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Determination of Reactivity by MO Theory (XVIII). An Intermolecular Perturbation Study of the Acid-Catalyzed Hydrolysis of Diformamide *

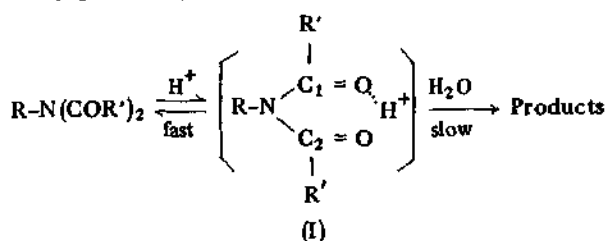
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The Murrell-Fueno type of the intermolecular perturbation approach was applied to the acid-catalyzed hydrolysis of diformamide. The results show that: (1) the attack of a water molecule on the protonated carbonyl carbon is favored over that on the unprotonated carbonyl carbon; (2) the σ -approach model of water is preferred to the π -approach model; (3) the major contributing term to the total energy is the Coulomb energy, E_q , especially in the σ -approach, while the contribution of E_{ct} (and E_k) increases moderately in the π -approach; (4) the reaction is a charge-controlled one, a hard-hard type in the language of the HSAB principle.

Introduction

Recently it has been shown that the mechanism for the acid-catalyzed hydrolysis of diacylamines, $RN(COR')_2$, involves the attack by a water molecule on one of the carbonyl carbon of the conjugate acid (I) as the rate determining step.¹



The protonation was found to occur on a carbonyl oxygen,^{1b,2} the *trans-trans* form of diacylamine (I) being preferred when protonated.^{2,3} Laurent and coworkers suggested that the attack by a water occurred on the carbon atom of the unprotonated carbonyl group, C_2 . However, based on a simple interpretation of MO properties we have argued that the attack should occur on the carbon atom of the protonated carbonyl group, C_1 ,³ since protonation caused an increase in the positive charge as well as in the AO coefficient of the π -LUMO (lowest unoccupied MO) of C_1 enhancing both charge-controlled and orbital-controlled S_N reactivities of C_1 .

In this work we will pursue further this problem of deciding which carbonyl carbon that is attacked by a water molecule in

the acid-catalyzed hydrolysis of diacylamines adopting the intermolecular interaction approach developed by Murrell^{4a} and Fueno.^{4b} In this type of intermolecular perturbation method, various interaction energies, *i.e.*, the Coulomb E_q , exchange-repulsion E_k , induction E_p , dispersion E_d , and charge-transfer E_{ct} , energies, are evaluated separately for assumed geometries of the reacting systems and their relative contributions to the orienting effect are assessed.

In this work we have chosen the simplest form of diacylamine, diformamide $HN(COH)_2$, and the interaction energies between protonated diformamide and water were calculated at various distances and orientations of approach.

Calculations

In the intermolecular perturbation theory of Murrell *et al.*,^{4a} the ground-state configuration (AB) of the two interacting system A and B are mixed with the locally excited (A^*B and AB^*), doubly excited (A^*B^*) and charge-transfer (A^+B^- and A^-B^+) configurations, and the stabilization energy of the ground-state due to the configuration interaction is calculated by a double perturbation expansion with respect to the intermolecular potential U and overlap S up to the order of U^2S^2 . Thus expressions for the Coulombic (U^1S^0), exchange-repulsion (U^1S^2), induction-dispersion (U^2S^0) and charge-transfer (U^2S^2) energies are derived. These expressions are then expanded into terms associated with atomic orbitals. Actual

* This paper is dedicated to the memory of the late Professor Suk-kee Lee of the Busan National University, who was a respected teacher, colleague and scientist. On his suggestion this work was originally initiated.

numerical evaluations are performed assuming zero-differential overlaps within molecules but retaining the overlaps between the interacting molecules.^{4b} The final expressions for each component energies contain intermolecular atomic orbital integrals such as the electron-core attraction, interelectronic repulsion, and atomic overlap integrals which are evaluated by using the Slater valence-shell s AQ's and Mulliken's formula.^{4b} The FORTRAN program for this calculation was kindly provided to us by Professor T. Fueno and Dr.S.Nagase of the Osaka University.

