518 Russian Chemical Bulletin, International Edition, Vol. 61, No. 3, pp. 518—527, March, 2012

Mechanism of urethane formation from cyclocarbonates and amines: a quantum chemical study

M. V. Zabalov, R. P. Tiger, and A. A. Berlin*

N. N. Semenov Institute of Chemical Physics, Russian Academy of Sciences,
4 ul. Kosygina, 119991 Moscow, Russian Federation.
Fax: +7 (499) 137 8247. E-mail: zabalov@chph.ras.ru

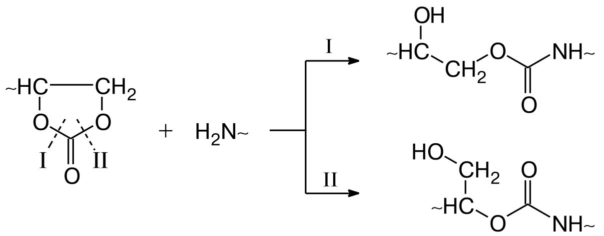
The mechanism of the reaction of cyclic esters with amines, providing non-isocyanate urethanes, was studied in terms of DFT by the PBE/TZ2P method using as examples the reactions of ethylene carbonate and propylene carbonate with methylamine. The reaction can proceed through the one- or multistage path involving one or two amine molecules. The second amine molecule plays the role of the catalyst of the process, resulting in a substantial decrease in the activation energy of the reaction.

Key words: aminolysis, cyclocarbonate, polyurethane, DFT, PBE functional, ester, reaction mechanism.

Industrial synthesis of polyurethanes is based on the reaction of di- or polyisocyanates with di- or polyols.[1] In turn, isocyanates are synthesized by the phosgenation of primary amines. The production of polyurethanes is not irreproachable from the ecological point of view, and alternative routes for synthesis of both polyurethanes and isocyanates are being developed in recent years.[2]

Among few reactions that can form a basis for the development of non-isocyanate polyurethanes, the reaction of primary amines with cyclocarbonates is very promising. Oligomers with cyclocarbonate groups are synthesized from epoxide or hydroxyl-containing oligomers.[3] The reaction of cyclocarbonate groups with amines (Scheme 1) affords polyurethanes containing hydroxyl groups, which provides routes for the corresponding modification of these polymers. In addition, the primary and secondary hydroxyl groups at the urethane group favors an enhancement of the hydrolytic stability of polyurethanes due to intra- and intermolecular hydrogen bonds.[4]

Scheme 1



The reaction of cyclocarbonate ring opening under the action of primary amines with the formation of hydroxyurethanes was not earlier studied by quantum chemical methods. There are no literature data on the detailed mechanism of this process. A few kinetic data[5,6] indicate the first order of the reaction with respect to reactants at their equimolar ratio and the second order with respect to amine in an excess of the latter. This indirectly indicates the possible participation of the second amine molecule in the reaction; however, its role was not exactly established.

In the present work, we studied the mechanism of addition of the amino group to the cyclocarbonate group in terms of the DFT method using the reactions of ethylene carbonate (**1**) and propylene carbonate with methylamine as examples.

Calculation Methods

Calculations were performed in terms of DFT using the nonempirically generalized gradient approximation and the PBE functional[7,8] in the TZ2P basis set by the PRIRODA program.[9,10] Geometry optimization was carried out for all starting reactants, stable intermediates, and transition states. The character of the found stationary points (a minimum or a saddle point on the potential energy surface (PES)) were determined by the calculation of the eigenvalues of the matrix of the secondary energy derivatives with respect to the nuclear coordinates. Belonging of transition states to transformation under consideration was established by the calculations of the reaction coordinate. Corrections to zero-point energy vibrations were introduced to refine relative energies.

