Available online at www.sciencedirect.com

ScienceDirect

Mendeleev Commun., 2023, 33, 515–518

Mendeleev Communications

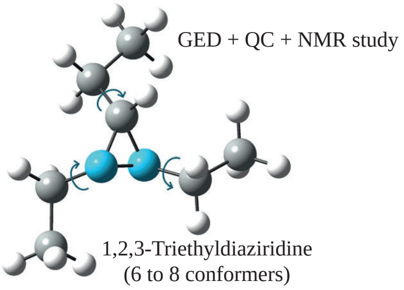
Molecular structure of 1,2,3-triethyldiaziridine: gas-phase electron diffraction and theoretical calculations

Georgiy G. Ageev,*[a] Vladimir V. Kuznetsov,[b] Anatoly N. Rykov[a] and Igor F. Shishkov[a]

[a] *Department of Chemistry, M. V. Lomonosov Moscow State University, 119991 Moscow, Russian Federation.*
E-mail: ageev.george@yandex.ru, ggageev@phys.chem.msu.ru
[b] *N. D. Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences, 119991 Moscow, Russian Federation*

DOI: 10.1016/j.mencom.2023.06.024

For the first time, the equilibrium molecular structure and conformational composition (6 to 8 conformers) of 1,2,3-triethyldiaziridine in the gas phase were determined by gas-phase electron diffraction. Using 1D and 2D ^{1}H and ^{13}C NMR spectroscopy, it was shown that in a $CDCl_3$ solution under normal conditions on the NMR time scale, the molecule exists only as one conformer. The enthalpy of formation $\Delta_f H^0_{298}$ of the studied molecule in the gas phase was calculated by the method of atomization reactions and is equal to 92.2 ± 1.7 kJ mol^{-1}.



Keywords: gas-phase electron diffraction, equilibrium structure, conformational composition, diaziridines, enthalpy of formation, quantum chemical calculations, gas phase, NMR spectroscopy.

Diaziridines (1,2-diazacyclopropanes) are widely used in both theoretical and practical fields.[1,2] They are convenient objects for studying the stereochemistry of nitrogen, since under normal conditions the nitrogen atoms in monocyclic diaziridines are chiral.[1,3] The strained diaziridine ring is prone to ring expansion reactions, resulting in various five- to eight-membered mono- and bicyclic heteroatomic moieties.[1,4–11] Diaziridine derivatives exhibit neurotropic activity, having a direct action on the central nervous system.[12,13] Important properties of diaziridines are high enthalpy of formation and low toxicity; therefore, they are of interest as potential components of liquid rocket propellants to replace toxic hydrazine derivatives.[14] Lone electron pairs, as well as substituents at the nitrogen atoms of monocyclic diaziridines, are always in the *trans* position, which is due to the steric and four-electron destabilizing interaction of *cis*-oriented N-substituents and lone pairs.[1,15] According to *ab initio* calculations, unsubstituted *cis*-diaziridine is destabilized by 29.7–32.6 kJ mol^{-1} compared to its *trans*-isomer.[16]

The study of the simplest diaziridine structures, such as 1,2-dimethyl-, 1,2,3-trimethyl- and 1,2-diethyldiaziridines, by gas-phase electron diffraction (GED) showed that in all molecules the alkyl groups at nitrogen atoms occupy the *trans* position[17–19] with respect to the ring plane. The GED study of 3-cyclopropyl-1,2-dimethyldiaziridine,[20] supplemented by quantum chemical (QC) calculations, indicated the stabilization of *gauche*- and *anti*-conformers in a ratio of 1 : 1.5 with a conformational energy barrier of ~25 kJ mol^{-1} due to the presence of a cyclopropyl substituent at carbon atom in the diaziridine ring. In this communication, we report our experimental and theoretical results on studying the structure of a possible conformer of the 1,2,3-triethyldiaziridine (TEDA) molecule (Figure 1) and obtaining its structural parameters using gas electron diffraction data and our previously published QC calculations.[21] TEDA is a liquid with bp 59–61 °C (15 Torr). This compound, unlike other alkyl-substituted diaziridines, proved to be an effective substrate in the [3+3]-cycloaddition reaction with donor–acceptor cyclopropanes, leading to little-known substituted perhydropyridazines.[4] The presence of three ethyl groups in TEDA makes the study of its structure interesting due to internal rotation and expands the possibilities of practical application in organic synthesis.