Molecular geometries used for diformamide were CNDO/2 optimized values of Capparelli.⁵ Proton was placed at 0.96 Å from a carbonyl oxygen with 120° angle within the molecular plane.⁶ Coordinate axes chosen for the interacting system is given in Figure 1. The oxygen atom of water was assumed to approach from directly above a carbonyl carbon. The molecular plane of water was followed to rotate clockwise (θ) around an axis which passes through the water oxygen and is parallel to the X axis. Another (clockwise) rotational axis (ϕ) is also considered, which passes through both water oxygen and one of the carbonyl carbon atom and is parallel to the Z axis.

Results and Discussion

We first consider approach of water molecule to C_1 and C_2 respectively at varying intermolecular distance z along ϕ -axis with ϕ fixed to 0°. Tables 1 and 2 summarize the results for the σ - ($\theta=90^\circ$) and π - ($\theta=0^\circ$) approach models.⁷ It is quite clear from these tables that the attack of a water is favored on the protonated carbonyl carbon C_1 over the attack on the unprotonated carbonyl carbon C_2 . Furthermore as the intermolecular distance decreases the C_1 -attack tends to be stabilized more relative to the C_2 -attack.

Comparison of the total stabilization energies in Table 1 with those in Table 2 reveals that the σ -approach is much more preferred to the π -approach, although in both models the main contributing term to the total stabilization energy is

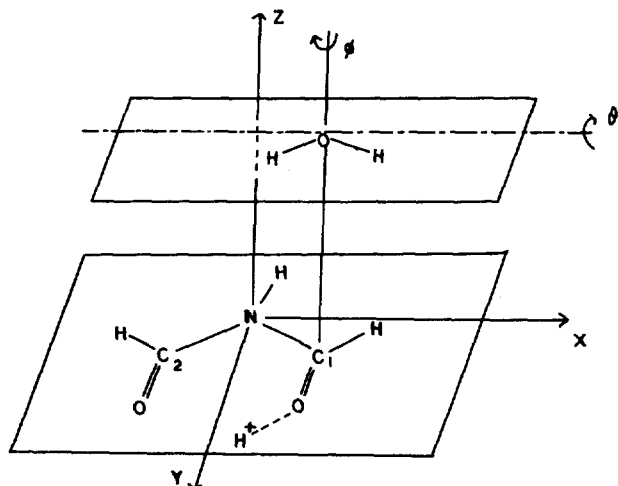


Figure 1. Coordinate axes for the interacting system. The spatial arrangement corresponds to the π -approach ($\theta=0^\circ$ and $\phi=0^\circ$) to C_1 .

the Coulomb term E_q . Figure 3 shows the variations in various types of interaction energies with the intermolecular distance for the π -approach to C_1 . It can be seen in this figure that the total interaction energy E_{tot} is determined almost exclusively by E_q , while the small stabilizing contribution from E_{ct} , E_i and E_d are nearly cancelled by the destabilizing contribution from E_k ; all the contributions increase however as the distance decreases.

TABLE 1: Interaction Energies for σ -Approach ($\phi=0^\circ$ and $\theta=90^\circ$) of H_2O Molecule Toward Protonated Diformamide at Varying Distances, in kcal/mol

Carbon atom	Energy	3 Å	4 Å	5 Å
C_1	E_q	-4.328	-2.708	-1.852
	E_k	0.233	0.003	0.000
	E_i	-0.483	-0.193	-0.093
	E_d	-0.112	-0.025	-0.008
	E_{ct}	-0.501	-0.005	0.000
	E_{tot}	-5.191	-2.928	-1.953
C_2	E_q	-3.436	-2.310	-1.671
	E_k	0.235	0.003	0.000
	E_i	-0.350	-0.156	-0.078
	E_d	-0.106	-0.024	-0.007
	E_{ct}	-0.302	-0.003	0.000
	E_{tot}	-3.959	-2.490	-1.756

TABLE 2: Interaction Energies for π -Approach ($\phi=0^\circ$ and $\theta=0^\circ$) of H_2O Molecule Toward Protonated Diformamide at Varying Distances, in kcal/mol

Carbon atom	Energy	3 Å	4 Å	5 Å
C_1	E_q	-1.303	-0.611	-0.348
	E_k	0.459	0.008	0.000
	E_i	-0.067	-0.019	-0.007
	E_d	-0.173	-0.044	-0.014
	E_{ct}	-0.672	-0.012	0.000
	E_{tot}	-1.756	-0.678	-0.369
C_2	E_q	-1.087	-0.525	-0.318
	E_k	0.455	0.008	0.000
	E_i	-0.134	-0.042	-0.015
	E_d	-0.174	-0.044	-0.014
	E_{ct}	-0.418	-0.008	0.000
	E_{tot}	-1.358	-0.611	-0.347

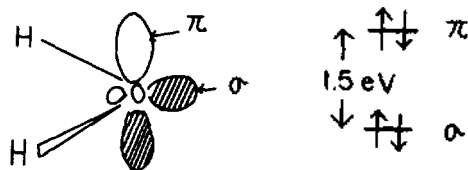


Figure 2. Energetically nonequivalent lone-pair orbitals in H_2O .

