

# Ab Initio Study of the Internal Rotation Barrier of Formamide and the Formamide-H<sub>2</sub>O Complex

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## Abstract

The barriers to internal rotation about the N—C bond of formamide and the formamide-H<sub>2</sub>O complex have been examined by ab initio quantum chemistry methods. Both self-consistent field and correlated approaches have been utilized to determine the geometries, energies, and local harmonic vibrational frequencies of the minimum-energy and transition-state structures of these two systems. We find that formamide's rotation barrier of 14–15 kcal/mol is *increased* to 16–18 kcal/mol when a single H<sub>2</sub>O molecule is attached. This result contrasts with the effect of a single H<sub>2</sub>O solvent molecule on the barrier to tautomerization of formamide (to form formamidic acid HN—CHOH) for which a barrier *lowering* of ca. 20 kcal/mol has been observed. The rotation barriers obtained for formamide and for its H<sub>2</sub>O complex are compared with barriers obtained experimentally in various solvents. © 1993 John Wiley & Sons, Inc.

## I. Introduction

The fundamental importance of formamide's internal conformation has attracted scientists for many years. Motivated by a desire to understand the structures and behavior of many biological molecules that contain the R—NH—CR'O functional group, experimental and theoretical chemists have carried out a number of studies on the barrier to internal rotation of isolated formamide H<sub>2</sub>N—CHO as well as formamide in various solutions [1–12].

In earlier work [13], we examined the tautomerization H<sub>2</sub>NCHO → HNCHOH reaction both for an isolated formamide molecule and for its complex with a single H<sub>2</sub>O molecule. In the latter case, the tautomerization involves two H atom transfers—one from the H<sub>2</sub>N—group to the H<sub>2</sub>O solvent and another from the solvent to the carbonyl group's O atom. The primary conclusion of that work was that involvement of even a single solvent molecule *lowers the activation barrier for tautomerization by ca. 20 kcal/mol*. In the present work, we examine the effect of such "intimate" H<sub>2</sub>O solvent molecules on the rotation of the H<sub>2</sub>N— group, the question being to what extent the barrier to rotation is altered by the solvent.

Previous ab initio studies of formamide's internal rotation used experimental ground-state geometries and performed either (i) semirigid rotation (i.e., in which all other geometrical parameters are frozen) about the C—N bond or

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(ii) limited geometrical variations of the internal coordinates (e.g., the C—O, C—N, C—H, and N—H bond lengths). To our knowledge, all previous theoretical studies on this internal rotation barrier involved Hartree–Fock self-consistent-field (SCF) optimization of various limited geometrical parameters.

To investigate the influence of electron correlation, these earlier studies performed correlated calculations at the local-minimum or transition-state geometries that had been identified by SCF-level calculations. Thus far, no rigorous theoretical work has been reported on the internal rotation of formamide in the presence of one or more H<sub>2</sub>O molecules or in solution. For these reasons, we chose to study the internal rotation of isolated formamide and of formamide in the presence of a single H<sub>2</sub>O molecule using both SCF and correlated second-order Møller–Plesset (MP2) methods. The configuration interaction including singly and double excited configurations (CISD) method was also employed at selected geometries (e.g., near the transition state) to make sure that the electronic wave function was dominated by a single electronic configuration in which case the MP2 energies are likely to be reliable.

## II. Methodology

### A. Basis Sets and Ab Initio Calculation Methods

Studying the internal rotation barrier of formamide, Jasien et al. [1] found a large change in the hybridization of the nitrogen atom when polarization functions were used. They also noted that polarization functions strongly affected the calculated height of the rotational barrier. Boggs and Liu [2] states that “the amino group angle is the result of a delicate balance between lone pair character of the nitrogen electrons and delocalization of these electrons into other portions of the molecule.”

