ISSN 1070-4280, *Russian Journal of Organic Chemistry, 2007, Vol. 43, No. 8, pp. 1101–1105.* © *Pleiades Publishing, Ltd., 2007.*
Original Russian Text © A.V. Shevtsov, V.P. Ananikov, N.N. Makhova, 2007, published in Zhurnal Organicheskoi Khimii, 2007, Vol. 43, No. 8, pp. 1113–1117.

Dedicated to the Full Member of the Russian Academy of Sciences
V.A.Tartakovsky on occasion of his 75th birthday

Quantum-Chemical Investigation of the Mechanism of Reaction between 1,2-Dialkyldiaziridines and Heterocumulenes

A. V. Shevtsov, V. P. Ananikov, and N. N. Makhova

Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences, Moscow,119991 Russia
e-mail: mnn@ioc.ac.ru

Received May 30, 2007

Abstract—By quantum-chemical method in the framework of the density functional theory [B3LYP/6-31G(d)] a mechanism of reaction between 1,2-dialkyldiaziridines and ketenes $CH_2=C=O$, PhCH=C=O, and aroyl isocyanates was investigated. The fragment Ph–CH–C(O) in the intermediate governing the cleavage of the N–N bond of the diaziridine ring is virtually planar leading to a considerable loosening of the bond. In the intermediate governing the cleavage of the C–N bond of the ring the fragment Ph–C(O)–N–C(O) is nonplanar resulting in significantly lesser loosening of the N–N bond and in the C–N-opening of the diaziridine ring. The calculated thermodynamical parameters are well consistent with the experimental data on the reactivity.