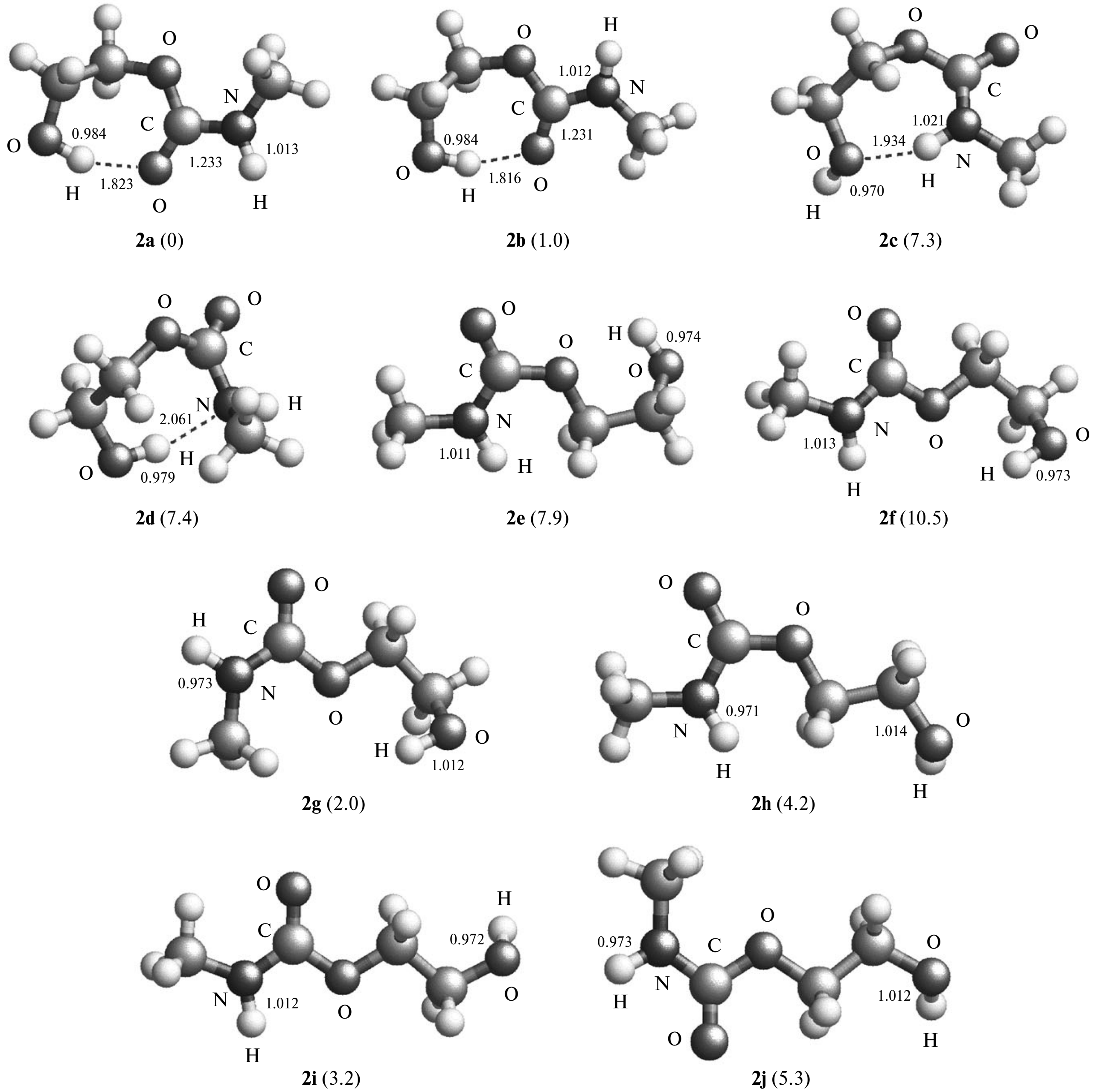
Results and Discussion

Analysis of the addition products of methylamine to cyclocarbonates. The addition product of methylamine to

Published in Russian in *Izvestiya Akademii Nauk. Seriya Khimicheskaya,* No. 3, pp. 518—526, March, 2012.

cyclocarbonate can exist as numerous conformers and isomers with the intramolecular hydrogen bond. We searched for all possible stable structures to determine the most stable conformer corresponding to the global minimum on the PES and to calculate the enthalpy of the reaction. Ten minima corresponding to four cyclic isomers **2a**—**d** with the intramolecular hydrogen bond and six open conformers **2e**—**j** were found (Fig. 1).

Cyclic isomer **2a** with the hydrogen bond at the carbonyl O atom turned out to be the most stable. Due to the H...O=C hydrogen bond (l = 1.82 Å), the O—H bond is elongated by ~10%. Isomer **2b** differs from analog **2a** only by the arrangement of substituents at the N atom relative to the rest part of the molecule (hindered rotation of the NHMe group). The difference in energies of isomers **2a** and **2b** is only 1 kcal mol^{-1}. Other isomers with hydrogen bonds at the N atom (**2c**,**d**) and noncyclic conformers without hydrogen bonds (**2e**—**j**) are less stable. One of the noncyclic products (**2g**) is only 2 kcal mol^{-1} less stable than compound **2a**; *i.e.*, hydrogen bonding is not the main



2a (0) **2b** (1.0) **2c** (7.3)

2d (7.4) **2e** (7.9) **2f** (10.5)

2g (2.0) **2h** (4.2)

2i (3.2) **2j** (5.3)

Fig. 1. Structures of the conformers and isomers by hydrogen bonds of the addition products of methylamine to ethylene carbonate. Here and in Figs 2, 3, 5—8, and 10, the relative energies of molecular species are given in kcal mol^{-1} in parentheses. The absolute energies (au) for structure **2a**, methylamine, and ethylene carbonate are –437.961974, –342.168688, and –95.769226, respectively.

stabilizing factor. As can be seen from Fig. 1, the scatter of energies of the conformers is rather large: up to 10.5 kcal mol^{-1}.

The enthalpy of the reaction (ΔH) calculated taking into account the difference in the energies of the starting reactants and product **2a** corresponding to the global minimum on the PES was −15.1 kcal mol^{-1}.

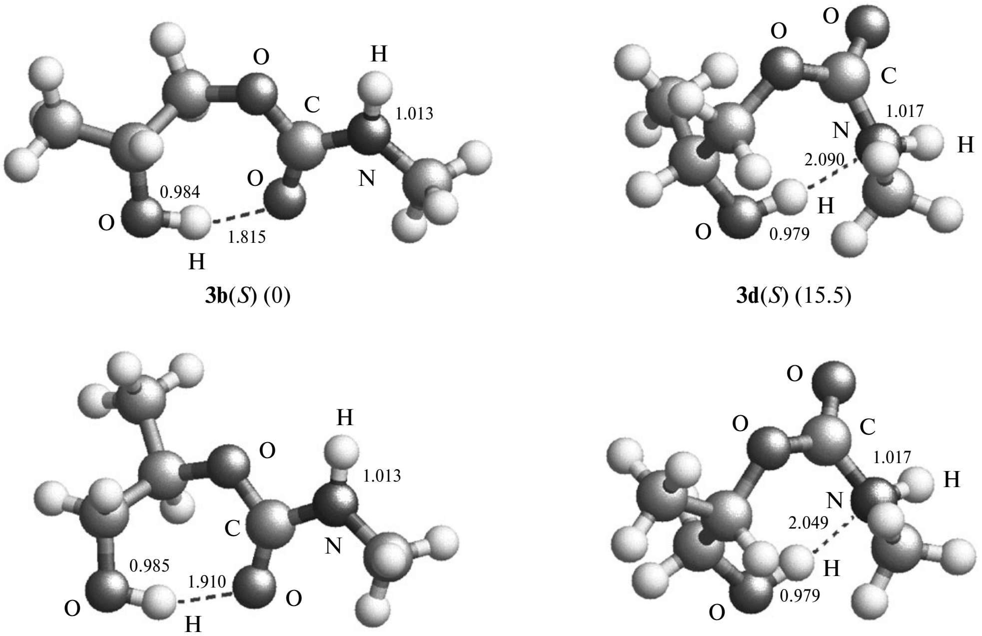
Analogous search for all possible conformers was carried out for the reaction product of propylene carbonate. Since two hydroxyurethanes (with the primary and secondary hydroxyl groups) can be formed and stereoisomerism is possible for each of them, the number of conformers/isomers increased to 40. The energy distribution of the conformers (Table 1) turned out to be the same as for the products of the reaction involving ethylene carbonate (**1**): the most stable conformers had the hydrogen bond at the carbonyl O atom (**3b**(*S*), **4b**(*R*)), and the most unstable conformers had the hydrogen bond at the amide N atom (**3d**(*S*), **4d**(*S*)) (Fig. 2). As can be seen from the data in Table 1, the differences in energies of the conformers are fairly high, and the maximum differences observed are 15.5 and 14.5 kcal mol^{-1} for the products with the secondary and primary hydroxyl group, respectively.

