated Synchronous Transit-Guided Quasi-Newton (STQN) method. For example, while searching for the transition state between conformers **11** and **13** the STQN method converged to the transition state between **12** and **13** instead.

Microwave Spectroscopy. The free-jet expansion, Stark-modulated spectrometer used in the present study has previously been described.¹³ Liquid samples of 10% glycolic acid in water were vaporized at 300°C in a stream of argon before expansion through the jet. Broad-band line-search scanning covered the range of $48-60.3\text{ GHz}$. Precise line frequencies were obtained from narrow-band computer-averaged repetitive scans throughout the full spectrometer frequency range of $48-72\text{ GHz}$.

Mono- and dideuterated glycolic acid were prepared by making a 10% glycolic acid solution in 1:1 $\text{D}_2\text{O}/\text{H}_2\text{O}$. Both possible monosubstituted isotopomers and disubstituted isotopomers were obtained in sufficient quantities for their spectra to be observed and assigned. To aid with the elimination of lines due to glycolic- d_2 acid from the otherwise unassigned spectrum, a sample of glycolic- d_2 acid was obtained by using D_2O instead of $\text{D}_2\text{O}/\text{H}_2\text{O}$.

Results and Discussion

Conformers Identified via *ab Initio* Calculations. In all a total of 14 structural forms were studied via *ab initio* MP2 calculations using the 6-31G(d,p) basis set and these are shown in Figure 2. Forms **2**, **7**, and **8** required constraint to C_s symmetry. Subsequent frequency calculations showed the C_s forms **1**, **2**, **3**, and **7** to be first-order saddle points and **8** to be of second order rather than any of these being true local energy minima conformers at this level of *ab initio* calculation. The six structural forms that were found to be true local energy minima conformers of C_1 symmetry also necessarily possessed an additional enantiomeric form. The torsional angles and relative energies are given in Table 1. A complete set of optimized structures is available as Supporting Information. Flock and Ramek¹⁰ report an additional “conformer” designated **VII**. It is referred to as a “stationary point of inflexion”;

(12) (a) Gonzalez, C.; Schlegel, H. B. *J. Chem. Phys.* **1989**, *90*, 2154. (b) Gonzalez, C.; Schlegel, H. B. *J. Phys. Chem.* **1990**, *94*, 5523.

(13) Brown, R. D.; Crofts, J. G.; Godfrey, P. D.; McNaughton, D.; Pierlot, A. P. *J. Mol. Struct.* **1988**, *190*, 185–193.

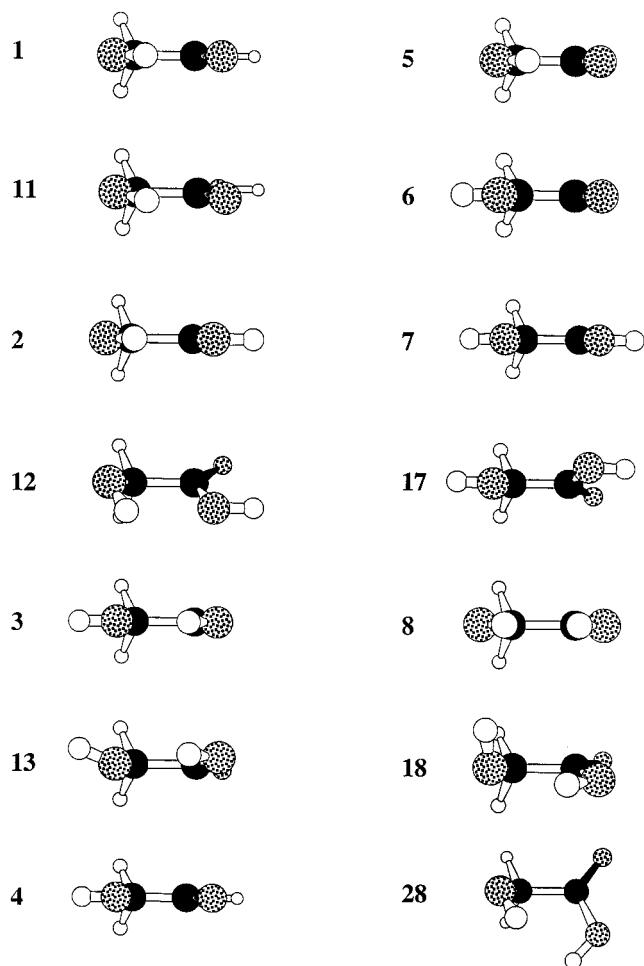


Figure 2. Structural forms of glycolic acid identified via constrained and fully optimized *ab initio* MP2 calculations using the 6-31G(d,p) basis set. Use has been made of bond tapering and varying the atom size by depth to aid the perspective. For example, in **1** the two methylene hydrogens and the carboxyl group hydrogen are smaller and therefore at the back whereas the larger alcoholic group hydrogen is toward the front.