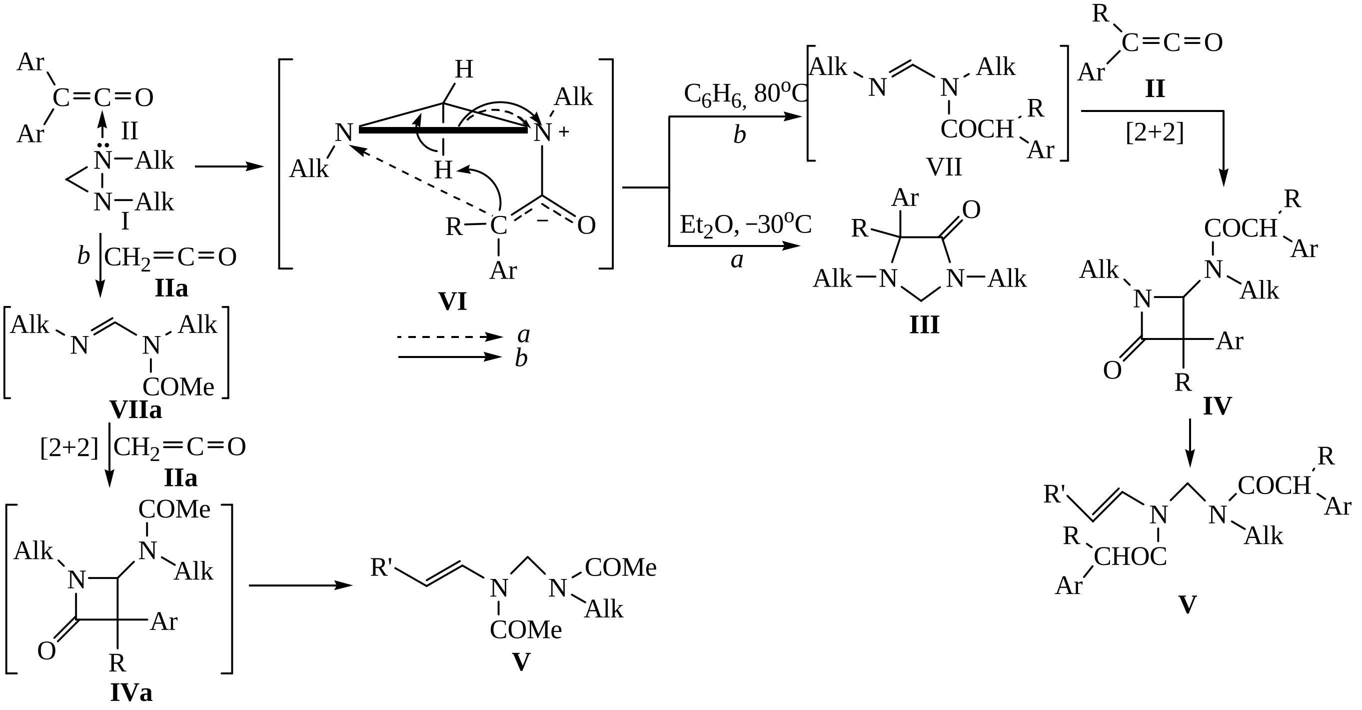
DOI: 10.1134/S1070428007080015

We recently [1–3] studied in detail the reaction of 1,2-dialkyldiaziridines **I** with ketenes of various structures **II** and demonstrated that these reactions occurred with the cleavage of N–N bond and the formation of three type structures containing an N–C–N fragment: 1,3-dialkylimidazolidin-4-ones **III**, 4-(acylamino)azetidin-2-ones (examples of β-lactams) (**IV**), and 3,5-diaza-1-heptenes (**V**) (Scheme 1). The most probable mechanisms of these reactions were described in [1–3]. In the first stage in all events formed a zwitterionic intermediate **VI**. The reaction of 1,2-dialkyldiaziridines **I** with arylketenes **II** at low temperature (kinetic control of the reaction) and the presence in the ketene of aryl substituents ensure the intramolecular ring closure of the zwitterionic intermediate **VI** by a synchronous mechanism (path *a*) giving 1,3- dialkylimidazolidin-4-ones **III**. The reaction of the same reagent at elevated temperature (thermodynamic control), and also the use of the simplest ketene **IIa** (here the conjugate anion in intermediate **VI** is not compensated by the presence of aryl radicals) facilitate a proton elimination from the carbon atom of the diaziridine ring (path *b*) followed by the ring opening at the N–N bond and the formation of the second intermediate of amidine type **VII** (**VIIa**) that enters into the [2+2]-cycloaddition reaction with the second ketene molecule leading to the formation of 4-(acylamino)azetidin-2-ones **IV** (**IVa**) which due to structural factors are mostly converted with ring opening into 3,5-diaza-1-heptenes (**V**).

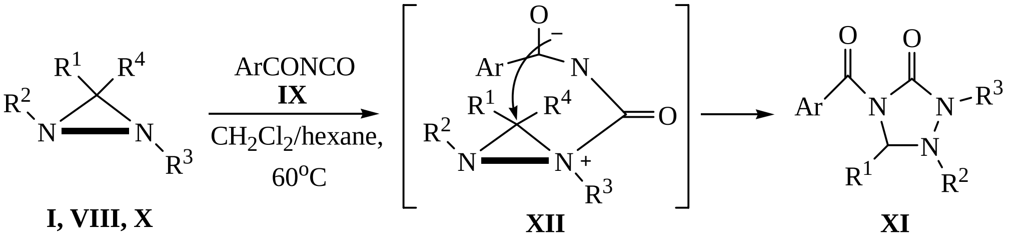
It was presumable that a reaction of dialkyldiaziridines **I** with other heterocumulenes (for instance, with isocyanates) would also occur with the cleavage of the N–N bond. However the known reaction of 1,2,3-trialkyldiaziridines **VIII** with benzoyl isocyanate (**IX**) (boiling in benzene) [4], and also our study [5] of the reaction of 1,2-dialkyl- **I** and 1,2,3,3-tetraalkyldiaziridines **X** with aroyl isocyanates at room temperature in dichloromethane followed by heating in hexane show that here the diaziridinering opened at the C–N bond with the formation of 4-benzoyl-1,2,4-triazolidin-3-ones **XI** (Scheme 2). The mechanism of formation of compound **XI** suggested in [4, 5] involves the participation in the first reaction stage of a zwitterionic intermediate **XII** with a subsequent attack of the conjugate anion on the carbon atom of diaziridine ring with simultaneous rupture of C–N bond along a concerted mechanism.

The results obtained do not provide an understanding of the different behavior of 1,2-dialkyldiaziridines **I** in reactions with similar electrophilic reagents, ketens and isocyanates. Why in the first case occurs the cleavage of N–N bond and in the second, of C–N bond? In order to

Scheme 1.



Scheme 2.



I, R^2, R^3 = Alk, R^1, R^4 = H; **VIII**, R^2, R^3, R^4 = Alk, R^1 = H; X, R^1, R^2, R^3, R^4 = Alk.

get clearer insight into the pathways of the discovered reactions in this study the mechanism of the reactions is subjected to quantum-chemical investigation by an example of the process involving 1,2-dimethyldiaziridine (**Ia**) with the simplest ketene **IIa**, phenylketene (**IIb**), and benzoyl isocyanate (**IX**).