Table 1. Relative energies of isomers and conformers of the products of the reaction of propylene carbonate with methylamine*

Product	ΔE /kcal mol^{-1}	Product	ΔE /kcal mol^{-1}
3a(*S*)	1.0	**4a**(*S*)	2.0
3a(*R*)	1.7	**4a**(*R*)	1.0
3b(*S*)	0	**4b**(*S*)	1.0
3b(*R*)	0.7	**4b**(*R*)	0
3c(*S*)	7.1	**4c**(*S*)	7.1
3c(*R*)	7.3	**4c**(*R*)	10.5
3d(*S*)	15.5	**4d**(*S*)	14.5
3d(*R*)	14.7	**4d**(*R*)	3.2
3e(*S*)	7.2	**4e**(*S*)	8.8
3e(*R*)	8.3	**4e**(*R*)	8.4
3f(*S*)	3.8	**4f**(*S*)	3.8
3f(*R*)	3.7	**4f**(*R*)	3.3
3g(*S*)	1.6	**4g**(*S*)	2.0
3g(*R*)	2.8	**4g**(*R*)	1.7
3h(*S*)	9.8	**4h**(*S*)	11.1
3h(*R*)	9.7	**4h**(*R*)	11.4
3i(*S*)	4.0	**4i**(*S*)	3.2
3i(*R*)	4.0	**4i**(*R*)	3.0
3j(*S*)	5.0	**4j**(*S*)	5.0
3j(*R*)	4.9	**4j**(*R*)	4.6

* For propylene carbonate, the total energy is $E = -381.448080$ au.

The enthalpies of the reactions are only slightly lower than that of the reaction of ethylene carbonate, being −14.0 and −13.5 kcal mol^{-1} for the products with the secondary and primary hydroxyl group, respectively. The difference in energies of the stereoisomers (*R*/*S*) is insubstantial and, hence, our further attention will not be concentrated on stereoisomerism (the difference in energies of the corresponding isomers *R* and *S* is ≤1 kcal mol^{-1}). It is important that the difference in energies of the most stable con-



3b(*S*) (0) **3d**(*S*) (15.5)

4b(*R*) (0) **4d**(*S*) (14.5)

Fig. 2. Structures of the most and least stable isomers by hydrogen bonds of the addition products of methylamine to propylene carbonate.

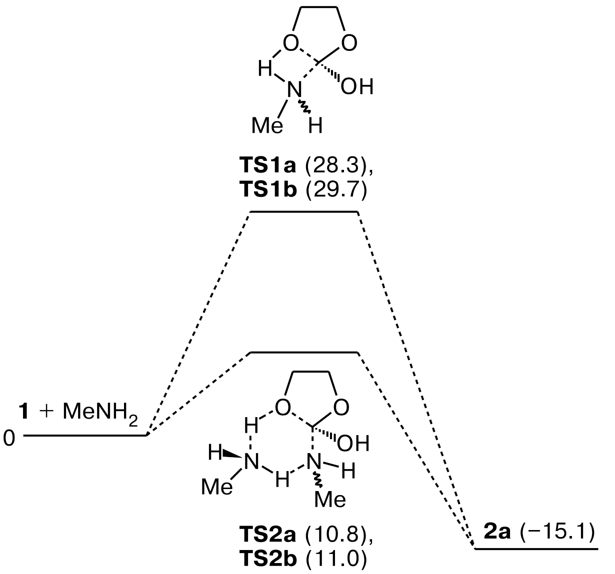


Fig. 3. One-stage addition of amine to compound **1** involving one and two $MeNH_2$ molecules.

formers of two possible products with the primary and secondary hydroxyl groups (**3b**(*S*) and **4b**(*R*)) is only 0.5 kcal mol^{-1}; *i.e.*, the formation of this or another product is not regiospecific.

Mechanism of the reaction of methylamine with ethylene carbonate. The experimental data indicate[5,6] that the reactions of amines with cyclocarbonates can be of both the first and second order with respect to amine. Thus, the second amine molecule can participate in the process forming H-bonded associates and playing the role of the catalyst, thus facilitating the proton transfer from amine to cyclocarbonate through cyclic transition states, as it occurs in reactions of aminolysis, hydrolysis, and alcoholysis of carbonyl-containing compounds.[11,12]

We considered two models of the reaction: involving one and two methylamine molecules. Note that several paths of the reaction were found for the both models: one-stage and multistage paths with the formation of a series of intermediates.

One-stage reaction path. Two cyclic transition states were observed for the one-stage path (Fig. 3): four-membered involving one amine molecule (**TS1a**, **TS1b**) and six-membered involving two amine molecules (**TS2a**, **TS2b**). The transition states can exist as isomers with different orientations of methylamine relative to the five-membered ring. The formation of four isomers is theoretically possible for both **TS1** and **TS2** with allowance for the relative arrangement of the carbonyl O atom, but only two of four isomers are formed, whereas other isomers somewhat change and transform into another type of transition states (**TS3** and **TS7**, see further). The activation energies for the transition states are given in parentheses in Fig. 3 and all subsequent figures, and the energies relative to the sum of energies of the starting reactants accepted to be zero are presented for the intermediates and stable compounds.

The activation energies of the reaction proceeding through species **TS2** are almost 3 times lower (see Fig. 3) than those in the case of species **TS1**; *i.e.*, the participation of the second amine molecule substantially accelerates the process. The three-dimensional images of the transition states of the one-stage path, which contain data on the selected interatomic distances characteristic of the corresponding structures, are shown in Fig. 4.