Based on these earlier experiences, we chose to use Dunning’s correlation-consistent double-zeta plus polarization (CCDZP) basis set [14] for all atoms. Based on our earlier work on the tautomerization of formamide in the presence of H<sub>2</sub>O, we knew that inclusion of a second polarization function or enhancement of the DZP basis to the triple-zeta level would produce little change in the thermodynamic energy differences, but would greatly increase the computer time needed. For these reasons, we settled on the CCDZP basis.

We chose to perform full geometry optimization for the ground electronic state both for the formamide and solvated formamide structures and at their respective rotational transition-state structures. These optimizations were first carried out at the SCF level using full analytical gradient and Hessian information and, subsequently (starting at the resultant SCF geometries), at the MP2 correlated level using gradient information and a finite-difference-based Hessian.

### B. Finding the Transition State

The potential energy surfaces for internal rotation were computed at the SCF level using our in-house electronic structure codes together with the GAMESS

computer programs.<sup>‡</sup> The minimum-energy geometries of the formamide molecule and of the formamide-H<sub>2</sub>O complex were already available from our previous work [13], so in this work, our effort was devoted to finding the respective transition states.

For the formamide molecule and the formamide-H<sub>2</sub>O complex, we began our search for the rotational transition states by starting from the SCF converged minimum-energy geometry. We then calculated the energy at a "grid" of geometries in which the NH<sub>2</sub> group was rotated about the C-N bond with all of the remaining internal coordinates held fixed. Along this highly constrained path, we located the point of highest energy; this geometry was then used to provide a reasonable starting point for the subsequent transition-state search. We then performed a full geometry optimization using the "eigenmode following" methods [16, 17] discussed briefly in the next section.

The effects of electron correlation on the barrier height both for isolated formamide and for the formamide-H<sub>2</sub>O complex were investigated using the singles and doubles configuration interaction (CISD) and MP2 methods at the SCF-optimized geometries. In addition, for the isolated formamide, we carried out an MP2-level full geometry optimization with the same basis set using the GAUSSIAN 86 program.<sup>§</sup> This MP2 geometry optimization used our SCF-level optimized geometry as a starting point; the resultant MP2-optimal geometry was found to be very similar to the SCF-level geometry. Not surprisingly, even though the algorithm in the GAUSSIAN 86 program is not as sophisticated as that contained in more recent versions of the GAUSSIAN code (which we did not have access to on our IBM 3090-600s), this optimization required very few "steps" since the gradients along all degrees of freedom were already small at the SCF-level geometry. Finally, zero-point energy (ZPE) corrections to the rotation barrier were estimated from the SCF-level calculated harmonic vibrational frequencies of the respective minima and transition states.

### C. Streambed following Optimization Strategy

In earlier papers [16, 17], we outlined a potential energy surface walking algorithm that uses local analytical first (gradient) and second (Hessian) energy derivatives to provide a series of "steps" along a "streambed" on the energy surface that can either (i) lead to a local minimum by moving "downhill" in energy along all internal degrees of freedom or (ii) lead to a transition state, by moving "uphill" along one eigenmode of the local Hessian matrix while moving "downhill" along all other eigenmodes. This Hessian eigenvector following algorithm was used in this work (except for the MP2-level treatments) and is now part of the "Berny" routine that occurs in the Gaussian 9X program suite.<sup>§</sup>

<sup>‡</sup>GAMESS is an ab initio electronic structure program described in [15].

<sup>§</sup>Gaussian 86 was an earlier version of the highly popular Gaussian 9X series of codes. The Gaussian 90 version is detailed in [18].