A TEDA sample was synthesized and characterized by 1D ^{1}H and ^{13}C NMR, 2D NMR (^{1}H–^{13}C HSQC, ^{1}H–^{13}C HMBC and ^{1}H–^{1}H gNOESY) and IR spectroscopy (Figures S1–S8 and Tables S1 and S2, see Online Supplementary Materials) at the N. D. Zelinsky Institute of Organic Chemistry, RAS. In a $CDCl_3$ solution under normal conditions, only one conformer was found, corresponding to structure **1c** (Figure 2).

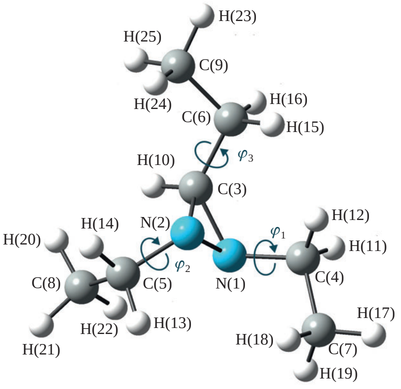
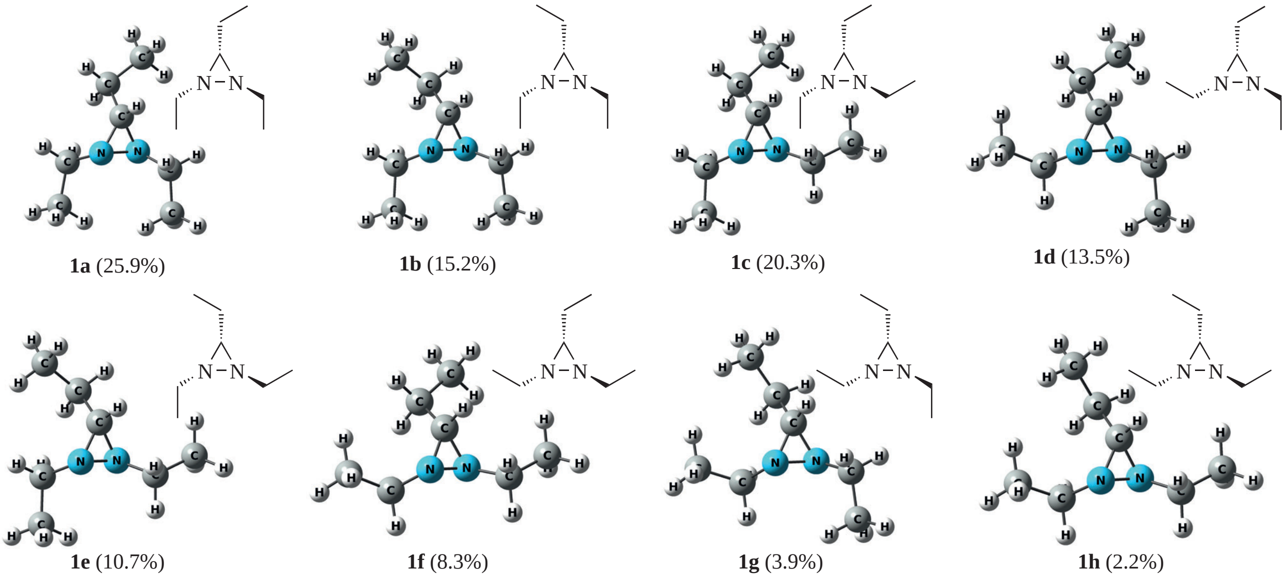


Figure 1 Structure of the TEDA molecule (C_1 point group symmetry) with atom numbering. Dihedral rotation angles of ethyl groups are designated as φ_1 = C(7)–C(4)–N(1)–N(2), φ_2 = C(8)–C(5)–N(2)–C(3) and φ_3 = C(9)–C(6)–C(3)–N(1).

© 2023 Mendeleev Communications. Published by ELSEVIER B.V. on behalf of the N. D. Zelinsky Institute of Organic Chemistry of the Russian Academy of Sciences.


1a (25.9%) **1b** (15.2%) **1c** (20.3%) **1d** (13.5%)

1e (10.7%) **1f** (8.3%) **1g** (3.9%) **1h** (2.2%)

Figure 2 Structures of eight TEDA conformers corresponding to the minima on PES in coordinates of torsional angles showing rotations of ethyl substituents. Their content in the gas mixture, calculated by the Gaussian-4 method, is given in parentheses.

The GED experiment was carried out in the Laboratory of Electron Diffraction of Molecules of M. V. Lomonosov Moscow State University. Experimental conditions, equipment and the resulting experimental curves of the total electron scattering intensity are given in Figure S9 and Tables S3–S5.