Multistage reaction path involving one methylamine molecule. The multistage path is more complicated than the one-stage path and includes stages of formation of a series of intermediates. If in transition state **TS1** amine attacks not the alkoxy but carbonyl bond, then intermediate **5** (amino alcohol) is formed (Fig. 5). This is an endothermic process, the enthalpy of formation of intermediate **5** from ethylene carbonate and methylamine is 6.6 kcal mol^{-1}, and the activation energies of the reactions proceeding through species **TS3a** and **TS3b** are very high. Species **TS3a** and **TS3b** do not almost differ by energies, since they are enantiomers.

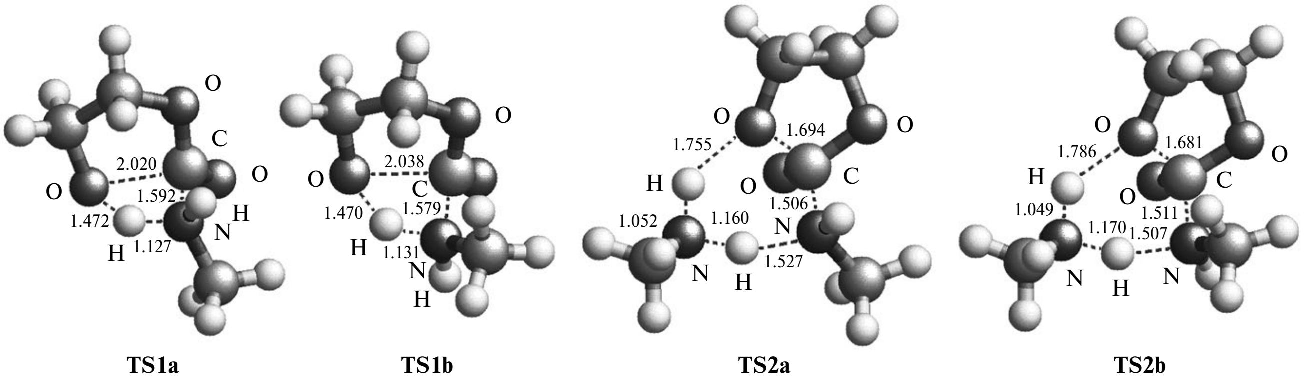


Fig. 4. Three-dimensional images of the transition states of the one-stage path of the reaction proceeding through species **TS1** and **TS2**.

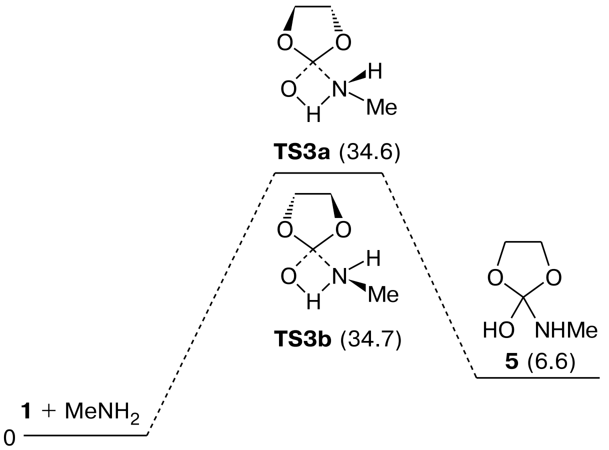


Fig. 5. Formation of intermediate **5** for the reaction of compound **1** with one $MeNH_2$ molecule.

The further transformations of intermediate **5** are related to the proton transfer from the hydroxy or amino group to alkoxy oxygen with the simultaneous cleavage of the alkoxy bond (Fig. 6). The proton transfer from the hydroxy group to alkoxy oxygen immediately results in the product. As the previous transition states, complex **TS4** can exist as two isomers with different arrangements of the methylamino group relative to the five-membered ring. Since the both isomers have the same energy, only one of them is shown in Fig. 6.

The proton transfer from the amino group first results in intermediate **6** (imino alcohol) in which the second proton transfer occurs. The activation energy of the reaction proceeding through transition state **TS5** is fairly high, and this process can be considered hypothetical. As a whole, the process of formation and decomposition of intermediate **5** is substantially less favorable than the one-stage path involving two amine molecules (through **TS2**) and, probably, that is why it does not occur in practice.

Multistage path involving two amine molecules. The addition of the second amine molecule to the model substantially decreases the activation energies of all stages. This is due to the lower strain and higher stability of the six-membered transition states compared to the four-membered states. Substantial complication appears due to the formation of numerous solvates in the reaction: weakly bonded complexes of intermediates **5** and **6** with the second amine molecule. Since for different stages of the process the second amine molecule should be from different sides of intermediates **5** and **6**, additional resolvation stages are needed.

Four isomers with different arrangement of methyl groups are possible for species **TS7** and **TS8** and intermediates **7** and **8** (Fig. 7). Only two isomers are possible for each of analogous structures **TS9**, **TS10**, **9**, **10**, and **11** (Fig. 8). Structures **TS7** and **TS3** are similar. Due to the participation of the second methylamine molecule, the activation energy decreases more than 3 times. Solvate **7** that formed cannot immediately transform into product **2a**. Its resolvation with the formation of solvate **8** (see Fig. 7) or **9** (see Fig. 8) is required.

Species **TS8** and **TS9** are similar to structures **TS4** and **TS5**, whereas **TS8** immediately results in the product and includes the proton transfer from the hydroxy group with the simultaneous cleavage of the alkoxy bond. For the reaction through **TS9**, the proton transfer occurs from the amino group and solvate **10** is formed (solvate of intermediate **6**). The second amine molecule is again in the position not proper for further transformation, and resolvation is required (transition **10** → **11**). Structures **TS10** and **TS6** are similar (see Figs 6 and 8).