Firstly we carried out a quantum-chemical investigation of the reaction mechanism of 1,2-dimethyldiaziridine (**Ia**) with the simplest unsubstituted ketene **IIa** on the level B3LYP/6-31G(d). The reaction equation and some structural parameters obtained by complete optimization of the geometry of initial compounds **Ia** and **IIa**, of transition state **XIII**, of its transformation product, amidine **XIVa**, and also the charges on atoms for the stationary point **XIII** are presented on Scheme 3. The optimized molecular structures are depicted on Fig. 1.

According to calculations zwitterionic intermediate **VIa** formed as a result of the reaction between compounds **Ia** and **IIa** is unstable and dissociates into the initial compounds. Hence the transition state **XIII** forms directly from reagents **Ia** and **IIa**. The visualization of the oscillation corresponding to the imaginary frequency and the calculation of the reaction coordinate (IRC) confirmed the nature of the transition state **XIII**. In moving along the reaction coordinate a proton migration occurs from atom C^3 to fragment CH_2 leading to the formation of amidine **XIVa.** The calculated activation energy of the

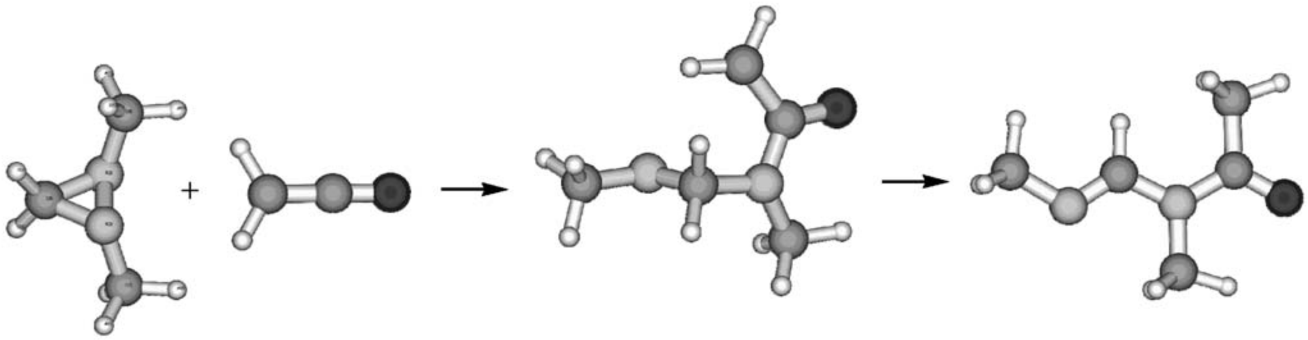
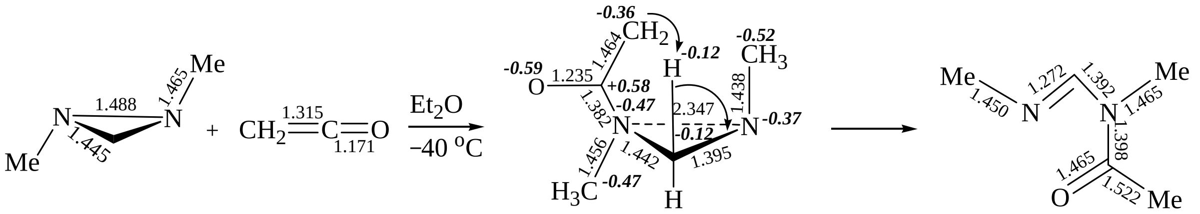


Fig. 1. Molecular structures of compounds **Ia, IIa, XIII**, and **XIV**, calculated on the level B3LYP/6-31G(d).

Scheme 3.