The percentage contributions of various energy terms to the total energy are summarized in Table 3. It is to be noted from this table that the contribution of E_q is larger in the σ -approach than that in the π -approach, whereas the relative stabilizing contribution of E_{ct} and destabilizing contribution of

E_k are larger in the π -approach as compared with those in the σ -approach. These are compatible with the generally accepted notion that the σ lone-pair orbital on oxygen has a considerable amount of s character and is more tightly bound, while the π lone-pair orbital is the one from which electrons are most easily ionized and therefore is the one from which donation is most likely to occur.⁸

Net charges of C_1 and C_2 were +0.451 and +0.378 and the AO coefficients of the π -LUMO were 0.793 and 0.253 respectively. As we have shown previously³ these can be interpreted as increase in both charge-controlled and orbital-controlled S_N reactivities⁹ of the protonated carbonyl carbon atom. In this case the reaction will be a charge-controlled one since the contribution of E_q to the total stabilization energy is much greater than that of E_{ct} . This is in good accord with the prediction based on the HSAB principle (Table 4)¹⁰; carbonyl carbon and water are known to belong to the hard acid and hard base categories respectively¹⁰.

In the qualitative approach to the intermolecular interaction, the charge-transfer term E_{ct} is approximated as¹¹

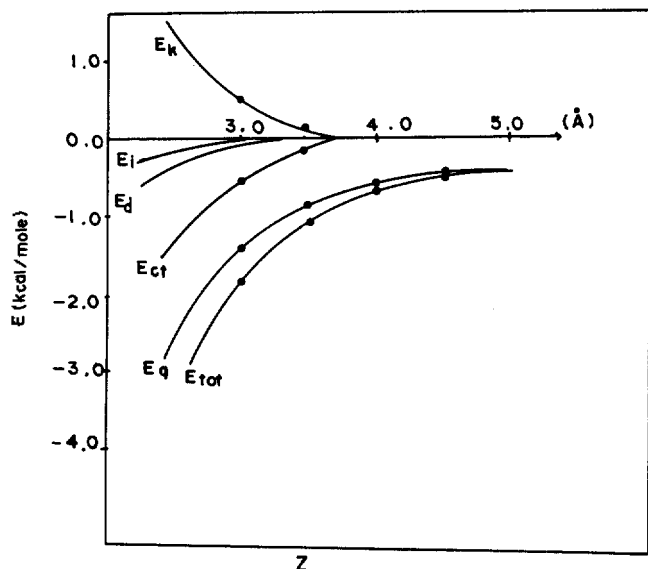


Figure 3. Variations in various types of interaction energies with the intermolecular distance, z , for C_1 - π -approach.

TABLE 3: Percentage Contributions of Various Interaction Energies to the Total Energy, E_{tot} at $z = 3.0 \text{ \AA}$ and $\phi = 0^\circ$

Energy (%)	C_1		C_2	
	σ	π	σ	π
E_q	83.4	74.1	86.7	80.1
E_k	-4.5	-26.1	-5.9	-33.5
E_i	9.3	3.8	8.9	9.8
E_d	2.1	9.8	2.7	12.8
E_{ct}	9.6	38.4	7.6	30.8

TABLE 4: Classification of Reaction Types According to MO and HSAB Languages

MO (dominant term)	Classification of Reaction	
	Orbital-controlled (E_{ct})	Charge-controlled (E_q)
HSAB	Soft-soft	Hard-hard