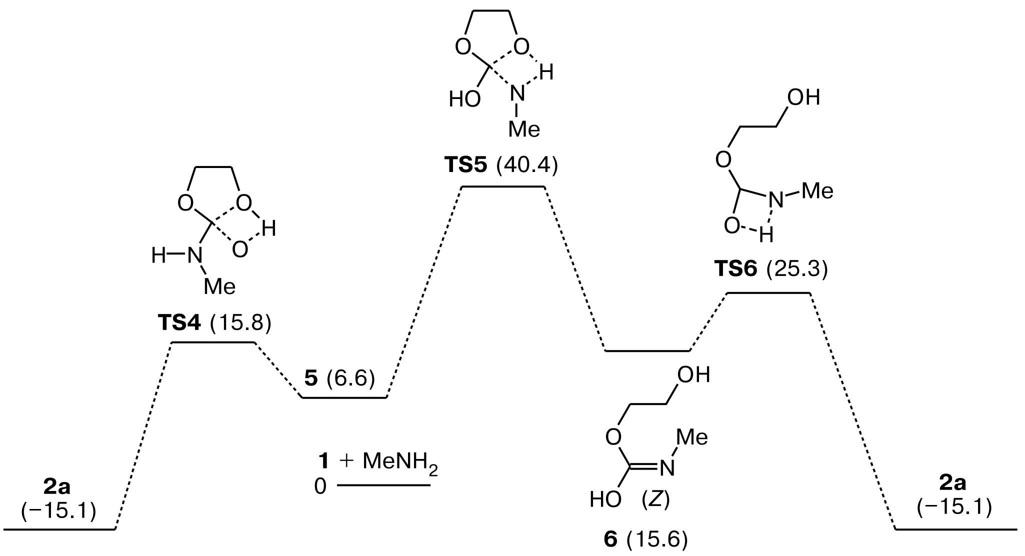


Fig. 6. Two paths of transformation of intermediate **5** into product **2a** (involving one $MeNH_2$ molecule).

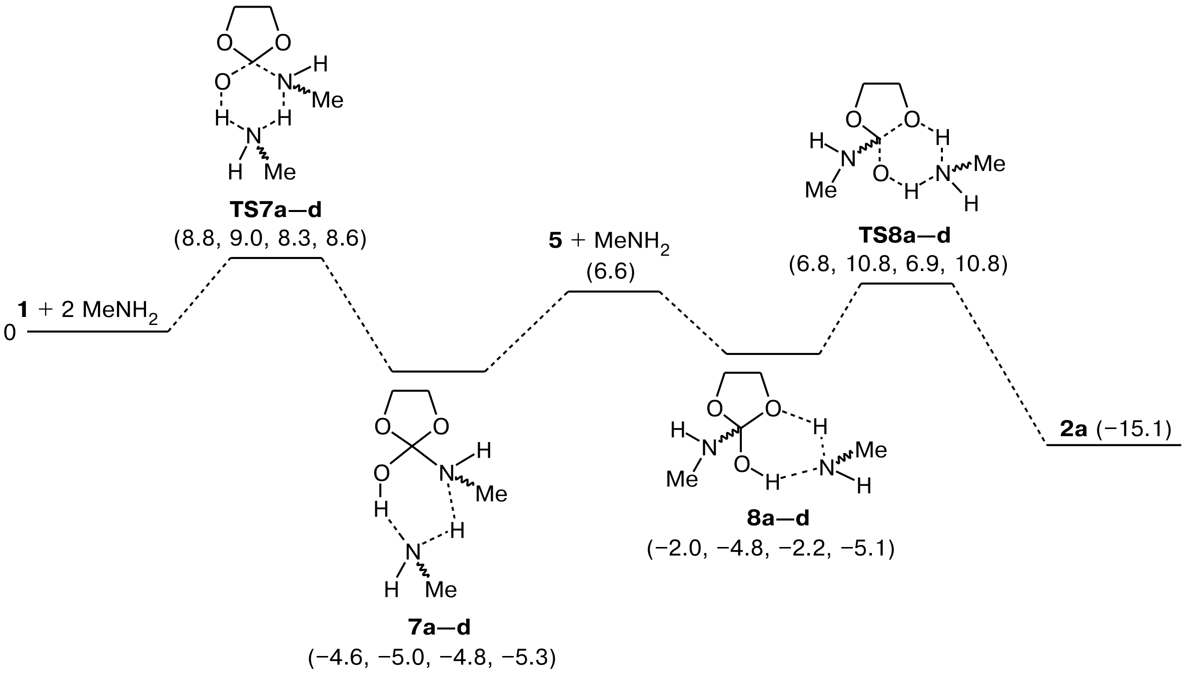


Fig. 7. Formation of solvated intermediate **5** and its transformation into product **2a** involving two $MeNH_2$ molecules.

Thus, the route through imine even involving two amine molecules looks unpromising. On the contrary, the way through species **TS7** and **TS8** turned out to be the most energetically favorable of all considered paths. The highest reaction barriers correspond to species **TS7** (8.3—9.0 kcal mol^{-1}). The formation of solvates **7a**—**d** is an exothermic process (see Fig. 7), unlike the stage of formation of intermediate **5** (see Fig. 6). The energy necessary for the resolvation of compounds **7** and **8** is low and can easily be attained under the reaction conditions. The difference in energies of intermediates **7** and **8** does not exceed 1 kcal mol^{-1}, and the energy consumed to desolva-

