4. N. N. Lebedev and M. M. Smirnova, Kinet. Kat., 6, 457 (1965).
5. J. T. Smith, Polymer, 2, 95 (1961).
6. Kh. A. Arutyunyan, E. A. Dzhavadyan, A. O. Topoyan, S. P. Davtyan, B. A. Rozenberg, and N. S. Enikolopyan, Zh. Fiz. Khim., 50, 2016 (1976).
7. S. Scheiner and L. B. Harding, J. Phys. Chem., 87, 1145 (1983).
8. W. A. Lathan, L. Radom, P. C. Hariharan, W. J. Hehre, and J. A. Pople, Top. Curr. Chem., 40, 1 (1973).
9. R. H. Nobes, W. R. Rodwell, W. J. Bouma, and L. Radom, J. Am. Chem. Soc., 103, 1913 (1981).
10. T. J. Zielinsky, D. L. Breen, and R. Rein, J. Am. Chem. Soc., 100, 6266 (1978).
11. D. H. Aue, H. M. Webb, and M. T.Bowers, J. Am. Chem. Soc., 98, 318 (1976).
12. A. Gordon and R. Ford, Chemist's Companion, Wiley-Interscience (1973).
13. S. Scheiner, J. Am. Chem. Soc., 103, 315 (1981).
14. W. J. Hehre, W. A. Lathan, R. Dietchfield, M. D. Newton, and J. A. Pople, QCPE, Catalogn 11, Program 236 (1973).

MECHANISM OF AMINATION OF AZIRIDINES AND OXIRANES.

4.* QUANTUM-CHEMICAL INVESTIGATION OF THE EFFECT OF THE POLAR SOLVENT

S. G. Koldobskii, G. F. Tereshchenko,
V. A. Bobylev, and A. R. Dalin

UDC 547.717:541.124'12.038.2

The effect of nonspecific solvation on the mechanism of the amination of three-membered rings was investigated by the MINDO/3 quantum-chemical method and by the solvaton model.

The energy of nonspecific solvation is determined primarily by electrostatic interactions between the self and induced charges of the solvate and the solvent. Interactions of this type can be calculated by means of the solvation model of Germer [2], in which the solvent is modelled by a set of point charges (solvatons) surrounding the dissolved molecule, and it is assumed that each atomic center of the molecule induces one solvaton with a charge having a sign opposite to the charge of the atom. We used the version of the solvaton model proposed in [3]. This model, realized within the framework of the CNDO/2 method, was calibrated for a set of neutral and positively charged molecules similar in structure to the calculated systems (see the computation procedure section). Since the protonated aziridine–ammonia (I) and ethylene oxide – ammonium ion (II) complexes are some of the most likely participants in amination reactions, calculation of the energy parameters of the reactions of these associates with ammonia (1,2) with allowance for electrostatic solvation makes it possible at a qualitative level to study the effect of both general and specific solvation effects.

$$\mathrm{I} + NH_3 \xrightarrow{-NH_3} NH_2CH_2CH_2NH_3^+ \quad (1)$$

$$\mathrm{II} + NH_3 \xrightarrow{-NH_3} HOCH_2CH_2NH_3^+ \quad (2)$$

Here the specific solvation is taken into account by MINDO/3 calculation in the supermolecule approach through inclusion of the solvent molecule in the reaction system, and the heats of interaction of the solvate with the polar solvent medium are calculated by means

---

*For Communication 3, see [1].

State Institute of Applied Chemistry, Leningrad. Translated from Khimiya Geterotsiklicheskikh Soedinenii, No. 8, pp. 1042-1047, August, 1986. Original article submitted June 4, 1985.