### III. Findings and Comparison with Earlier Work

#### A. Earlier Results on Formamide

An early study by Radom et al. [3] on the isolated formamide molecule found a rotation barrier of 24.7 kcal/mol at the SCF level using a 4-31G basis set. Later, Radom and Riggs [4] obtained an extremely low barrier of 8.2 kcal/mol when performing full gradient-based geometry optimization at the STO-3G basis SCF level. However, when these authors then employed a 4-31G basis set at the STO-3G optimized geometry, they found a barrier of 20.0 kcal/mol. Nalewajski [5] showed that full geometry optimization decreases the barrier and obtained a barrier 6 kcal/mol lower than in [4]. Sunners et al. [12] obtained an 18.1 kcal/mol barrier by performing a 4-21G basis SCF full geometry optimization. More recently, Jasien et al. [1] added polarization functions and concluded that electron correlation decreases the barrier height by less than 1 kcal/mol and that zero-point energy corrections change the barrier height only slightly. They then computed a final barrier of 14.2 kcal/mol. Harding and Goddard [19] reported a rotation barrier of 14.2 kcal/mol using the generalized valence bond (gVB) method with a DZ basis set. Finally, Lii and Allinger [20] used the parameterized MM3 method to compute a rotation barrier of 14.3 kcal/mol. It therefore seems that the most reliable estimate of the barrier for isolated formamide is ca. 14 kcal/mol.

#### B. Our Findings on Formamide

Our SCF-level calculations produce an internal rotational barrier of 14.9 kcal/mol. Using the correlated CISD method (at the SCF-optimized geometry), we find a 14.4 kcal/mol barrier, and MP2 with full geometry optimization provides a barrier of 15.2 kcal/mol (see Table I). Clearly, electron correlation has an effect on the rotational barrier of formamide, but it is less than 1.0 kcal/mol, which is consistent with Jasien et al.'s conclusion. The zero-point correction to the barrier height at the SCF level is ca. 0.4 kcal/mol. Therefore, our final zero-point cor-

TABLE I. Calculated rotation barriers for formamide (F) and the (F...H<sub>2</sub>O) complex (kcal/mol).

Method	Barrier without ZPE		ZPE correction	
	F	F...H <sub>2</sub> O	F	F...H <sub>2</sub> O
SCF	14.9	17.5	-0.4	-1.0
CISD/SCF <sup>a</sup>	14.4	18.0		
MP2/SCF <sup>b</sup>	15.5	19.0		
MP2	15.2			
Jasien et al. [1]	14.2			
Harding and Goddard [19]	14.2			
Lii and Allinger (MM3) [20]	14.3			

<sup>a</sup> CISD single-point energy at SCF-optimized geometries.

<sup>b</sup> MP2 single-point energy at SCF-optimized geometries.

rected rotational barrier for gas-phase formamide is 14.5 kcal/mol at the scf level, 14.0 kcal/mol at the CISD level, and 14.8 kcal/mol at the MP2 level.

To our knowledge, there are no direct experimental data available for the rotational barrier of formamide in the gas phase. However, analysis of experimental data on the internal rotational barrier in solution shows that barrier heights decrease as the hydrogen-bonding ability of the solvent decreases. Therefore, we expect that the rotation barrier of formamide in the gas phase should be a few kcal/mol *lower* than the lowest experimental rotation barrier in solution. From Table II we see that the lowest barriers in solution are  $16.8 \pm 1.0$  and  $1.69 \pm 1.9$  kcal/mol in dioxane and acetone, respectively. Our calculated barrier heights of 14.0–14.8 kcal/mol at different levels of theory lie a few kcal/mol below these experimental values, as anticipated.

Our scf geometry for the internal-rotation transition state produces a 57° change in the H–N–C–O torsion angle relative to the minimum-energy geometry, and the NH<sub>2</sub> group assumes an orientation of 89° relative to the N–C–O–H<sub>3</sub> plane (see Table III and Fig. 1). Jasien et al. also found a H–N–C–O torsion angle of 57° based on their scf-level calculations with their DZP basis set. The path connecting the minimum-energy geometry and the rotational transition state for formamide is described in Figure 2.

Comparing our MP2-optimized geometry with the scf geometry (see Table III), we find only very small differences. The bond lengths of the minimum-energy and transition-state structures have an average deviation of less than 0.02 Å, with the scf-level bond lengths being slightly shorter than the MP2 lengths. For the bond angles, there is an average deviation of 0.5°, except for the angles  $\angle\text{CNH1}$  and  $\angle\text{CNH2}$ , which have ca. 2.0° differences at the transition-state geometry.