Table 1. The Torsional Angles and Relative Energies of the Glycolic Acid Forms Identified via *ab Initio* MP2/6-31G(d,p)

form	O ₄ C ₁ C ₂ O ₃	H ₈ O ₃ C ₂ C ₁	H ₆ O ₅ C ₁ C ₂	ΔE (kJ mol ⁻¹)
1 ^a	0.000	0.000	180.000	0.015
2 ^a	180.000	0.000	180.000	12.328
3 ^a	180.053	179.997	0.000	16.030
4	0.000	180.000	180.000	19.495
5	0.000	0.000	0.000	25.571
6	0.000	180.000	0.000	51.222
7 ^a	180.000	180.000	180.000	21.753
8 ^a	180.000	0.000	0.000	69.520
11	6.911	-11.877	181.405	0.000
12	-153.779	-50.322	177.818	8.285
13	172.584	155.689	2.007	15.798
17	161.379	177.072	181.474	21.661
18	-168.938	89.985	-1.434	14.293
28	250.821	-51.688	16.927	54.144

^a Saddle points.

however, using the reported geometry and level of theory employed by these authors we were unable to optimize to this conformer and local *ad hoc* exploration of the potential surface failed to reveal any point at which the energy derivative approached zero.

Relative Stabilities of the Conformers. The relative energies for the conformers of glycolic acid are given in Table 1. The relative order of the energies of the *C_s* conformers agree

with that found by Flock and Ramek¹⁰ calculated at the RHF/4-31G level and with that of Ha *et al.*⁹ at the RHF/4-21G level. The order does not agree with that found by Hollenstein *et al.*,⁸ who found conformer **7** to be of lower energy than that of **4** at the RHF/6-31G* level.

The lowest energy conformer identified by *ab initio* calculations at the MP2/6-31G(d,p) level was found to be the non-*C_s* conformer **11**, not considered by previous *ab initio* calculations. This at first appears to be in disagreement with the microwave experiments^{7a-c} which identified the *C_s* form **1** as the species present. On closer examination one finds that conformer **11** is a slightly twisted version of form **1** and is calculated to be of only slightly lower energy (0.015 kJ mol⁻¹). In this circumstance the most probable *r_p* geometry^{4e,14a,b} would be expected to be that of **1** which is in agreement with the experimental findings (see below).

A significantly higher temperature, 190–235 °C,^{4a-d} was needed to measure the original glycine microwave spectrum than the 25 °C required for glycolic acid^{7a,b} due to the differences in volatility of the two species, with glycine being less volatile than glycolic acid. Had the higher temperature required for glycine also been used for glycolic acid, then this would have made it possible to detect the analogous minor conformer since at this temperature the predicted mole fraction of the second conformer is significant (ca. 11%) for both compounds. In contrast only ca. 3% of the second conformer of glycolic acid is expected at room temperature.

We decided to measure the glycolic acid microwave spectrum at an elevated temperature (300 °C) with our Stark-modulated free-expansion jet spectrometer in order to test for the presence of a second glycolic acid conformer. In planning the experiment it was necessary to consider the energy barriers separating the species because in jet spectroscopy it has been observed that if the barrier to interconversion is low enough between two species the molecules in the higher energy form will collisionally relax to the lower energy state during the free jet expansion.^{4f,15a,b} Therefore if the barrier between conformers **x** and **y** is low enough and **x** is of higher energy than **y** then it follows that conformer **x** may relax to **y** and therefore not be detected in our jet spectrometer.

Barriers between the Conformers. A summary of the calculated barriers to interconversion between the conformers is shown in Table 2. As a guide to the reliability of these calculations Hehre¹⁶ gives an overview of the performance of *ab initio* calculations for calculating conformational barriers and finds that for simple molecules at the MP2 level of theory the discrepancy between theory and experimental values is typically ca. 50–100 cm⁻¹ but sometimes exceeds 500 cm⁻¹.

It should be explained why all the conformers are not included in Table 2 and why barrier heights have been given for certain conformers proceeding to themselves.

Because forms **1**, **2**, **3**, and **7** actually were not conformers but rather were first order saddle points and form **8** second order they have been omitted from the table. Conformers **11**, **12**, **13**, and **17** are of *C₁* symmetry and therefore exist in enantiomeric forms. This means that there is a barrier between each of these conformers and their mirror image where the saddle

(14) (a) Brown, R. D. *Chem. Br.* **1988**, 24, 770. (b) Brown, R. D. In *Structures and Conformations of Non-Rigid Molecules; Proceedings of NATO Advanced Workshop*; Laane, J., Dakkouri, M., van der Veken, B., Oberhammer, H., Eds; Kluwer Academic: Dordrecht, 1993; pp 99–112 and references therein.