TABLE 1. The Energy Characteristics of Reactions (1-8) in the Gas Phase and in Solution, Determined by the MINDO/3 Method and the Solvaton Model [2]

Reaction	E_a, kJ/mole	ΔH_C, kJ/mole	E_a^p, kJ/mole
1	87,5 [5, 6]	5,4	93,0
2	72,0 [5, 6]	0,8	72,9
3	198,9 [5, 6]	−116,4	82,5
4	167,9 [5, 6]	−141,1	26,8
5	66,2* [5, 6]	13,4	79,6
	130,2† [5, 6]	3,8	134,0
6	34,8* [1]	−8,0	26,8
	100,5†	23,9	124,4
7	188,8	−56,5	132,3
8	138,6	−46,5	92,1

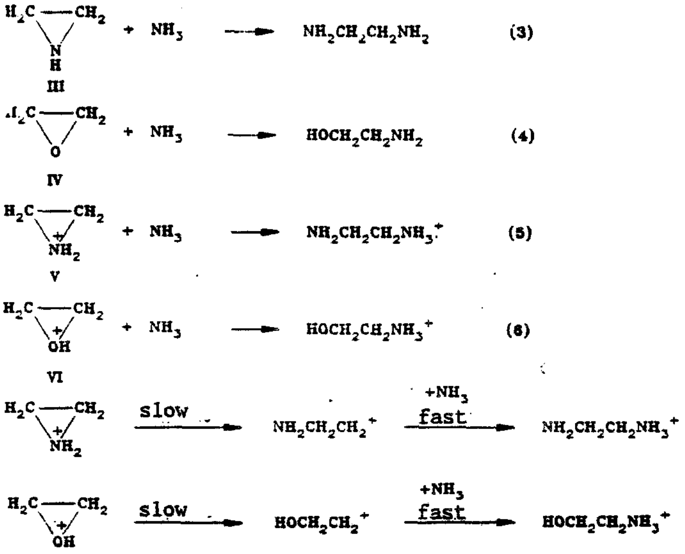
---

*Rear nucleophilic attack.

†Frontal nucleophilic attack.

of the solvaton model. The potential barrier for the liquid-phase reaction (E_a^r) is determined as the sum of the potential barrier in the gas phase and the ΔH_C value (the difference between the calculated heats of solvation of the transition state and the reagents). During the calculations it was assumed that the structures of the stable compounds and transition states do not change in the transition from the gas phase to the solution. Published data [4] indicate that this assumption is valid on the whole for reactions (1) and (2). From Table 1 it is seen that electrostatic solvation retards reactions (1) and (2) little. According to the obtained results, specific interactions with the protic solvent have a larger effect on the rate of the acid-catalyzed amination reactions than the polar medium. The obtained values for the potential barriers (93.0 and 72.9 kJ/mole) are close to the experimental activation energies of the single kinetically investigated reaction of aziridine with a nitrogen-containing nucleophile, i.e., the polymerization of aziridine (62.8 - 81.6 kJ/mole [7]) and the reaction of ethylene oxide with ammonia in aqueous solution (61.1 kJ/mole [8]).

The solvaton model was also used to investigate the effect of a polar solvent on the ratio between the various mechanisms of the amination reactions. The following were considered: 1) Reactions (3) and (4), which model the amination processes in the absence of acid catalysis; 2) reactions which model the nucleophilic opening of the rings under the conditions of catalysis by acids and take place both by a bimolecular A2 mechanism (5, 6) and by a monomolecular A1 mechanism (7, 8).



For reactions (5) and (6) we considered the cases where the ammonia approaches the substrate from the side of the C–C (rear nucleophilic attack) and from the side of the carbon–heteroatom (frontal nucleophilic attack) bonds. The characteristics of the transition states for the majority of the reactions listed above in the gas phase had been calculated before [1, 5, 6]. The results from MINDO/3 calculations for the gas-phase reactions (6) (for the case of frontal nucleophilic attack), (7), and (8) are given in the present work.

The structural parameters of the transition state (VII) corresponding to frontal addition of ammonia to the molecule of the protonated oxirane are given in Fig. 1. Its characteristics are similar to the data obtained for the corresponding reaction with protonated aziridine. The potential barrier in this case is also appreciably higher than for rear addition (Table 1).