### C. Our Findings on the Formamide–H<sub>2</sub>O Complex

Our primary findings on the minimum-energy and transition-state geometries of the formamide–H<sub>2</sub>O complex are summarized in Table IV and Figure 3. In this case, our calculated rotational barrier is 17.5 kcal/mol at the scf level, and 18.0 and 18.9 kcal/mol at the CISD and MP2 levels, respectively (using the scf-optimized geometries of Table I). The zero-point energy correction to the barrier

TABLE II. Experimental rotation barriers for formamide in solution<sup>a</sup> (kcal/mol).

Solvent	Barrier
Neat	$18.9 \pm 1.0$
Water	$21.3 \pm 1.3$
Acetone	$16.9 \pm 1.9$
Dioxane	$16.8 \pm 1.0$
Diglyme	$19.7 \pm 0.2$
MPK	$19.2 \pm 0.2$

<sup>a</sup> See [11, 12].

TABLE III. Geometries of minimum-energy and rotational transition-state structures of formamide.

Distance (Å)	Minimum			
	SCF	MP2	Experimental	
C—O	1.190	1.217	1.193 <sup>a</sup>	1.219 <sup>b</sup>
C—N	1.354	1.371	1.376	1.352
N—H1	0.997	1.012	1.002	1.002
N—H2	1.000	1.015	1.014	1.002
C—H3	1.101	1.115	1.102	1.098
O—H1	3.125	3.163		
O—H2	2.025	2.053		
H1—H2	1.712	1.729		

Distance (Å)	Transition state			
	SCF	MP2	SCF	MP2
C—O	1.181	1.210	C—H3	1.098
C—N	1.428	1.447	O—H1	2.576
N—H1	1.010	1.027	O—H2	2.575
N—H2	1.010	1.027	H1—H2	1.594

Angle (deg)	Minimum			
	SCF	MP2	Experimental	
∠OCN	125.0	125.1	123.8 <sup>a</sup>	124.7 <sup>b</sup>
∠CNH1	120.2	118.8	120.0	
∠CNH2	118.0	116.5	117.1	118.5
∠OCH3	122.5	123.3	123.0	122.5

Angle (deg)	Transition state			
	SCF	MP2	SCF	MP2
∠OCN	125.2	125.8	∠CNH1	107.5
∠OCH3	121.4	121.8	∠CNH2	107.5

<sup>a</sup>From Ref. [9].<sup>b</sup>From Ref. [10].

height is ca.  $-1.0$  kcal/mol. We therefore estimate the barrier to lie in the range of  $16.5$ – $17.9$  kcal/mol. The path connecting the minimum-energy and transition-state geometries of this complex is described in Figure 4.

As discussed above, there are experimental results [12, 13] for the internal rotation barrier of formamide in various solvents including water, acetone, dioxane, and diglyme. The trends in these barriers are clear. Isolated formamide has the smallest barrier—ca.  $15$  kcal/mol. In weakly interacting solvents such as dioxane and acetone, the barriers are  $2$ – $5$  kcal/mol larger. With only one  $H_2O$  molecule present, the barrier is approximately the same as for acetone and dioxane. Fi-

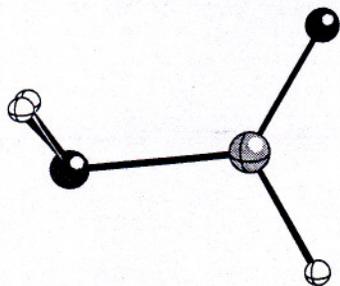


Figure 1. Transition state for internal rotation of formamide.

