

An *ab initio* Study of the $A_{Ac}1$ Hydrolysis Mechanism of Formamide

A. C. Hopkinson

Department of Chemistry, York University, Downsview, Ontario, Canada

I. G. Csizmadia

Lash Miller Chemical Laboratories, University of Toronto, Toronto 181, Ontario, Canada

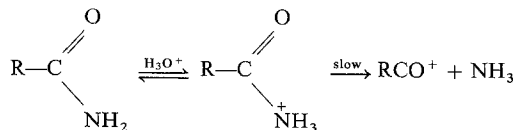
Received March 26, 1973

Ab initio calculations have been used to examine the reaction profile for the $A_{wc}1$ hydrolysis mechanism for formamide, giving a value of 67.3 kcal/mole for ΔH^\ddagger . Comparisons between computed and experimental proton affinities are used to assess the reliability of the calculations. Orbital energies are reported for formamide, N-protonated and O-protonated formamide, carbon monoxide and the formyl cation.

Key words: Protonation of Formamide — Geometry of Formyl Cation — Reaction Profile — Computed Activation Energy.

We have previously reported a theoretical study [1] on the acid catalysed hydrolysis of amides, esters and carboxylic acids (O^{18} exchange). The results of a small basis set *ab initio* calculation on the formic acid "hydrolysis" were markedly different from the majority of the calculations, which employed the semi-empirical extended Hückel molecular orbital (EHMO) method. Recent *ab initio* studies [2, 3] have also shown that the EHMO predictions on the site of protonation of formamide were also incorrect. It was therefore decided to reexamine the $A_{wc}1$ reaction profile for the decomposition of protonated formamide, this time using the more reliable *ab initio* method.

Experimentally the reaction, which occurs in concentrated mineral acid solutions, is believed to proceed through a fast protonation step followed by a slow decomposition of the nitrogen protonated tautomer to produce the acylium ion and ammonia.



Acylium ions are stable only as salts with SbF_6^- ions [4–6] or in oleum solutions [7], and quickly pick up water in most acidic solutions to produce carboxylic acids. In the present theoretical study only formamide ($\text{R}=\text{H}$) was considered.

Computational Details

The calculations were all carried out on an IBM 360-65, using a modified version of IBMOL-IV [8]. The basis set consisted of 8^s and 3^p type Gaussian functions on oxygen, nitrogen and carbon, and 3^s type functions on hydrogen, contracted to 2^s , 1^p and 1^s respectively [9].

The molecular geometries were those used in previous theoretical treatments [10–12]. Previous workers [13] using minimal basis set calculations found the carbon-oxygen bond length of HCO^+ to be 0.02 a.u. shorter than in carbon monoxide. In the initial calculations in the present study the geometry of this ion was reoptimised with the larger basis set and was again found to be linear, but with the carbon-oxygen bond 0.075 a.u. larger than in carbon monoxide [14] (Fig. 1).

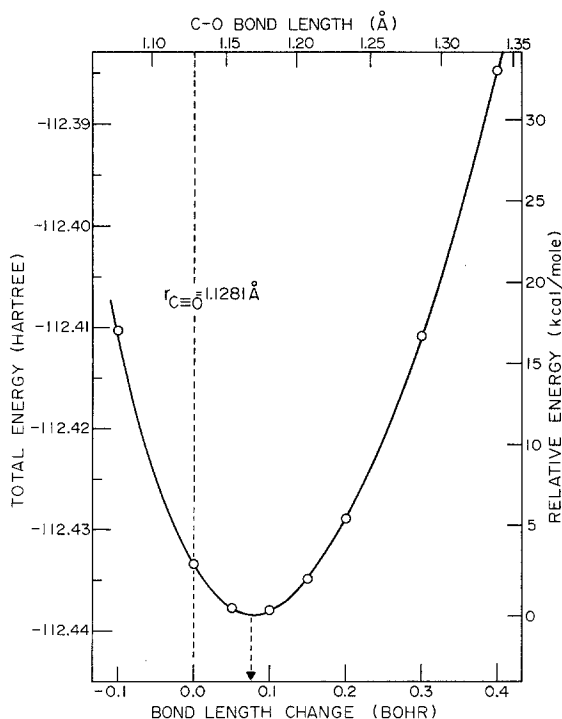


Fig. 1. Plot of computed total energy against carbon-oxygen bond length for the formyl ion

Results and Discussion

The computed total energies for all the species are recorded in Table 1 along with the estimated Hartree Fock limits [15, 12, 11]. These were used to construct the reaction profile shown in Fig. 2. The *O-protonated* formamide, although not a possible intermediate in this mechanism, was included to show the difference between the *N-* and *O-protonated* tautomers. The initial protonation reaction is