During investigation of the gas-phase reactions (7) and (8) we considered the possible products from monomolecular opening of the protonated rings. The MINDO/3 calculation revealed two stable conformers $NH_2CH_2CH_2^+$ (VIII, IX) and one conformer $HOCH_2CH_2^+$ (X) (Fig. 2). The geometric parameters of conformer (X) were close to the data from nonempirical calculation on the 4-31G basis set [9]. At the same time calculation of the characteristics of the $NH_2CH_2CH_2^+$ cation in this basis set [10] indicated the presence of only one conformer with a structure intermediate between structures (VIII, IX). The procedure for the calculations in the reaction coordinate mode was unsuitable for determination of the saddle points in reactions (7, 8). To determine the structural and energy characteristics of the transition states for these processes we therefore made the assumption that all the geometric parameters of the reaction systems vary synchronously on the reaction path in the transition from the initial to the final compounds. According to this scheme, the transition states correspond to degrees of transformation where the curve for the dependence of the energy of the system on the degree of transformation passes through a maximum. (In the course of the reaction α changes from 0 to 1). The method is quite suitable for the production of qualitatively correct conclusions and has been used successfully for the solution of analogous problems in nonempirical calculations [9, 10]. During determination of the characteristics of the transition state (XI) for the controlling stage of reaction (7) it was assumed that its product is the conformer (IX). (The choice is substantiated in the computation procedure section). The structure (XI) is close to structure (IX) (α = 0.85). The transition state (XII) in reaction (8) is significantly less product-like (α = 0.65).

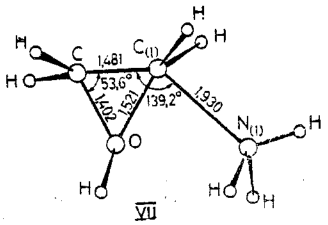
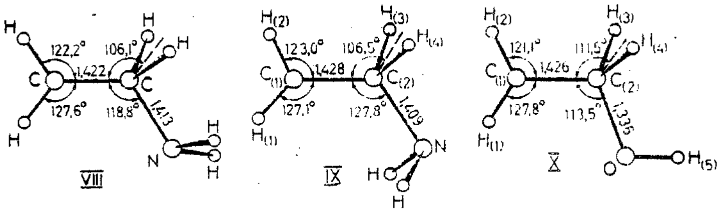


Fig. 1. The geometric structure of the transition state in reaction (6) (frontal nucleophilic attack), determined by the MINDO/3 method. Here and subsequently the numbers along the bonds are the bond lengths (Å).



a b

Fig. 2. The structures of the conformers, determined by the MINDO/3 method: a) $NH_2CH_2CH_2^+$; b) $HOCH_2CH_2^+$.

TABLE 2.

Structure	ΔH_f, kJ/mole
VII	676,6
VIII	893,1
IX	893,9
X	716,0
XI	901,0
XII	754,1

TABLE 3. Comparison of the Calculated and Experimental Heats of Solvation of the Molecules

Molecule	ΔH_f*	$-H_{solv}$, kJ/mole					
		calculation, r, Å					experiment†
		r 0,8	r 1,0	r 1,2	r 1,4	r 1,6	
NH_3	−39,4	−27,2	17,6	20,1	16,3	12,6	35,2
NH_4^+	644,4	452,2	386,5	334,1	296,0	267,5	351,7
$(CH_3)_2NH$	16,3	276,8	100,9	46,1	25,1	15,9	53,2
$(CH_3)_2NH_2^+$	671,6	448,0	326,2	268,8	236,6	215,6	291,8

---

*Calculated by the MINDO/3 method.
†Heats of hydration [15].

TABLE 4.

Structure	$-H_{solv}$, kJ/mole	Structure	$-H_{solv}$, kJ/mole
I	288,9	XII	367,2
II	337,5	XIII	303,6
III	22,6	XIV	356,7
IV	44,4	XV	159,1
V	283,9	XVI	205,6
VI	307,3	XVII	289,0
VII	317,0	XVIII	298,5
XI	338,7	XIX	335,4