Previously, the intramolecular potential energy surface (PES) was analyzed as a function of the dihedral rotation angles of ethyl groups, E($\varphi_1, \varphi_2, \varphi_3$), where the dihedral angles are defined as φ_1 = C(7)–C(4)–N(1)–N(2), φ_2 = C(8)–C(5)–N(2)–C(3) and φ_3 = C(9)–C(6)–C(3)–N(1) (see Figure 1).[21] Briefly, the positions of minima on the PES and the equilibrium geometric parameters of the lowest energy conformations were refined in the MP2/cc-pVTZ approximation.[22,23] As a result, eight TEDA conformations with C_1 symmetry corresponding to these minima were found (see Figure 2). The differences in energy did not exceed 7 kJ mol^{-1}. Based on the MP2/cc-pVTZ calculations, the lowest energy conformation has structure **1a**. This conformation was taken as the global minimum.

In this work, we performed a structural analysis of the GED data in terms of the intramolecular PES parameters: the equilibrium internuclear distances r_e at the PES minima and the quadratic and cubic force constants. This approach allows for a direct comparison of experimental and calculated data. The equilibrium geometric parameters of the conformers obtained by QC calculations are given in Table 1. They were taken as the starting parameters of the molecular model indicated below. Based on the calculated quadratic and cubic force constants, harmonic and anharmonic corrections were calculated in determining the experimental equilibrium parameters of the TEDA molecule.

In order to perform the structural analysis, molecular models consisting of a finite set of low-energy stationary points were chosen to describe the molecular structure of TEDA as accurately as possible. As shown earlier, eight minima can be distinguished on the PES, corresponding to the lowest energy conformations. Therefore, mixtures of 8, 6 and 4 conformers were chosen as reference points to construct static (semi-rigid) molecular models. The criterion for selecting the number of conformers was the range of energies (6.8, 2.3 and 1.2 kJ mol^{-1}) counted from the global minimum, which were calculated in the MP2/cc-pVTZ approximation (Table S6).

For structural analysis, we used the equilibrium geometric parameters of all conformers and their quadratic and cubic force fields calculated by the MP2/cc-pVTZ method. These data, together

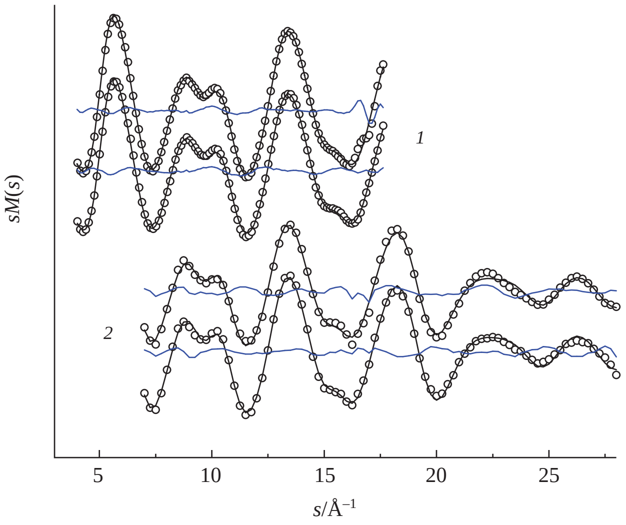


Figure 3 Experimental (○) and theoretical (–) molecular intensities $sM(s)$ for TEDA and differences $\Delta = sM^{\text{theor}}(s) - sM^{\text{exp}}(s)$ for (*1*) long and (*2*) short camera distances.

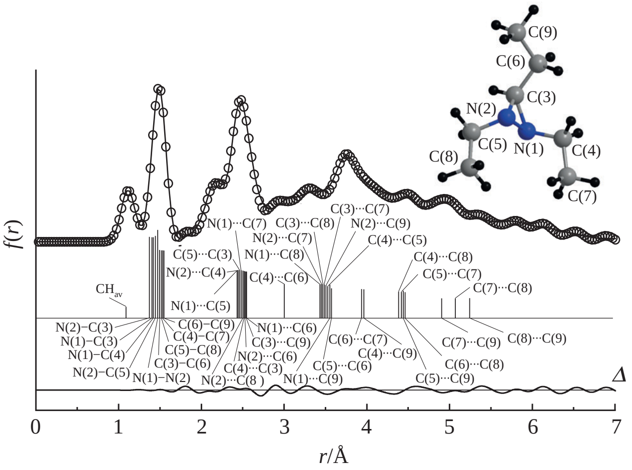


Figure 4 Experimental (○) and theoretical (–) radial distribution curves $f(r)$ and difference curve Δ for the TEDA molecule. Vertical bars show the distribution of intramolecular distances between heavy atoms. CH$_{av}$ is the average length of all C–H bonds. Atom numbering is shown in the inset.