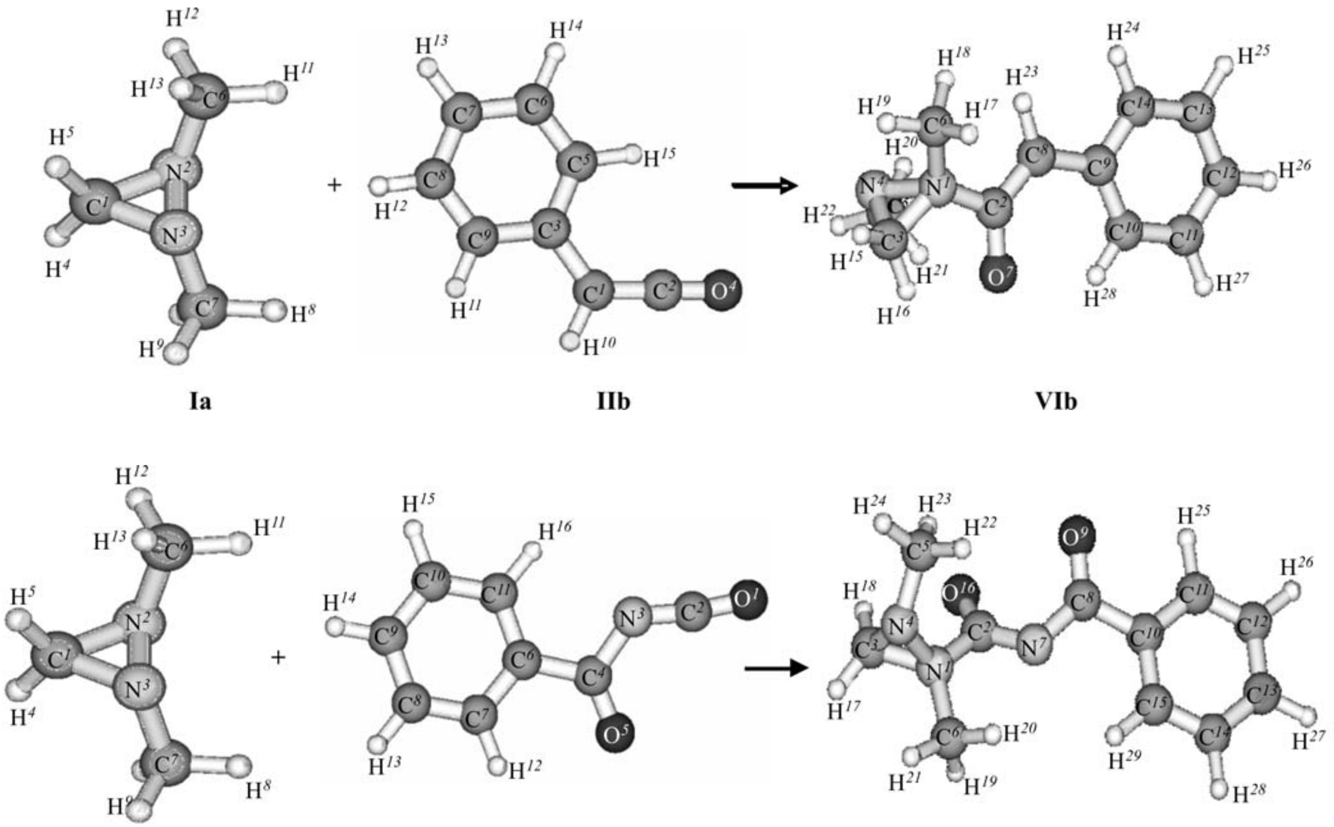
Ia **IIa** **XIII** **XIVa**

reaction **Ia** + **IIa** > **XIII** > **XIVa** is ΔE“ 20 kcal mol^{-1} and the energy gain from the formation of amidine **XIVa** ΔE –79.4 kcal mol^{-1}. The thermopositive process ensures the driving force of the reaction.

In the second stage of the investigation we carried out a comparative quantum-chemical study of reaction between 1,2-dimethyldiaziridine (**Ia**) and phenylketene (**IIb**) or benzoyl isocyanate (**IX**) (Scheme 4). According to experimental findings in the first case formed compound **IIIa** (cleavage of N–N bond), and in the second case compound **XIa** (cleavage of C–N bond of the diaziridine ring).

In order to reveal the reasons of different opening of the diaziridine ring we carried out calculation of model structures of intermediates **VIb** and **XIIa** with geometry optimization at a fixed length of the bond N–C(O) 1.4Å (analogous to the value obtained for compound **XIII**, Scheme 3). The energy of intermediates **VIb** and **XIIa** proved to exceed that of the initial reagents by 9.8 and 20.4 kcal mol^{-1} respectively. The calculated energy values are well consistent with the geometrical parameters (Fig. 2). For instance, the fragment Ph–CH–C(O) of intermediate **VIb** is virtually planar ensuring an efficient delocalization of the electron density; as a result the N–N bond of the diaziridine ring loosens and its length increases by ~0.1 Å; evidently this fact facilitates the rupture of the bond. Therewith the spatial arrangement of the reacting fragments in intermediate **VIb** does not contradict the previously proposed concerted cyclization mechanism. In intermediate **XIIa** the fragment Ph–C(O)–N–C(O) is not planar, and thus the N–N bond of the diaziridine ring is less loosened (elongation by ~0.033 Å). The bond lengths C–N of the diaziridine rings in zwittherions **VIb** and **XIIa** in both cases vary slightly. Inasmuch as both types of bonds in the three-membered ring of compound **XIIIa** are insignificantly lengthened the C–N-opening of the diaziridine ring should be governed by thermodynamic parameters, as has been found experimentally: The formation of compound **XI** requires much higher temperature (40–60°C), than for generating compounds **III** (–30°C). To confirm the thermodunamical control of the reaction a calculation was performed of the relative stability of compound **XIa** and the other possible reaction product, 2-benzoyl-1,4-dimethyl-1,2,4-triazolidin-3-one (**XVI**) at the level B3LYP/6-31G(d). The calculation showed that compound **XIa** is more stable (by 4.1 kcal mol^{-1}) than compound **XVI**.