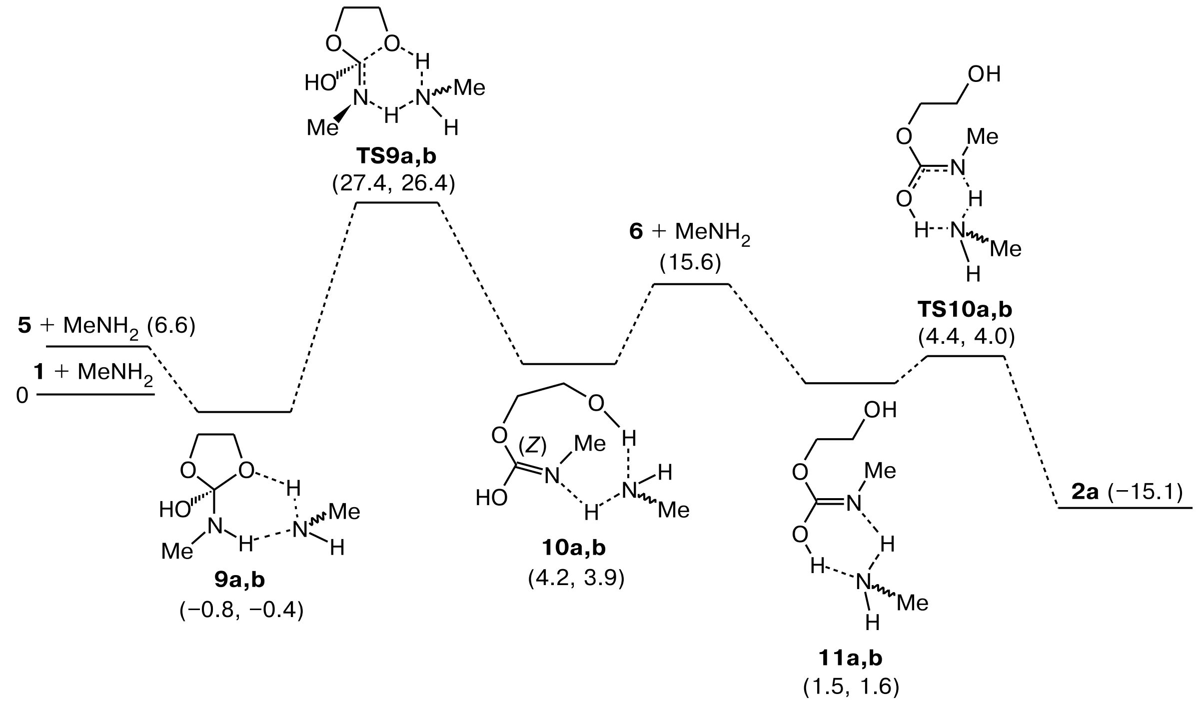
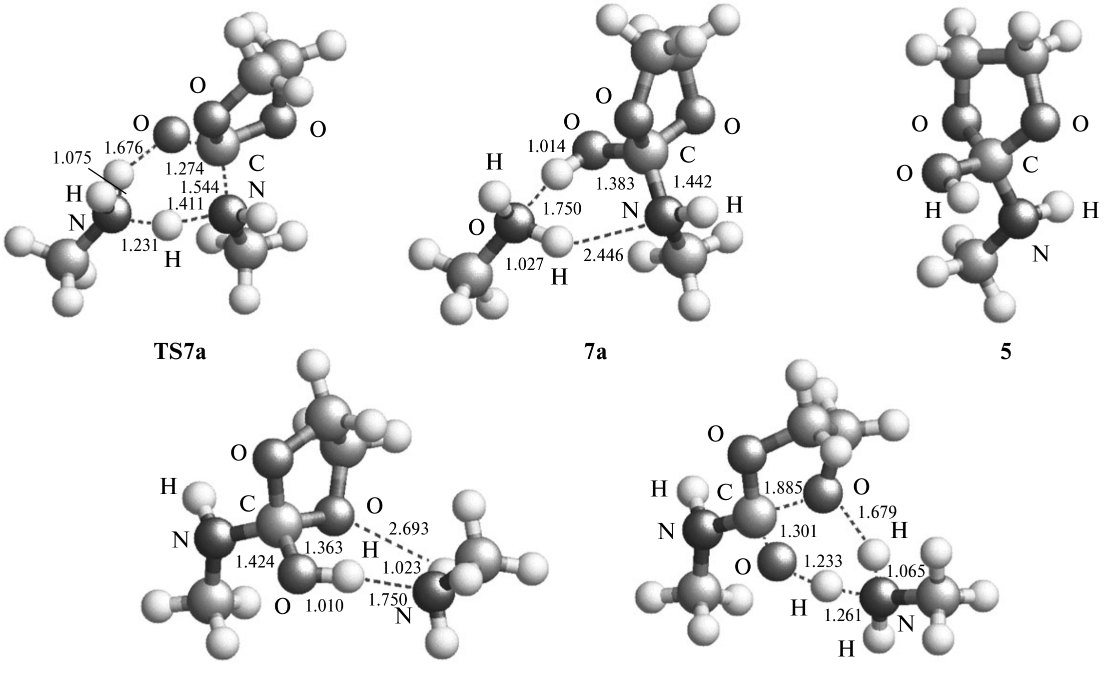


Fig. 8. Transformation of solvated intermediate **5** into product **2a**.



TS7a **7a** **5**

8a **TS8a**

Fig. 9. Three-dimensional images of the transition states and intermediates of the two-stage reaction path.

tion will return to the process due to the solvation of intermediate **5**. The three-dimensional images of the transition states and intermediates for one of the found isomeric routes of the reaction are presented in Fig. 9.

One more transition state was found (**TS11**) involving two methylamine molecules (Fig. 10) in which the second molecule is not incorporated into the cycle but solvates structure **TS4**. In fact, the second amine molecule does not substantially participate in the transformation. The activation energy of the reaction through **TS11** turned out to be intermediate between the activation energies through **TS4** (without participation of the second amine molecule) and **TS8** (involving the second amine molecule as a catalyst). Solvate **12** precedes the formation of **TS11**.

Reaction of methylamine with propylene carbonate: an effect of the alkyl substituent in cyclocarbonate. Cyclocarbonates arranged at the ends of the oligomer chain of different nature are practically significant for the chemistry of polyurethanes. We studied the influence of the alkyl substituent in ethylene carbonate on the regularities of the reaction using the reaction of methylamine with propylene carbonate as an example. In this reaction, as mentioned above, two isomeric products with the primary and secondary hydroxyl groups can be formed.