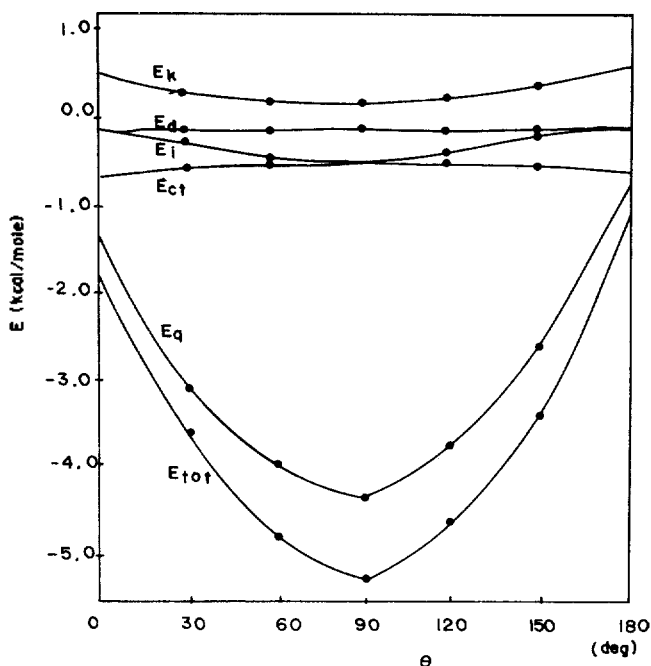


Figure 4. Angular dependence of various interaction energies at $z = 3.0 \text{ \AA}$ and $\phi = 0^\circ$

TABLE 5: Various Interaction Energies as a Function of ϕ at $z = 3.0 \text{ \AA}$ and $\theta = 90^\circ$ (C_1 -approach)

$E(\text{kcal/mol})$	ϕ°					
	0	30	60	90	120	150
E_q	-4.328	-4.316	-4.325	-4.347	-4.352	-4.343
E_k	0.233	0.232	0.228	0.225	0.229	0.232
E_i	-0.483	-0.482	-0.481	-0.479	-0.477	-0.482
E_d	-0.112	-0.118	-0.126	-0.129	-0.123	-0.114
E_{ct}	-0.501	-0.499	-0.499	-0.503	-0.501	-0.501
E_{tot}	-5.191	-5.184	-5.203	-5.234	-5.226	-5.208

$$E_{ct} \cong \frac{2H^2}{E_{HO} - E_{LU}}$$

where E_{HO} and E_{LU} are the energies of the highest occupied (HO) donor and the lowest unoccupied (LU) acceptor orbitals respectively, and H is the interaction matrix element between the two orbitals. Of the two nonbonding orbitals of water the π lone-pair orbital n_π is 1.5 eV above the σ lone-pair orbital n_σ .¹² The energy gap in Eq. 2 will therefore be smaller and hence E_{ct} larger for the π -approach ($HO = n_\pi$) compared with those for the σ -approach ($HO = n_\sigma$). This qualitative result is confirmed by our calculations; the stabilizing contribution of E_{ct} term is larger in the π -approach model (Table 2) as compared with that in the σ -approach model (Table 1.)

The addition of water ($\overset{H}{\text{H}} > \text{O}$) to carbonyl system ($> \text{C} = \text{O}$) might appear quite similar to the addition of singlet methylene ($\overset{H}{\text{H}} > \text{C}$) to ethylene ($> \text{C} = \text{C} <$),^{4b} but in fact the two cases form a striking contrast to each other: firstly in the former water plays a role of electron-pair donor and carbonyl carbon an acceptor, whereas in the latter methylene plays a role of electron-pair acceptor and ethylene a donor; secondly in the former the reaction is charge-controlled (E_q dominant and a hard-hard type), whereas in the latter the reaction is orbital controlled (E_{ct} dominated, a soft-soft type); thirdly in the former the σ -approach is favored, whereas in the latter the π -approach is favored.

Next we calculated angular (θ and ϕ) dependences of various interaction energies at a fixed distance of $z = 3.0 \text{ \AA}$. Figure 4 shows the variation of interaction energies as a function of θ for $\phi = 0^\circ$. The minimum at $\theta = 90^\circ$ corresponds to the σ -approach model. This figure again demonstrates the dominant stabilizing contribution of E_q and the relatively unimportant contributions of the rest. The curves are not exactly symmetric along a vertical axis through the E_{tot} minimum; the two π -approach models, *i.e.*, with $\theta = 0^\circ$ and $\theta = 180^\circ$, are not equivalent, the former being slightly favored. We have then varied the angle ϕ at C_1 for fixed values of $\theta = 90^\circ$ (σ -approach) and $z = 3.0 \text{ \AA}$. The results are in Table 5, which shows that the changes in interaction energies as a function of ϕ are small and insignificant. A shallow minimum at $\phi = 90^\circ$ is barely noticeable.

We thus conclude that the σ -approach model with $\phi = 90^\circ$

can be regarded as a useful approximation to the transition state for the acid-catalyzed hydrolysis of diacylamines.

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