Thus the calculations performed showed that the transformation of intermediate **VIb** into the final imidazolidine **IIIa** occurred in all likelihood by a concerted mechanism which had been previously suggested. The mechanism involves an attack of a carbon atom of the conjugate anion on the second nitrogen of the diaziridine ring with the simultaneous rupture of the N–N bond.

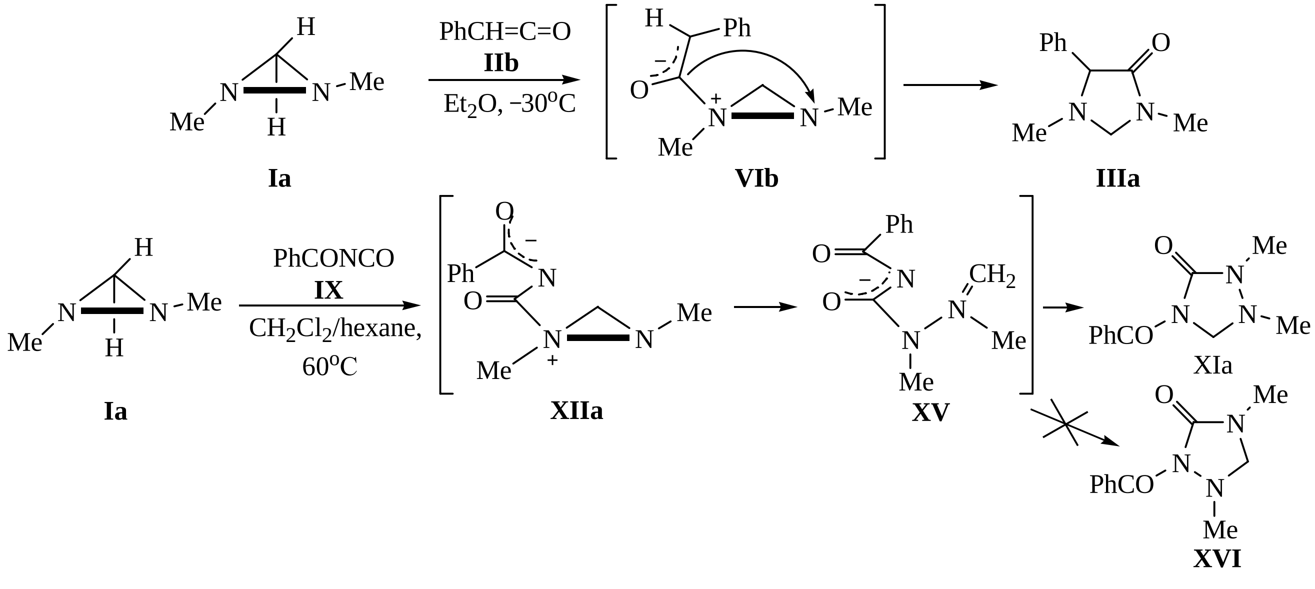


Ia **IIb** **VIb**

Ia **IX** **XIIa**

Fig. 2. Molecular structures of initial compounds **Ia, IIb**, and **IX**, and also of zwitterionic intermediates **VIb** and **XIIa** calculated on the level B3LYP/6-31G(d).

Scheme 4.



The geometrical features of zwitterionic intermediate **XIIa** and the hindered rotation of the substituent C(O)NC(O) necessary for efficient contact at the formation of the C–N bond in the final product **XIa**, and also considerably higher energy consumption required for formation of intermediate **XIIa** compared with the similar value for intermediate **VIb** suggest that compounds **XI** form via intermediates **XII** and **XV** apparently by a two-step mechanism.