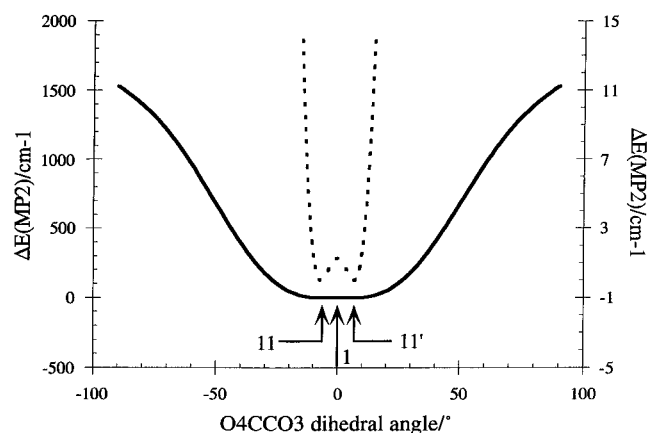
(15) (a) Felder, P.; Günthard, H. H. *Chem. Phys.* **1982**, 71, 9–25. (b) Ruoff, R. S.; Klots, T. D.; Emilsson, T.; Gutowsky, H. S. *J. Chem. Phys.* **1990**, 93, 3142–3150.

(16) Hehre, W. J. *Practical Strategies for Electronic Structure Calculations*; Wavefunction: Irvine, 1995; p 168.

Table 2. The Relative Energies and Barriers (cm^{-1}) to Interconversion of the Conformers of Glycolic Acid As Identified by *ab Initio* MP2/6-31G(d,p)^a

ΔE	conformer from	conformer to									
		4	5	6	11'	12'	13'	17'	18'	28'	
1630	4				154			707			
2138	5				2503						
4282	6										
0	11	1739	4641		1	1658					
693	12				966	338	4316	1214	5268		
1321	13				3688	19	4576	9	3225		
1811	17	526			96	4086	8				
1195	18				4766	135			3348		
4526	28					19			16		

^a The quantities shown represent the barrier in proceeding from the row conformer number to the column conformer number. For example, the barrier in proceeding from conformer **11** to conformer **4** is 1739 cm^{-1} .

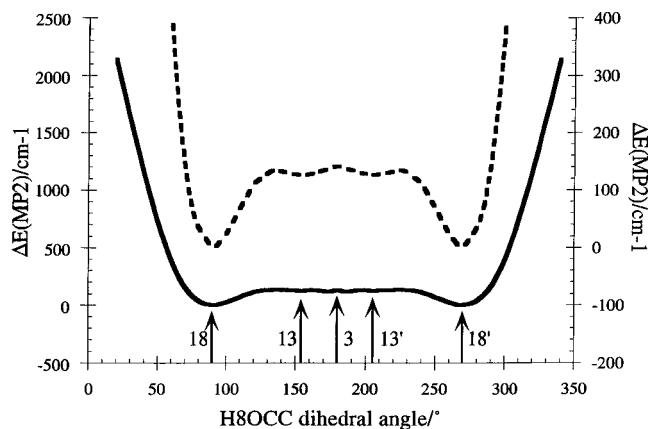
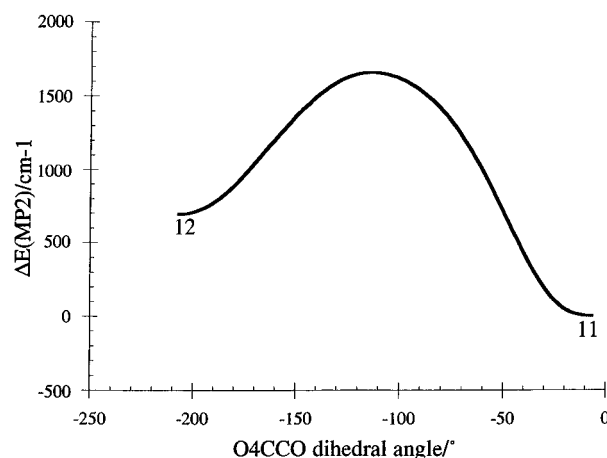
**Figure 3.** Energy profile between glycolic acid **1** and **11**. The left axis applies to the solid line and the right axis to the broken line.

point is of C_s symmetry. The saddle points for each are the forms **1**, **2**, **3**, and **7**, respectively. Therefore the value given for the barrier between a conformer and itself in these cases really represents the barrier to inversion between itself and its mirror image. Conformers **4**, **5**, and **6** have C_s symmetry so are achiral.

The energy profiles for the conformers interconversions **11** \leftrightarrow **11'**, **12** \leftrightarrow **12'** and **17** \leftrightarrow **17'** are of a similar shape, the profile for **11** \leftrightarrow **11'** being shown in Figure 3. The respective heights to the saddle points are 1.3, 337.9, and 7.7 cm^{-1} . If the ground vibrational state energy in these symmetric double wells is greater than the height of the saddle point then the effective (r_p) structure of the observed conformer would match closely the C_s conformer of the saddle point. In recognition of this from now on the conformer numbers **11**, **12**, and **17** will be used to represent the vibrationally averaged structures **{11,1,11'}**, **{12,2,12'}**, and **{17,7,17'}**, respectively.

A similar but more complicated situation exists for conformers **13** and **18**. The energy profile between this pair is shown in Figure 4. Here there is effectively a single very broad well which contains the species **18**, **13**, **3**, **13'**, and **18'**. There is a barrier of just 8.8 cm^{-1} for the transformation of species **13** to **18** and one of 19.4 cm^{-1} for the inversion of conformer **13**. The resulting single effective conformer will be designated **{13,18}**.