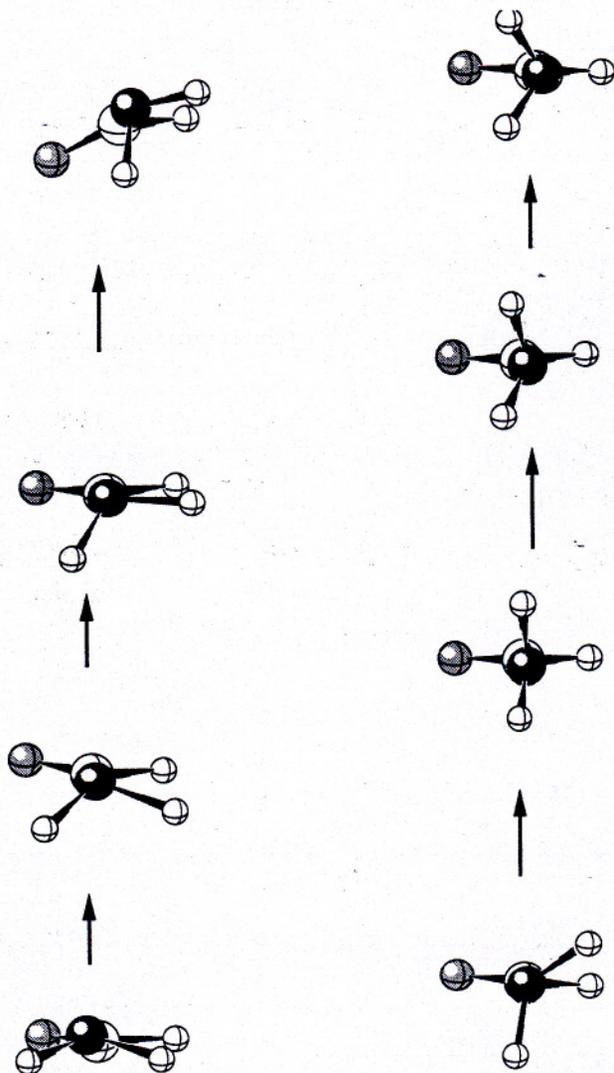
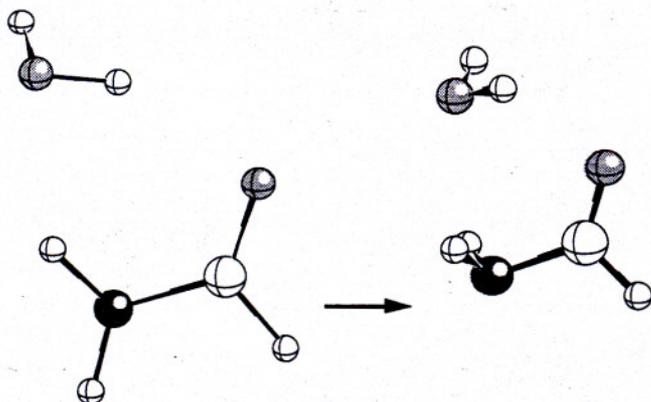


Figure 2. Reaction path for rotational isomerization of formamide.

TABLE IV. SCF geometries of minimum-energy and rotational transition-state structures of formamide  $\cdots$  H<sub>2</sub>O.

	Distance (Å)			Angle (deg)	
	Minimum	Transition state		Minimum	Transition state
C—O1	1.200	1.190	∠O1CN	125.2	125.4
C—H3	1.099	1.097	∠CNH1	120.7	107.3
C—N	1.341	1.354	∠CNH2	118.8	107.0
O1—H1	3.133	2.557	∠NCH3	113.5	114.0
O1—H2	2.517	2.578	∠CNO2	91.3	86.2
O1—H4	3.376	3.524	∠O1O2H4	111.8	116.5
O1—H5	2.058	2.194	∠O1O2H5	22.1	27.0
O1—O2	2.910	2.998	∠O2H4N	44.8	29.3
O1—N	2.256	2.319			
N—O2	2.995	3.105			
N—H1	0.996	1.011			
N—H2	1.004	1.013			
N—H4	3.591	3.897			
N—H5	2.762	2.906			
H1—H2	1.732	1.586			
H2—O2	2.154	2.331			
O2—H4	0.947	0.946			
O2—H5	0.954	0.950			
H4—H5	1.505	1.505			