Table 1. Computed total energies (hartrees)

| Species | Calculated total energy | Hartree Fock limit |
|-------------------------------|---|------------------------|
| | - 168.1296 (planar) - 168.1299 (experimental geometry) | - 168.942 ^a |
| | - 168.5358 | — |
| | - 168.5259 | — |
| | - 187.8161 | - 188.957 ^b |
| | - 188.1576 | — |
| H ₂ O | - 75.6121 | - 76.048 ^c |
| H ₃ O ⁺ | - 75.9726 | — |
| NH ₃ | - 55.9452 | - 56.190 ^c |
| NH ₄ ⁺ | - 56.3512 | — |
| CO | - 112.2118 | - 112.781 ^c |
| HCO ⁺ | - 112.4380 | — |

^a See Ref. [15].^b See Ref. [12].^c See Ref. [11].

predicted to be exothermic by 22.3 kcal/mole. However this energy difference, neglecting changes in zero point vibrational energy, is ΔH_0^0 , the heat of reaction at 0°K. The equilibrium at 25° C depends on ΔG_{298}^0 , a thermodynamic property which has large contributions from enthalpies and entropies of solution. The hydration energy of the hydronium ion (H₃O⁺) alone is estimated to be

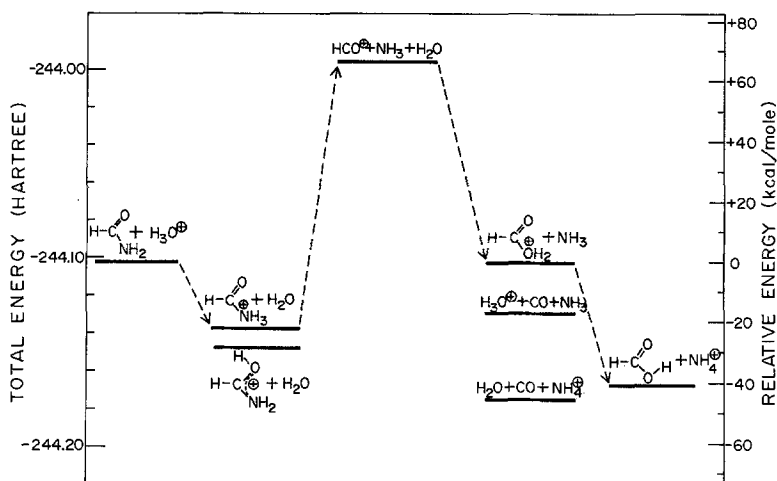
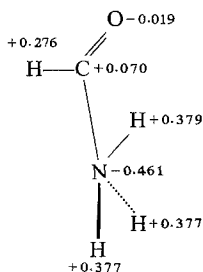


Fig. 2. Computed reaction profile for the $A_{Ac}1$ hydrolysis mechanism for formamide

100 kcal/mole, [15] and this ion due to its ability to form strong hydrogen bonds will probably be the species most stabilised by solvation. Solvation then could easily reverse the relative energies of the reactants and products of the first step on the reaction profile.

Experimentally the conversion of the *N-protonated* amide to the acylium ion and ammonia is the slow step. Formally this requires heterolytic fission of the carbon-nitrogen bond and will be assisted by the partial positive charge (+0.67) on the NH_3 group.



The products of this fission reaction are computed to be 89.6 kcal/mole less stable than the *N-protonated* formamide. If these unstable products have similar energy to the transition state for this reaction, [17] then ΔH^\ddagger for the hydrolysis is calculated to be 67.3 kcal/mole. This compares with experimental values of between 27.2 and 31.8 kcal/mole for different benzamides [18].

Decomposition of the formyl ion into carbon monoxide is computed to be more favourable than nucleophilic attack by water to produce formic acid. All these processes are predicted to be very exothermic, consistent with the experi-

mental observation that the formyl ion is very unstable [19]. The most stable products are carbon monoxide, water and the ammonium ion, the usual products found in the decomposition of formamide.

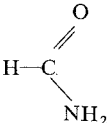
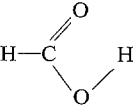
The overall profile is similar to that obtained in *ab initio* studies on the A_{Ac1} decomposition of formic acid [1, 12], and is markedly different from that produced by the EHMO calculations. In particular, it predicts high energy intermediates as products of the kinetically slow step, whereas the semi-empirical calculations gave these to be the most stable species on the profile.

In an attempt to assess the accuracy of calculations with this particular basis set, the proton affinities for the several weak bases were compared with experimental values. These are recorded in Table 2.

Hydroxy-protonated formic acid, the only tautomer used in construction of this profile, was previously found to be 25 kcal/mole less stable than the *cis-trans* carbonyl protonated formic acid [12]. The computed proton affinity for formic acid in Table 2 will therefore be too high by this amount. All the computed proton affinities overestimate the experimental values, but the energy differences vary considerably. The largest difference is for water, for which the calculation overestimates the experimental value by almost 50 %. Therefore it is safe to conclude that errors due to inadequacies in the basis set lead to an overestimation of energy differences for *gas phase* reactions of at most a factor of two.