Use of the Calculated Barriers to Predict the Expected Experimental Observations. There are two primary reasons for the non-detection of conformers in jet spectra. Firstly, the energy of a conformer may be so high that it is not thermally accessible at the pre-expansion temperature. At the experi-

**Figure 4.** Energy profile between glycolic acid conformers **13** and **18**. The left axis applies to the solid line and the right axis to the broken line.**Figure 5.** IRC calculated energy profile between conformers **11** and **12**.

mental pre-expansion temperature used ($300 \text{ }^\circ\text{C}$) and ignoring the role of the effective zero-point energy, one would expect a mole fraction of ca. 77% of conformer **11**, 14% conformer **12**, 7% conformer **{13,18}** (from 3% conformer **13** and 4% conformer **18**), 1% conformer **4**, and less than 1% of both conformers **17** and **5**. Conformers **6** and **28** would be present in negligible concentrations. The second possible reason for the non-detection of a conformer is if the conformer, although thermally accessible, collisionally relaxes during the expansion to lower energy conformers. This is dependant on the presence of a sufficiently low barrier between the conformers to permit relaxation. In the case of glycolic acid the barriers which need investigating in this light are those between **11**, **12**, **{13,18}**, and perhaps **4**.

Prior to expansion conformer **12** is expected to be next to **11** in abundance. Conformer **11** is the only conformer of lower energy and therefore is the only possible conformer to which **12** can relax. Figure 5 shows the energy profile between these two conformers. The barrier for the conversion of conformer **12** to **11** is 966 cm^{-1} . It is interesting to note that this value is significantly lower than the ca. 2100 cm^{-1} implied in the previously reported HF/4-21G calculations of Hollenstein *et al.*⁸ The barrier is higher than the 400 cm^{-1} that Ruoff *et al.*^{15b} give as the maximum barrier permitting relaxation to a lower energy conformer following expansion from room temperature. However, according to Felder and Günthard^{14a} the critical barrier height may vary depending on factors such as the initial temperature and stagnation pressure of the gas and also on the molecular size. This means that the critical barrier height to

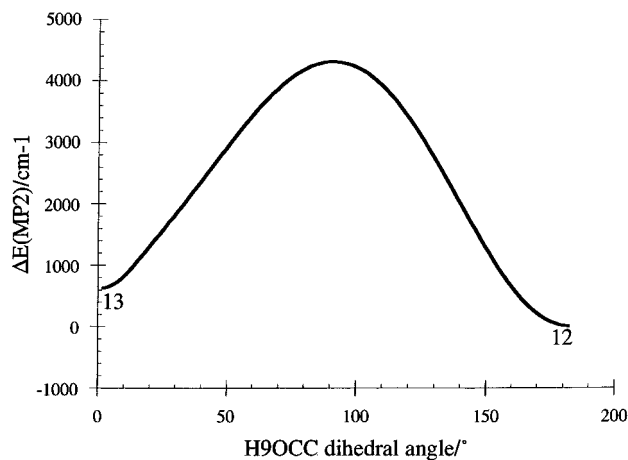


Figure 6. IRC calculated energy profile between conformers **12** and **13**.

relaxation in the present experiment may be somewhat higher. This was found to be the case with glycine at 235 °C where the critical barrier height was found to be ca. 800 cm^{-1} .^{4f} Therefore a barrier height of 966 cm^{-1} between conformers **12** and **11** may be low enough to allow relaxation. Thus it is likely that conformer **12** may not be detected experimentally due to its relaxation to conformer **11** resulting in an increase in the amount of conformer **11** detected.

Conformers **18** and **13** are of next abundance and may coalesce to produce a single detectable conformer {**13,18**}. Species {**13,18**} could in principle relax to either conformers **11** or **12**, or perhaps even both. However, as can be seen in the energy profile between conformers **13** and **12** (Figure 6) the barrier to relaxation is 3688 cm^{-1} which is much too high to permit relaxation between these conformers. Despite exhaustive attempts, we were unable to locate the transition state between {**13,18**} and conformer **11** and so an energy profile for this conversion could not be obtained. Nevertheless, this conversion involves the *trans* to *cis* conversion of the $-\text{COOH}$ group and so one is able to draw some conclusions as to the height of the barrier by comparison with some of the other calculated barriers. It has been observed that any barrier involving this *cis* to *trans* rotation is high. For example, the barrier is 4576 cm^{-1} between conformers **13** and **17** and 2503 cm^{-1} between conformers **5** and **11**. In formic acid it is ca. 3000 cm^{-1} .^{4f} One can therefore assume that the barrier between {**13,18**} and **11** will also be high thus precluding relaxation. The lower level *ab initio* calculations of Hollenstein *et al.*⁸ imply that the barrier to relaxation between **11** and **13** is of the order of several thousand cm^{-1} . We conclude that because {**13,18**} is unable to relax to either conformers **11** or **12** one may expect to find it experimentally in a free jet expansion.