Figure 3. Minimum-energy and internal-rotation transition-state geometries of the formamide-H<sub>2</sub>O complex.

nally, in aqueous solution, the barrier increases by another 2–4 kcal/mol. Thus, in stark contrast to the tautomerization reaction, the intimate involvement of water solvent molecules *increases* the internal rotation barrier; the tautomerization reaction barrier is *lowered* by ca. 20 kcal/mol when even a single solvent molecule is present.

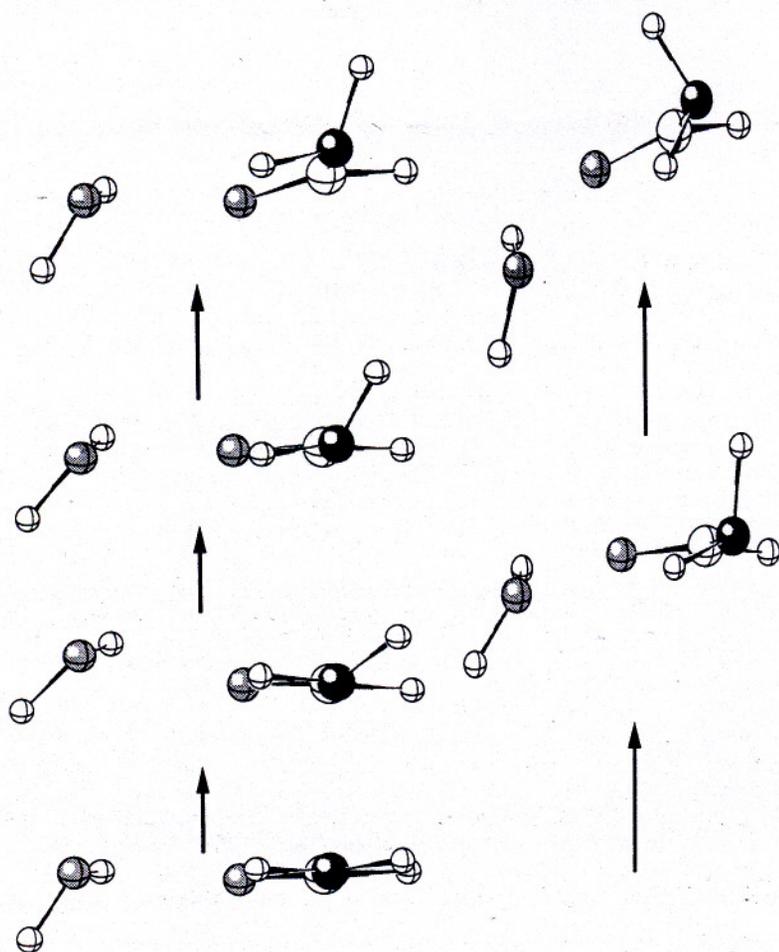


Figure 4. Reaction path for rotational isomerization of formamide-H<sub>2</sub>O complex.

#### IV. Summary

The barriers to internal rotation about the N—C bond of formamide and the formamide-H<sub>2</sub>O complex have been examined by self-consistent field and correlated (MP2 and CSID) approaches. Geometries, energies, and local harmonic vibrational frequencies (available upon request) of the minimum-energy and transition-state structures of these two systems are reported here. We find that formamide's rotation barrier is 14–15 kcal/mol and that of the formamide-H<sub>2</sub>O complex is 16–18 kcal/mol. In our earlier study of the barrier to tautomerization of formamide, we found a *lowering* of the barrier by ca. 20 kcal/mol by even a single H<sub>2</sub>O solvent molecule. The rotation barriers obtained for formamide and for its H<sub>2</sub>O complex fit in well with experimentally measured barriers obtained in a variety of solvents of various hydrogen-bonding strengths.

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