In the calculations of the reaction involving propylene carbonate as compared to that with ethylene carbonate, an increase in the number of isomers results in a substantial complication. For example, for all transition states and intermediates presented above, other isomers with different arrangements of the methyl group in the ring can additionally be formed, as it was shown for isomers **TS13a—p**. The calculation showed that the corresponding activation energies of all stages of the reaction involving propylene carbonate or ethylene carbonate differed insignificantly. As earlier, the two-stage path involving two amine molecules

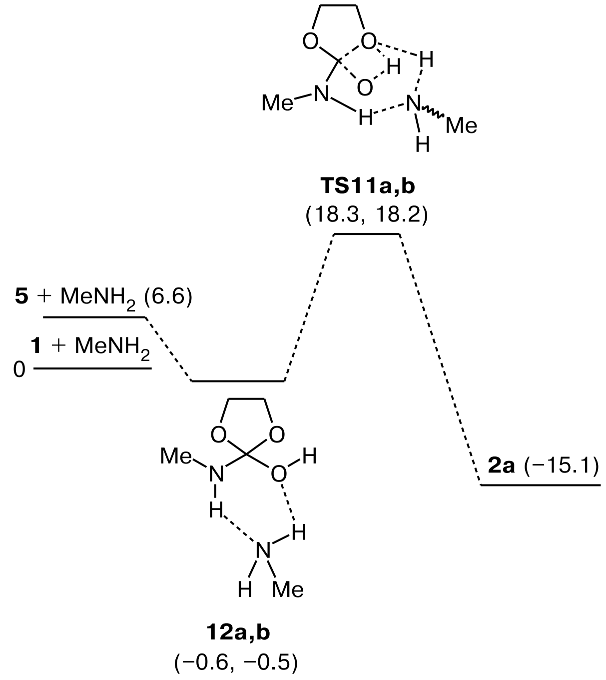
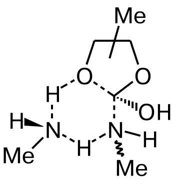
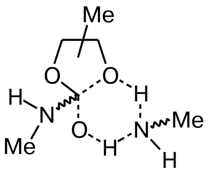
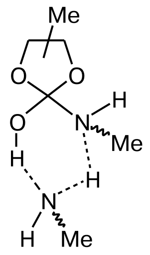
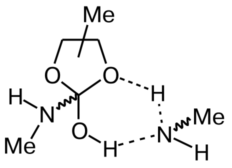


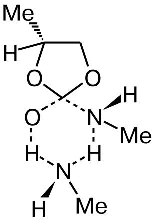
Fig. 10. Transformation of solvated intermediate **5** into product **2a** through species **TS11**.

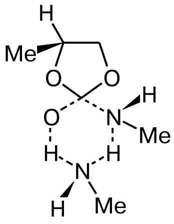

TS12

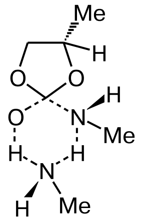

TS14

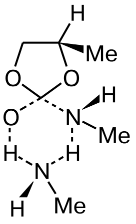

13

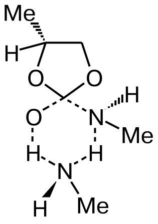

14

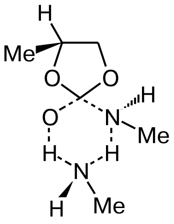

TS13a

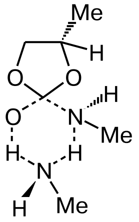

TS13b

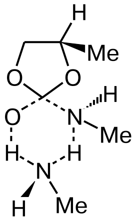

TS13c

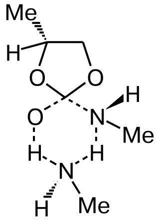

TS13d

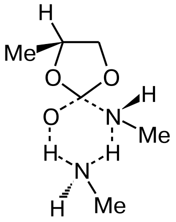

TS13e

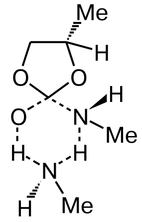

TS13f

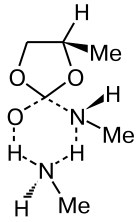

TS13g

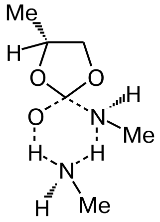

TS13h

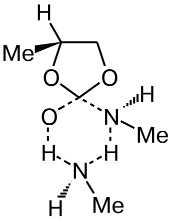

TS13i

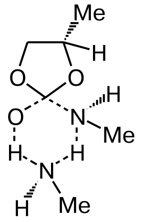

TS13j

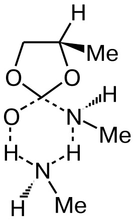

TS13k


TS13l


TS13m


TS13n


TS13o


TS13p

turned out to be the most favorable. The data for all stable isomers **TS12**, **TS13**, and **TS14** and intermediates **13** and **14** observed for this and for one-stage path involving two methylamine molecules are given in Table 2.

The alkyl substituent in the ring, being rather remote from the reaction center, exerts no substantial effect on the process. The calculations show that in the reaction with propylene carbonate the formation of products with the secondary and primary hydroxyl groups is nearly equiprobable. However, if cyclocarbnate contains bulky substituents, their influence can be enhanced and affect the ratio of the products.

Thus, the results presented in this work indicate that the addition of primary amines to cyclocarbonates can proceed *via* both the one- and multistage mechanisms including the formation of a series of intermediates of different stability. In the both cases, the calculated activation energy of the reaction involving two amine molecules is threefold lower than that of the simple bimolecular reaction. We interpret this as the catalytic assistance of the second amine molecule to the proton transfer to cyclocarbonate in the six-membered transition state, which is substantially less strained than the four-membered state.

It is natural to ask: how our calculations in the "gas-phase" approximation reflect the mechanism of the reaction in the condensed phase? The reaction of amines with cyclocarbonates is classified as nucleophilic addition involving neutral molecules, and no charge separation oc-

Table 2. Activation energies (E_a) of the reactions of propylene carbonate proceeding through transition states **TS12**, **TS13**, and **TS14** involving two amine molecules, the enthalpies of formation (ΔH, kcal mol^{-1}) of intermediates **13** and **14** from propylene carbonate and two methylamine molecules, and the energies of formation (ΔE, kcal mol^{-1}) of intermediates **13** and **14** from amino alcohol and methylamine