Summarizing the situation for the other conformers: **4** has the possibility of relaxing to the lower energy conformers **13**, **12**, or **11**. A small barrier of 154 cm^{-1} is found between **4** and **11** which would permit relaxation. The barrier between **4** and **12** is irrelevant since if relaxation to **12** occurred conformer **12** would then relax to conformer **11**, a relaxation which has already been shown to be possible from **4** directly. Again since conversion between conformer **4** and **13** means rearrangement of the $-\text{COOH}$ group from *trans* to *cis*, it is unlikely to occur. In conclusion, conformer **4** is expected to rearrange to conformer **11** during the jet expansion. Conformer **17** likewise would relax to **11** by passing through conformers **4** or **12**, or perhaps even directly. Relaxation to **13** would not be possible due to the inhibition by a barrier of 4086 cm^{-1} . Figure 7 schematically

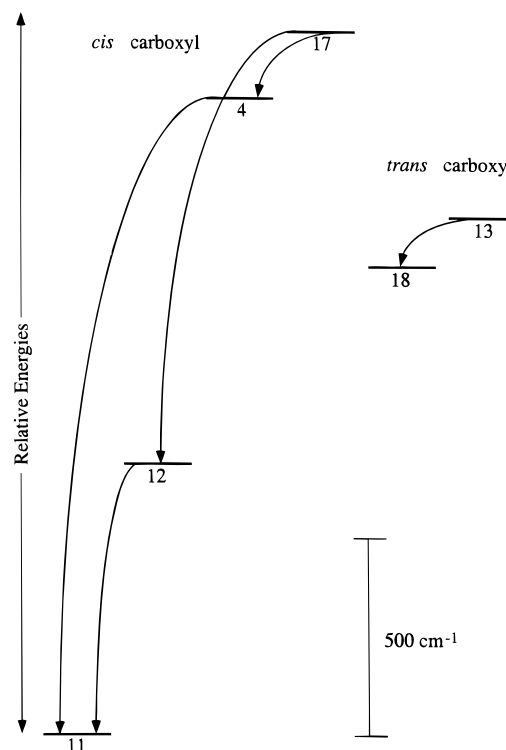


Figure 7. Schematic representation of some of the possible relaxation pathways for the conformers of glycolic acid.

represents the anticipated significant relaxation pathways for the conformers of glycolic acid for a pre-expansion temperature of 300 °C.

In conclusion, it is foreshadowed that microwave spectroscopy of glycolic acid with a seeded supersonic jet at 300 °C analysis should result in the observation of just two molecular species when taking into account thermal accessibility and the possibility of relaxation to lower energy conformers. The anticipated species are conformer **11**, which would be expected to have the r_p geometry of species **1** and which has previously been detected by microwave spectroscopy,^{7a-c} and the conformer consisting of the vibrational ground state in the composite potential well {**13,18**}. This is illustrated in Figure 8 which shows the expected abundance of each conformer before and after allowance for relaxation. The predicted electric dipole moment components for glycolic acid are shown in Table 3. Since the dipole moments for **13** and **18** are significantly higher than that of conformer **11** the intensity of lines of {**13,18**} relative to **11** will be higher than would be expected from the predicted relative abundances alone.

Experimental Observations. After elimination of all water dimer lines and the transitions associated with the conformer (**x**) previously detected by Blom and Bauder^{7a,b} including ¹³C isotopomers and excited vibrational states there remained some unassigned lines. These were found to have an intensity typically 25% of those of conformer (**x**). The lines were fitted to the spectrum of a single species (**y**) with the rotational constants of $A = 10273.601$ MHz, $B = 4207.0094$ MHz, and $C = 3048.4958$ MHz. Following the assignment of the lines of the new species no additional unassigned lines remained in the observed spectrum.

To attempt to identify conformer (**y**) firstly we compared the fitted rotational constants with the predicted rotational constants listed in Table 4 for the various structural forms shown in Figure 2. Secondly to further assist in identifying the new species samples containing mono- and dideuterated glycolic acid were