The heats of electrostatic solvation of the reagents and the transition states for reactions (3-8) were calculated by the solvaton method. The results from the calculations (Table 1) make it possible to conclude that the effects of the polar solvents on the acid-catalyzed bimolecular reaction of the rings with the ammonia, on the one hand, and on the reactions taking place without catalysis, on the other, are qualitatively different in character. The solvent significantly stabilizes the highly polar transition states in reactions (3, 4) and changes the energy characteristics of the catalytic processes (5, 6) fairly little. The values obtained for the potential barriers of the liquid-phase reactions with unprotonated aziridines and ethylene oxide are undoubtedly low. This result can be explained both by the characteristics of the Germer model, which is insufficiently reliable for the calculation of solvation in uncharged systems, and by the fact that the MINDO/3 calculations could give values too low for the activation energies of the gaseous reactions. It is clear, however, that the solvaton model describes the effect of the polar solvent on the processes correctly in qualitative respects. According to the calculated data, the potential barriers of the uncatalyzed reactions in the gas phase are approximately 100-130 kJ/mole higher than for reactions (5, 6), which take place with inversion of the configuration, i.e., the gas-phase reactions (3, 4) must be practically unobservable. At the same time the reaction of substituted oxiranes with amines in the absence of acid catalysis in solution was investigated experimentally [11]. This showed a marked reduction of the break in rates between the catalyzed and uncatalyzed reactions in the transition from the gas phase to the solution, and this is fully consistent with the results from the present work. The calculated difference between the potential barriers of reactions (3) and (4) in the liquid phase (55 kJ/mole) is very large. Thus, according to the calculated data, the reactivity of the unprotonated aziridine is significantly lower than that of ethylene oxide. This result is consistent with the experimental data; the reaction of aziridine with ammonia hardly takes place at all without catalysis [12].

It is known that in some cases acid-catalyzed amination reactions take place with partial retention of the configuration at the reaction center [12, 13]. This is usually explained by a contribution from the A1 mechanism. In fact, according to the data in Table 1, electrostatic solvation appreciably accelerates reactions (7, 8). It seems to us that the retention of the configuration may be due also to the realization of frontal addition of the nucleophile by the A2 mechanism. The values obtained for the potential barriers of the liquid-phase reactions with frontal attack are approximately the same as the barriers in reactions (7, 8). It should also be borne in mind that the present calculation does not take account of specific solvation effects, which may be extremely significant for the given processes. The possibility that bimolecular reactions with retention of the configuration do take place in certain cases must not, therefore, be ruled out.

COMPUTATION PROCEDURES

The MINDO/3 calculations were made with full optimization of all the geometric parameters of the systems. The search for the saddle points on the potential energy surface for the reaction (6) was made in the reaction coordinate mode. The condition for localization of the saddle point was reversion to zero in the standard gradient of the potential energy function of the system and change in the sign of the component of the gradient along the reaction coordinate during passage through this point. As reaction coordinate we used the $C_{(1)}N_{(1)}$ distance. The obtained structure (VII) was identified as the transition state. (The Hessian for this structure had one negative eigenvalue). We used the program written by V. A. Pichko (of Rostov State University) for the identification of the transition states.

For the $NH_2CH_2CH_2^+$ cation we found two conformers (VIII, IX) (Fig. 2a). The MINDO/3 calculation of the transformation of the conformer (VIII) into the protonated aziridine [14] showed the presence of a fairly significant potential barrier (38 kJ/mole). This result does not agree well with the data from ab initio calculation [10], according to which the activation barrier amounts to about 10 kJ/mole, while the structure of the transition state is close to the structure of the open $NH_2CH_2CH_2^+$ cation. In the present work we considered the reaction of conformer (IX) [the reverse of reaction (7)], the heat of formation of which is only 0.8 kJ/mole higher than the heat of formation of structure (VIII). The value obtained for the potential barrier (7.1 kJ/mole) was appreciably lower than for the reaction involving the conformer (VIII). The enthalpy of formation (ΔH_f) of the systems examined in the present work, calculated by the MINDO/3 method, are given in Table 2.

For the calculations by means of the solvaton model [3] it was necessary to select a value for the parameter r (the distance between the solvaton and the atom to which it "belongs"). The heats of solvation were calculated for a set of neutral and positively charged molecules structurally similar to the investigated systems. If $r = 1.2$ Å (Table 3), the calculated heats of solvation (H_{solv}) are close to the experimental values, and we therefore used this value for r in the subsequent calculations. The heats of electrostatic solvation were calculated by means of the structural parameters of the systems, determined by the MINDO/3 method. The obtained H_{solv} values are given in Table 4. [The numbers (XIII-XIX) correspond to the transition states in reactions (1-4) and (5) for rear and frontal nucleophilic attack and (6) for rear nucleophilic attack.]

The authors are grateful to M. V. Bazilevskii, I. A. Abronin and L. G. Gorb for discussion of the results.