Compound	E_a/kcal mol^{-1}			Product	**13**		**14**	
	TS12	**TS13**	**TS14**		$-\Delta H$	$-\Delta E$	$-\Delta H$	$-\Delta E$
a	11.4	9.2	6.9	**3b**	4.2	11.5	1.8	9.2
b	11.6	9.6	8.8	**3b**	4.2	11.6	0.5	7.9
c	11.6	9.4	10.9	**3b**	4.6	12.0	4.6	12.0
d	12.0	10.1	13.8	**3b**	4.4	11.8	5.1	12.5
e	—	8.7	6.9	**3b**	4.4	11.8	2.0	9.4
f	—	9.1	8.8	**3b**	4.5	11.9	0.7	8.1
g	—	9.0	10.9	**3b**	4.9	12.2	4.9	12.3
h	—	9.2	12.8	**3b**	5.0	12.4	4.6	12.0
i	12.3	10.0	6.7	**4b**	4.2	11.0	0.8	7.6
j	11.0	9.0	7.3	**4b**	4.4	11.1	1.6	8.4
k	12.3	10.2	11.2	**4b**	4.8	11.6	4.1	10.9
l	11.2	9.2	11.2	**4b**	4.8	11.6	4.3	11.1
m	—	9.5	6.7	**4b**	4.5	11.3	0.9	7.6
n	—	8.4	7.4	**4b**	4.7	11.4	1.7	8.5
o	—	9.8	11.2	**4b**	5.1	11.8	4.5	11.2
p	—	8.8	11.3	**4b**	5.1	11.8	4.6	11.4

curs in the transition state. In these reactions, the electrostatic solvation does not play a substantial role, and specific effects of the medium should be taken into account.[13]

The "approximation of supermolecule" is considered to be very efficient in quantum chemical studies of mechanisms of molecular reactions in solutions. For this approximation, solvent molecules capable of solvating reactants due to specific intermolecular interactions are initially introduced into the starting model.[14] In the reactions involving neutral molecules, the energy of medium reorganization is approximately equal for the starting reactants, transition state, and addition product.[15] This is a basis for the inclusion of a restricted number of solvent molecules into the studied system, which considerably simplifies calculations. Moreover, in some cases, especially in systems where a hydrogen bond is the main type of interaction, it is enough to include only one molecule of the solvent, whose component is often one of the reactants, into the model to obtain satisfactory agreement of the calculated and experimental data.

The neutral hydrolysis of formaldehyde[16,17] and ammonolysis of esters[18] and carboxylic acids[19] are discussed as examples in the monograph.[14] In the case of these reactions, for the successful quantum chemical description of catalytic effects and the influence of the medium, it is enough to include one additional molecule of a nucleophilic reagent (water, ammonia) into the system. The results of calculations of the mechanism of the reactions of ethylene carbonate and propylene carbonate with two amine molecules, which simulate the process at high amine concentrations, exemplify the fruitfulness of this approach.

This work was financially supported by the Russian Foundation for Basic Research (Project No. 11-03-00432-a).

References

1. J. H. Saunders, K. C. Frisch, *Polyurethanes — Chemistry and Technology*, Interscience Publishers, New York—London, 1962, Vol. **16**, Part I.
2. R. P. Tiger, *Vysokomol. Soedin.*, 2004, *Ser. B*, 931 [*Polym. Sci.*, *Ser. B* (*Engl. Transl.*), 2004, **46**].
3. N. A. Plate, E. B. Slivinskii, *Osnovy khimii i tekhnologii monomerov* [*Foundations of Chemistry and Technology of Monomers*], MAIK "Nauka Interperiodika," Moscow, 2002, 696 pp. (in Russian).
4. L. D. Shapovalov, O. L. Figovskii, B. B. Kudryavtsev, *Voprosy Khim. Khim. Tekhnol.* [*Problems of Chemistry and Chemical Technology*], 2004, 231 (in Russian).
5. R. M. Garipov, V. A. Sysoev, V. V. Mikheev, A. I. Zagidullin, R. Ya. Deberdeev, V. I. Irzhak, A. A. Berlin, *Dokl. Akad. Nauk*, 2003, **393**, 61 [*Dokl. Chem.* (*Engl. Transl.*), 2003].
6. V. B. Nemirovski, S. S. Skorokhodov, *J. Polym. Sci.*, 1967, **16**, 1471.
7. J. P. Perdew, K. Burke, M. Ernzerhoff, *Phys. Rev. Lett.*, 1996, **77**, 3865.
8. M. Ernzerhoff, G. E. Scuseria, *J. Chem. Phys.*, 1999, **110**, 5029.
9. D. N. Laikov, *Chem. Phys. Lett.*, 1997, **281**, 151.
10. D. N. Laikov, Yu. A. Ustynyuk, *Izv. Akad. Nauk*, *Ser. Khim.*, 2005, 804 [*Russ. Chem. Bull., Int. Ed.*, 2005, **54**, 820].
11. L. M. Litvinenko, N. M. Oleinik, *Mekhanizm deistviya organicheskikh katalizatorov* [*Mechanism of Action of Or-*

ganic Catalysts], Naukova Dumka, Kiev, 1984, 264 pp. (in Russian).
12. R. P. Tiger, Doct. Sci. (Chem.) Thesis, Institute of Chemical Physics, Russian Academy of Sciences, Moscow, 1980, 500 pp. (in Russian).
13. S. G. Entelis, R. P. Tiger, *Reaction Kinetics in the Liquid Phase*, J. Wiley and Sons, New York—Toronto, 1976, 362 pp.
14. B. Ya. Simkin, I. I. Sheikhet, *Kvantovo-khimicheskaya i statisticheskaya teoriya rastvorov* [*Quantum Chemical Statistical Theory of Solutions*], Khimiya, Moscow, 1989, 251 pp. (in Russian).
15. J. D. Madura, W. L. Jorgensen, *J. Am. Chem. Soc.*, 1986, **108**, 2517.
16. I. H. Williams, D. Spangler, D. A. Femec, G. M. Maggiora, R. L. Schowen, *J. Am. Chem. Soc.*, 1980, **102**, 6619.
17. I. H. Williams, D. Spangler, D. A. Femec, G. M. Maggiora, R. L. Schowen, *J. Am. Chem. Soc.*, 1983, **105**, 17.
18. K. Ya. Burshtein, Yu. I. Khurgin, *Izv. Akad. Nauk SSSR*, *Ser. Khim.*, 1974, 1687 [*Bull. Acad. Sci. USSR*, *Div. Chem. Sci.* (*Engl. Transl.*), 1974, **23**].
19. T. Oce, G. H. Loew, S. K. Burt, R. D. MacElroy, *J. Am. Chem. Soc.*, 1983, **105**, 2221.

Received September 5, 2011;
in revised form December 20, 2011