Finally, the orbital energies of protonated formamide and the formyl cation have never been reported. These are listed in Table 3, along with those of the unprotonated bases. Similarly to other species [21], protonation clearly stabilises *all* molecular orbitals, including those composed mainly of core orbitals from the carbon, nitrogen and oxygen atoms. This analysis of orbital energies then clearly

Table 2. Proton affinities (kcal/mole)

| Molecule | Computed value | Experimental value |
|--|----------------|--------------------|
| H ₂ O | 226.3 | 151 ^a |
| NH ₃ | 254.9 | 200 ^a |
| CO | 142.0 | 131 ^a |
|  (O-protonation) | 254.8 | — |
|  (hydroxy-protonation) | 214.4 | 162 ^b |

^a See Ref. [11].^b See Ref. [20].

Table 3. Computed orbital energies

| | | | CO | HCO [⊕] |
|----------|---------------|---------------|----------|------------------|
| -20.6062 | -20.9956 | -20.9908 | -20.8203 | -21.3169 |
| -15.6202 | -15.9978 | -16.0895 | -11.4371 | -11.9789 |
| -11.4492 | -11.8096 | -11.7342 | -1.5294 | -1.8920 |
| -1.3719 | -1.6755 | -1.6428 | -0.7529 | -1.2155 |
| -1.1527 | -1.4816 | -1.5373 | -0.6071 | -1.0618 |
| -0.8006 | -1.1419 | -1.0949 | -0.6071 | -0.9721 |
| -0.6941 | -1.0311 | -1.0109 (a'') | -0.5001 | -0.9721 |
| -0.6165 | -0.9434 | -1.0090 | | |
| -0.5361 | -0.9084 | -0.9277 | | |
| -0.5295 | -0.8340 (a'') | -0.8285 | | |
| -0.3622 | -0.7543 | -0.7243 (a'') | | |
| -0.3362 | -0.6700 (a'') | -0.6784 | | |

shows that valence shell molecular orbital calculations (like the EHMO method), which assume the energies of the inner shell electrons are unchanged, cannot hope to successfully predict energy differences for even the simplest chemical reaction, protonation.

Acknowledgments. The authors wish to thank the National Research Council for continued financial support.

References

- Hopkinson, A. C., McClelland, R. A., Yates, K., Csizmadia, I. G.: *Theoret. Chim. Acta (Berl.)* **13**, 65 (1969)
- Bonaccorsi, R., Pullman, A., Scrocco, E., Tomasi, J.: *Chem. Phys. Letters* **12**, 622 (1972)
- Hopkinson, A. C., Csizmadia, I. G.: *Can. J. Chem.* **51**, 1432 (1973)
- Olah, G. A., Kuhn, S. J., Tolgyesi, W. S., Baker, E. B.: *J. Am. Chem. Soc.* **84**, 2733 (1962)
- Olah, G. A., Tolgyesi, W. S., Kuhn, S. J., Moffatt, M. E., Bastien, I. J., Baker, E. B.: *J. Am. Chem. Soc.* **85**, 1328 (1963)
- Olah, G. A., Comisarow, M. B.: *J. Am. Chem. Soc.* **88**, 4442 (1966)
- Deno, N. C., Pittman, C. U., Wisotsky, M. J.: *J. Am. Chem. Soc.* **86**, 4370 (1964)
- Veillard, A., IBMOL: Computation of wave functions for molecules of general geometry, version 4. IBM Research Laboratory, San Jose, California
- Klessinger, M.: *Theoret. Chim. Acta (Berl.)* **15**, 353 (1969)
- Costain, C. C., Dowling, J. M.: *J. Chem. Phys.* **32**, 158 (1960)
- Hopkinson, A. C., Holbrook, N. K., Yates, K., Csizmadia, I. G.: *J. Chem. Phys.* **49**, 3596 (1968)
- Hopkinson, A. C., Yates, K., Csizmadia, I. G.: *J. Chem. Phys.* **52**, 1784 (1970)
- Jansen, H. B., Ros, P.: *Chem. Phys. Letters* **3**, 140 (1969)

14. Herzberg, G., Rao, K. N.: J. Chem. Phys. **17**, 1099 (1949)
15. Robb, M. A., Csizmadia, I. G.: Theoret. Chim. Acta (Berl.) **10**, 269 (1968)
16. Bell, R. P.: The proton in chemistry, p. 24. Ithaca: Cornell University Press 1959
17. Hammond, G. S.: J. Am. Chem. Soc. **77**, 334 (1955)
18. Duffy, J. A., Leisten, J. A.: J. Chem. Soc. **1960**, 853
19. Olah, G. A., Dunne, K., Mo, Y. K., Szilagyi, P.: J. Am. Chem. Soc. **94**, 4200 (1972)
20. Harrison, A. G., Ivko, A., van Raalte, D.: Can. J. Chem. **44**, 1625 (1966)
21. Tel, L. M., Wolfe, S., Csizmadia, I. G.: J. Chem. Phys. (in press)

Prof. Dr. A. C. Hopkinson
Department of Chemistry
York University
Downsview, Ontario
Canada