LITERATURE CITED

1. S. G. Koldobskii, G. F. Tereshchenko, V. A. Bobylev, and A. R. Dalín, Khim. Geterotsikl. Soedin., No. 8, 1036 (1986).
2. H. A. Germer, Theor. Chim. Acta, 34, 145 (1974).
3. L. G. Gorb, I. A. Abronin, N. V. Kharchevnikova, and G. M. Zhidomirov, Zh. Fiz. Khim., 58, 9 (1984).

4. K. C. Westaway, Can. J. Chem., 56, 2691 (1978).
5. S. G. Koldobskii, V. A. Bobylev, G. F. Tereshchenko, and Yu. V. Puzanov, Zh. Obshch. Khim., 53, 2356 (1983).
6. A. Yu. Shibaev, N. V. Astrat'eva, and G. F. Tereshchenko, Zh. Obshch. Khim., 54, 2744 (1984).
7. D. S. Zhuk, Paper deposited at VINITI, No. 709-81 Dep.
8. P. Ferrero, F. Berbe, and I. R. Flamme, Bull. Soc. Chim. Belg., 56, 349 (1947).
9. A. C. Hopkinson, M. H. Lien, I. G. Crizmadia, and K. Yates, Theor. Chim. Acta, 47, 97 (1978).
10. A. C. Hopkinson, M. H. Lien, I. G. Crizmadia, and K. Yates, Theor. Chim. Acta, 55, 1 (1980).
11. Kh. A. Arutyunyan, A. O. Topoyan, S. P. Davtyan, and N. S. Enikolopyan, Dokl. Akad. Nauk SSSR, 214, 832 (1974).
12. P. A. Gembitskii, D. S. Zhuk, and V. A. Kargin, Chemistry of Ethylene Imine [in Russian], Nauka, Moscow (1966), p.256.
13. R. Ghirardelli and H. J. Lucas, J. Am. Chem. Soc., 79, 734 (1957).
14. L. M. Timofeeva and V. G. Avakyan, Izv. Akad. Nauk SSSR, Ser. Khim., 1557 (1980).
15. D. H. Aue, H. M. Webb, and M. T. Bowers, J. Am. Chem. Soc., 98, 318 (1976).

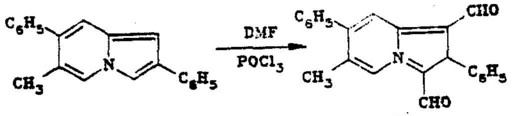
CRYSTAL AND MOLECULAR STRUCTURE OF 6-METHYL-2,7-DIPHENYL-1,3-DIFORMYLINDOLIZINE

D. S. Yufit, Yu. T. Struchkov,
N. S. Prostakov, and V. I. Kuznetsov

UDC 548.737:547.759.1

An x-ray crystallographic investigation was made of 6-methyl-2,7-diphenyl-1,3-diformylindolizine, obtained by the formylation of 6-methyl-2,7-diphenylindolizine. The effect of various carbonyl-containing substituents at positions 1 and 3 on the geometry of the indolizine ring in the structually investigated indolizine derivatives is discussed.

6-Methyl-2,7-diphenyl-1,3-diformylindolizine (I) was obtained by the formylation of 6-methyl-2,7-diphenylindolizine by the Vilsmeier reaction.



I

In view of the electrophilic character of this reaction it could be expected that formylation would take place at positions 1 and 3 of the indolizine ring. In order to obtain conclusive evidence for the structure of (I) we undertook its x-ray crystallographic investigation.

The general appearance of the molecule of (I), the numbering of the atoms, the bond lengths, and the bond angles are shown in Fig. 1. The five- and six-membered rings of the indolizine system in the molecule of (I) are planar within the limits of 0.012(8) and 0.025 (8) Å respectively. The dihedral angle between the planes of the rings is 3.5°, while the maximum deviation of the atoms from the mean-square plane of the whole bicyclic system amounts to only 0.051 (8) Å (for the $C_{(6)}$ atom). Subsequently, therefore, we will consider the orientation of the substituents in relation to this plane, drawn through all the indolizine rings as a whole.

A. N. Nesmeyanov Institute of Heteroorganic Compounds, Moscow. Translated from Khimiya Geterotsiklicheskikh Soedinenii, No. 8, pp. 1048-1051, August, 1986. Original article submitted April 15, 1985.