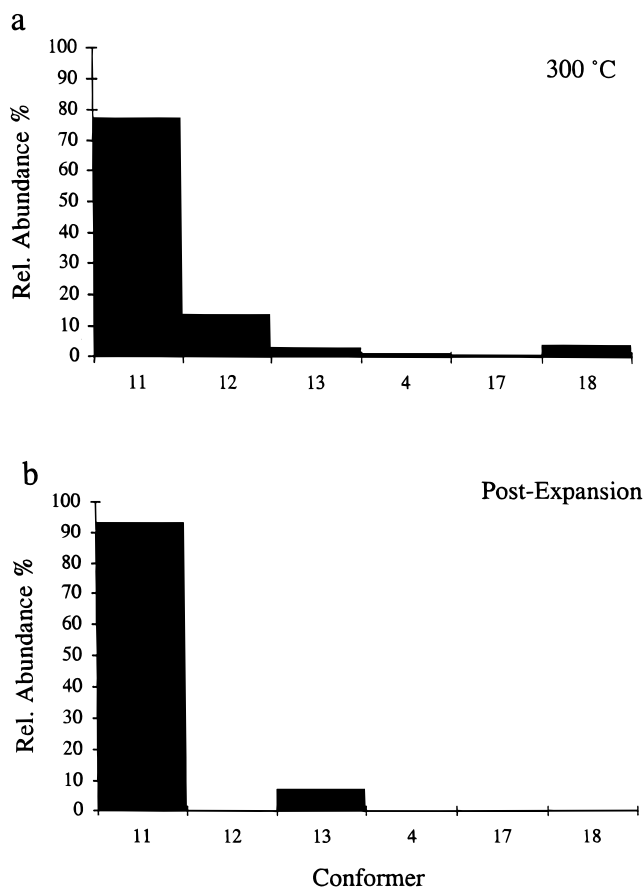


Figure 8. The expected relative abundance of each glycolic acid conformer using a pre-expansion temperature of 300 °C at (a) pre-expansion and (b) post-expansion after relaxation has been considered.

Table 3. Predicted *ab Initio* MP2/6-31G(d,p) Principal Inertial Axis Electric Dipole Moment Components (Debye) for the Glycolic Acid Forms

form	μ_a	μ_b	μ_c	form	μ_a	μ_b	μ_c
1	2.3	0.6	0.0	8	2.4	1.8	0.0
2	0.8	1.6	0.0	11	2.3	0.6	0.3
3	4.8	1.2	0.0	12	0.3	1.6	1.2
4	0.1	2.9	0.0	13	4.7	1.1	1.0
5	0.8	3.2	0.0	17	1.4	0.5	0.7
6	1.8	5.3	0.0	18	3.7	0.5	1.1
7	1.4	0.6	0.0	28	2.1	2.6	2.1

Table 4. The Rotational Constants (MHz) for Glycolic Acid Determined by *ab Initio* MP2/6-31G(d,p) Calculations

form	A	B	C	form	A	B	C
1	10571.7	4060.7	2988.0	8	9790.1	3946.5	2862.3
2	10213.6	4132.3	2996.3	11	10553.7	4058.2	2988.9
3	10241.9	4224.3	3047.8	12	10002.6	4112.3	3035.7
4	10448.3	3995.7	2943.1	13	10237.5	4210.3	3050.8
5	10456.4	4070.7	2984.5	17	10132.2	4119.0	3019.7
6	10318.1	3994.0	2932.1	18	10125.3	4142.5	3044.8
7	10245.2	4128.0	2997.1	28	8775.6	4113.2	3190.0

prepared by dissolving glycolic acid in 1:1 H₂O/D₂O and D₂O, respectively, and their microwave spectra measured.

Table 5 presents the experimentally derived rotational constants for the monodeuterated, dideuterated, and undeuterated isotopomers of the new species of glycolic acid. From consideration of the root mean square differences shown in Table 6 between the experimental and *ab initio* predicted values, averaged over all four isotopomers, of the planar moments of inertia P_a , P_b , and P_c (where $P_x = (-I_x + I_y + I_z)/2$) it can be seen that species **3**, **13**, and **18** provide a closer match to (y)

than the remaining species. A full tabulation of the predicted planar moments of inertia for the relevant isotopic variants of each form considered in the *ab initio* calculations is provided in the Supporting Information. The differences between the predicted and observed planar moments of inertia for species **3**, **13**, and **18** are shown diagrammatically in Figure 9. This presents a strong indication that conformer **13** provides the best match to the newly identified species.

To further test the validity of this assignment the principal moments of inertia obtained for the parent and monodeuterated isotopomers were used in conjunction with Kraitchman's equations¹⁷ to derive the principal axis substitution coordinates of each of the isotopically substituted atoms. These results are presented in Table 7. Again the agreement with the values for conformer **13** is much better than that for **3** or **18** so we conclude that this new conformer is conformer **13**, in very satisfactory agreement with the predictions from the use of MP2/6-31G(d,p) *ab initio* calculations.

It is satisfying to note the agreement between the structure of conformer **13** and the *trans* conformer of glycolic acid detected via infrared spectroscopy in an argon matrix by Hollenstein *et al.*⁸ although they had to rely on less direct evidence from isotopic frequency shifts and *ab initio* calculations for their identification.

A planar moment study for species (x) shown in Table 8, similar to that just described for species (y), gives a best match of (x) with species **1** and species **11** and substantially greater differences for the other species. This is consistent with our prediction that the conformer has an r_p geometry of **1**.

Conclusion

The results reported here show that glycolic acid in the gas phase is quite analogous to the structurally related amino acid glycine in that there are two species detectable by microwave spectroscopy. Previously only one glycolic acid conformer was reported and this is now seen to have been a consequence of the temperature used for the earlier spectral studies which was too low to generate sufficient population of the second conformer.