EXPERIMENTAL

The geometry optimization and the calculation of energy of the studied stationary points were performed using a hybride potential B3LYP [6–8] in a standard basis 6-31G(d) [9]. The charges were calculated in the NBO (Natural Bond Orbital Analysis) approximation [10, 11]. All calculations were carried out applying software complex GAUSSIAN-98 [12]. The character of the found stationary points was checked by calculating the eigenvalues of the matrix of second derivatives of the energy (the lack of imaginary frequencies for intermediates and one imaginary frequency for the transition states). Since the reactions under study were performed in aprotic solvents (benzene, hexane, ether) (Schemes 1–4) the solvent effect was not accounted for in the calculations due to the absence of strong solvation .

The visualization of molecular structures was performed using graphical software package MOLDEN [13]. The other details of the method were described before [14, 15].

The study was carried out under a financial support of the Russian Foundation for Basic Research (grant no. 04-03-32799).

REFERENCES

1. Shevtsov, A.V., Petukhova, V.Yu., Strelenko, Yu.A., Lyssenko, K.A., Fedyanin, I.V., Makhova, N.N., *Mendeleev Commun.*, 2003, p. 221.
2. Shevtsov, A.V., Petukhova, V.Yu., Strelenko, Yu.A., Makhova, N.N., *Mendeleev Commun.*, 2005, p. 29.
3. Shevtsov, A.V., Petukhova, V.Yu., Strelenko, Yu.A., Lysenko, K.A., Makhova, N.N., Tartakovskii, V.A., *Izv. Akad. Nauk, Ser. Khim.*, 2005, p. 997.
4. Komatsu, M., Nishikaze, N., Sakamoto, M., Ohshiro, Y., and Agawa, T., *J. Org. Chem.*, 1974, vol. 39, p. 3198.
5. Shevtsov, A.V., Kuznetsov, V.V., Molotov, S.I., Lysenko, K.A., Makhova, N.N., *Izv. Akad. Nauk, Ser. Khim.*, 2006, p. 534.
6. Becke, A.D., *Phys. Rev. A*, 1988, vol. 38, p. 3098.
7. Lee, C., Yang, W., and Parr, R.G., *Phys. Rev. B*, 1988, vol. 37, p. 785.
8. Becke, A.D., *J. Chem. Phys.*, 1993, vol. 98, p. 5648.
9. Ditchfield, R., Hehre, W.J., Pople, J.A., *J. Chem. Phys.*, 1971, vol. 54, p. 724.
10. Carpenter, J.E. and Weinhold, F., *J. Mol. Struct. THEOCHEM.*, 1988, vol. 169, p. 41.
11. Reed, A.E., Curtiss, L.A., and Weinhold, F., *Chem. Rev.*, 1988, vol. 88, p. 899.
12. Frisch, M.J., Trucks, G.W., Schlegel, H.B., Scuseria, G.E., Robb, M.A., Cheeseman, J.R., Zakrzewski, V.G., Montgomery, J.A. Jr., Stratmann, R.E., Burant, J.C., Dapprich, S., Millam, J.M., Daniels, A.D., Kudin, K.N., Strain, M.C., Farkas, O., Tomasi, J., Barone, V., Cossi, M., Cammi, R., Mennucci, B., Pomelli, C., Adamo, C., Clifford, S., Ochterski, J., Petersson, G.A., Ayala, P.Y., Cui, Q., Morokuma, K., Malick, D.K., Rabuck, A.D., Raghavachari, K., Foresman, J.B., Cioslowski, J., Ortiz, J.V., Baboul, A.G., Ste-fanov, B.B., Liu, G., Liashenko, A., Piskorz, P., Komaromi, I., Gomperts, R., Martin, R.L., Fox, D.J., Keith, T., Al-Laham, M.A., Peng, C.Y., Nanayakkara, A., Gonzalez, C., Challacombe, M., Gill, P.M.W., Johnson, B., Chen, W., Wong, M.W., Andres, J.L., Gonzalez, C., Head-Gordon, M., Replogle, E.S., and Pople, J.A., *GAUSSIAN-98*, Gaussian, Inc., Pittsburgh, PA, 1998.
13. Schaftenaar, G. and Noordik, J.H., *J. Comput.-Aided, Mol. Des.*, 2000, vol. 14, p. 123.
14. Ananikov, V.P., *J. Phys. Org. Chem.*, 2001, vol. 14, p. 109.
15. Ananikov, V.P., *J. Phys. Org. Chem.*, 2003, vol. 16, p. 253.