Ab initio calculations, at the MP2/6-31G(d,p) level, have indicated that forms **1**, **2**, **3**, **7**, and **8** are actually energy saddle points lying between adjacent true energy minimum conformers of lower symmetry. However, the calculated heights of the barriers separating these conformers are comparable to or considerably smaller than the 100–200 cm⁻¹ accepted systematic energy errors associated with *ab initio* calculations at this level of approximation. Thus the general question of the magnitude of the energy uncertainties in *ab initio* calculations is relevant to the significance of these structural conclusions. The uncertainty in theoretical predictions of whether a minimum on an energy surface is single or double, or has an adjacent inflection on the wall of a potential well, or other such features of topology, is perhaps less difficult because one might expect the systematic errors in energy computations to change only slowly with changes in nuclear coordinates. Thus, for example, while an energy difference of 0.015 kJ mol⁻¹ (1.3 cm⁻¹) between distant regions of the potential surface is clearly too small to be numerically significant, the theoretical prediction of a small local ripple of this magnitude in the vicinity of the species **1** minimum (creating the double minimum equivalent to conformers **11** and **11'**) indicates with some certainty that we are not dealing with just a simple single minimum in the surface. The primary physical consequence of such a feature on the energy surface is to indicate that there will be a large-

(17) Kraitchman, J. *Am. J. Phys.* **1953**, *21*, 17.

Table 5. The Experimentally Derived Rotational and Centrifugal Distortion Constants for the Monodeuterated, Dideuterated, and Nondeuterated New Glycolic Acid Species

	CH ₂ OHCOOH	CH ₂ OHCOOD	CH ₂ ODCOOH	CH ₂ ODCOOD
A/MHz	10273.601(16)	9836.713(21)	10233.500(28)	9794.052(39)
B/MHz	4207.0094(63)	4199.6651(30)	3988.3035(26)	3983.1442(32)
C/MHz	3048.4958(32)	3005.1231(19)	2931.7762(17)	2891.9439(27)
D _y /kHz	0.817(44)	0.7006	0.6384(77)	0.6114(82)
D _{jk} /kHz	3.45(40)	4.188(73)	4.02(14)	4.457(91)
D _v /kHz	7.0(13)			
D ₁ /kHz	-0.282(29)	-0.2264	-0.1856(63)	-0.1894(79)
d ₂ /kHz	-0.066(13)	-0.0565(35)	-0.0397(41)	-0.0496(48)
no. of lines in fit	37	31	31	32

Table 6. The Root-Mean-Square (rms) Differences between the Experimental (γ) and *ab Initio* Predicted Values, Averaged over All Four Isotopomers, of the Planar Moments of Inertia of All the Glycolic Acid Species

species	av Δ_{rms}^a	species	av Δ_{rms}^a
1	3.2595	8	4.2589
2	1.5053	11	3.2553
3	0.2734	12	1.4565
4	5.6038	13	0.0980
5	2.0137	17	1.7626
6	4.5543	18	1.1914
7	2.1385	28	7.4018

$$^a \text{Av } \Delta_{\text{rms}} = (1/4)(\Delta_{\text{rms}}(\text{CH}_2\text{OHCOOH}) + \Delta_{\text{rms}}(\text{CH}_2\text{ODCOOH}) + \Delta_{\text{rms}}(\text{CH}_2\text{OHCOOD}) + \Delta_{\text{rms}}(\text{CH}_2\text{ODCOOD})) \text{ where } \Delta_{\text{rms}} = \{\sum_{g=a,b,c}(P_{g(\text{obs})} - P_{g(\text{calc})})^2/3\}^{1/2}.$$

Table 7. Comparison of *ab Initio* Predicted Principal Axis Coordinates for *trans*-Glycolic Acid Species **3**, **13**, and **18** with the Experimental Principal Axis Substitution Coordinates of Each of the Isotopically Substituted Atoms for (γ) Calculated via Kraitchman's Equations

	MP2/6-31G(d,p)			exptl γ
	3	13	18	
a (H8)/pm	261	257	205	255.49
b (H8)/pm	40	31	5	33.56
c (H8)/pm	0	32	98	30.98
a (H9)/pm	50	50	49	45.16
b (H9)/pm	148	146	145	148.5
c (H9)/pm	0	4	12	3.41

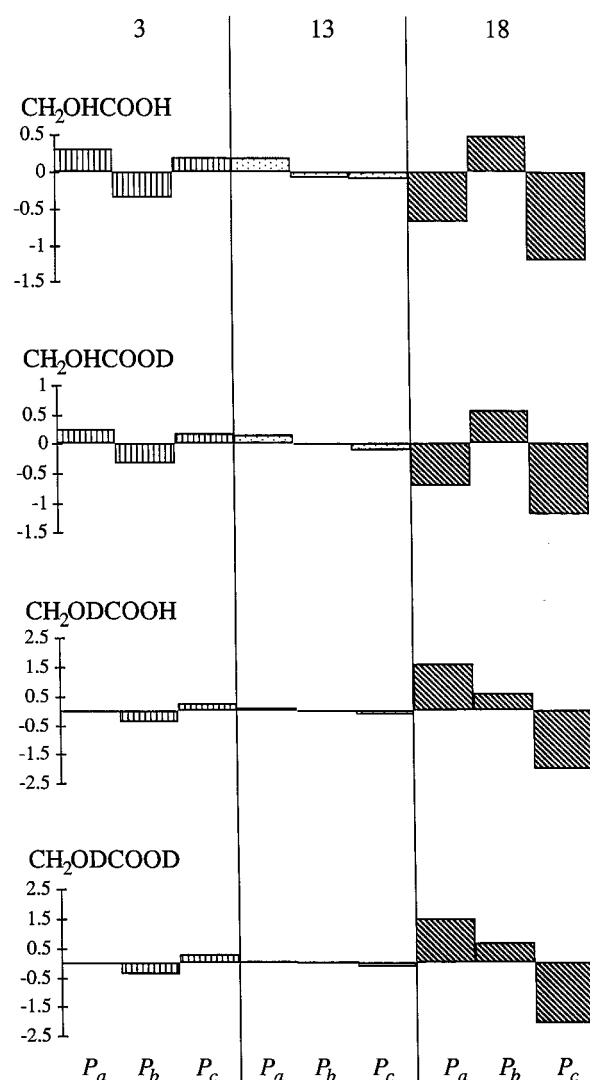
Table 8. The Root-Mean-Square (rms) Differences between the Experimental (x) and *ab Initio* Predicted Values, Averaged over All Four Isotopomers, of the Planar Moments of Inertia of All the Glycolic Acid Species

species	av rms ^a	species	av rms ^a
1	0.3858	8	3.9065
2	3.2580	11	0.3724
3	3.7030	12	3.6052
4	2.4398	13	3.6051
5	1.7678	17	2.4975
6	2.5942	18	3.8257
7	2.4871	28	9.9878

$$^a \text{Av } \Delta_{\text{rms}} = (1/4)(\Delta_{\text{rms}}(\text{CH}_2\text{OHCOOH}) + \Delta_{\text{rms}}(\text{CH}_2\text{ODCOOH}) + \Delta_{\text{rms}}(\text{CH}_2\text{OHCOOD}) + \Delta_{\text{rms}}(\text{CH}_2\text{ODCOOD})) \text{ where } \Delta_{\text{rms}} = \{\sum_{g=a,b,c}(P_{g(\text{obs})} - P_{g(\text{calc})})^2/3\}^{1/2}.$$

amplitude motion associated with the conformer in question. When vibrational effects are introduced into the model these features would almost certainly be located below the ground vibrational energy level and at best they would simply contribute to the breadth and anharmonicity of the resultant rather convoluted potential well. For such a low-energy barrier the most probable vibrationally averaged structure would coincide with the position of the saddle **1** rather than the true energy minimum **11**.

Ab initio methods, at the MP2/6-31G(d,p) level, were used to compare the relative energies of the conformers of glycolic

**Figure 9.** Schematic diagram showing the differences between the observed and calculated planar moments of inertia for the observed glycolic acid species (γ). The quantity plotted on the vertical axis is $P_{\text{obs}} - P_{\text{calc}}$ in (μA^2).

acid in the context of the analogous conformers of glycine. Due to the selective conformational relaxation of conformers in jet spectroscopy studies the *ab initio* calculations were extended to investigate the pathways and energy barriers involved in conformational interconversion in glycolic acid. The importance of this consideration was shown since the more abundant conformer **12** was seen to be able to relax in the jet expansion to conformer **11** and so will not appear in the spectrum. The next most abundant conformer {**13,18**} was predicted to be present following the jet expansion because it is unable to relax to any lower energy conformer.

The critical barrier to relaxation for glycolic acid at 300 °C

appears to be ca. 1000 cm^{-1} . This means that conformers **12**, **17**, and **4** should be able to relax to conformer **11** while conformer **28** (albeit with a negligible population at $300\text{ }^{\circ}\text{C}$) is predicted to relax to conformer {**13,18**}. No other detectable species was anticipated.

The new experimental measurements reported here were found to be consistent with the predictions based on the *ab initio* calculations in that (i) the observed rotational spectra of four isotopomers of a second glycolic acid conformer were detected and assigned, (ii) the new conformer was identified as {**13,18**} by comparison of fitted and *ab initio* predicted planar moments of inertia and the principal axis coordinates of the exchangeable hydrogen atoms, and (iii) the observed second conformer {**13,18**} was precisely the species predicted to be experimentally detectable from the *ab initio* calculations of conformer energies and relaxation pathways.

It was noted that conformer {**13,18**} was structurally quite similar to the “*trans*-glycolic” acid conformer earlier detected

via IR matrix isolation spectroscopy by Hollenstein and Günthard⁸ following broad-band IR irradiation of glycolic acid trapped in an argon matrix at liquid helium temperature.

Acknowledgment. The research was supported by a grant from the Australian Research Council.

Supporting Information Available: A listing containing the complete *ab initio* optimized geometries for each structural form of glycolic acid, all the measured and assigned microwave transition frequencies used to derive the rotational constants reported in this work, and calculated rotational constants and planar moments of inertia for all structural forms of glycolic acid and mono- and dideuterioglycolic acid (11 pages). See any current masthead page for ordering and Internet access instructions.

JA9616793