Table 1 Equilibrium geometric parameters of TEDA,[a] obtained from the analysis of GED data and QC calculations.[b]

Bond lengths / Å			Bond angles / deg		
Parameter[a,c]	GED[d]	MP2/ cc-pVTZ[b]	Parameter[a,c]	GED[d]	MP2/ cc-pVTZ[b]
N(1)−N(2)^{A}	1.484(17)	1.496	C(4)−N(1)−N(2)^{E}	110.7(14)	110.4
C(4)−N(1)^{B}	1.439(6)	1.464	C(5)−N(2)−N(1)^{E}	109.7(14)	109.0
C(5)−N(2)^{B}	1.440(6)	1.464	C(3)−N(1)−C(4)^{F}	118.5(10)	117.0
C(3)−N(1)^{B}	1.429(6)	1.451	C(6)−C(3)−N(1)	125.6[e]	125.8
C(3)−C(6)^{C}	1.499(6)	1.502	C(7)−C(4)−N(1)^{G}	111.2(11)	109.1
C(4)−C(7)^{C}	1.514(6)	1.516	C(8)−C(5)−N(2)^{G}	111.8(11)	110.1
C(5)−C(8)^{C}	1.513(6)	1.515	H(10)−C(3)−N(2)^{H}	115.8(30)	115.8
C(6)−C(9)^{C}	1.522(6)	1.526	C−C−$H_{av}$$^{I\,f}$	109.6(20)	–
C−$H_{av}$$^{D\,f}$	1.092(11)	–	C(3)−C(6)−C(9)^{J}	112.5(11)	109.6

[a] Atom numbering is given in Figure 1. [b] Reference 21. [c] Parameters denoted by the same superscript A–J were combined into one group with differences fixed at the QC level. The parameters with superscripts A – I form independent groups. [d] Values in parentheses are three times the standard deviation. [e] The value was fixed at the QC level. [f] Average value.

with experimental data, make it possible to study the equilibrium structure and internal rotations in a nonrigid TEDA molecule in terms of intramolecular PES. This approach has been used to study the structure of nitrogen-containing organic molecules (*e.g.*, orotic acid[24]), diaziridine derivatives (*e.g.*, tetramezine[3]) and molecules with large amplitude motions (*e.g.*, 3-nitrostyrene[25]). Structural analysis was implemented in the Symm/Disp/Eldiff/Large software package.[26–28]

Theoretical and experimental curves $sM(s)$ are presented in Figure 3. They are obtained as a result of structural analysis and are characterized by the disagreement factor R_f (see below). Radial distribution curves $f(r)$ depicting the positions of intramolecular internuclear distance terms are shown in Figure 4.

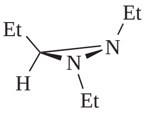
The static molecular model constructed for each of these eight conformers was described by nine groups of independent and three groups of dependent parameters. These groups were formed based on the similarity of parameters of the same physical nature and with slight differences in their magnitudes. The geometric parameters of the molecules calculated by QC methods were also considered in order to prevent large correlations between parameters within groups (Table S8).

Next, to determine the relative content of conformers in the mixture (see Figure 2) under normal conditions using the Boltzmann distribution, the Gibbs free energies of all conformers were calculated by the Gaussian-4 method[29] (see Table S6). This method takes into account zero-point energy and thermal corrections when calculating the energy of a molecule. Gaussian 09 (Revision C.01) was used for QC calculations.[30] Also by this method, using the technique of atomization reactions, the enthalpy of formation of TEDA ($\Delta_f H^0_{298} = 92.2 \pm 1.7$ kJ mol^{-1}) was calculated.

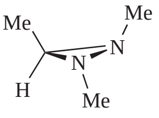
The minimum disagreement factors R_f between the theoretical and experimental curves $sM(s)$ were 5.0, 4.7 and 4.6 for mixtures of eight (structures **1a**–**h**), six (structures **1a**–**f**) and four (structures **1a**–**d**) conformers, respectively. Those are quite satisfactory values for such a non-rigid molecule; each of the conformers has three large amplitude motions with low frequencies less than 100 cm^{-1}, confirmed by MP2/cc-pVTZ calculations (Table S7).

Further, the equilibrium geometric parameters r_e were optimized. Comparing the obtained experimental data, we found that all relevant geometric parameters for heavy atoms do not differ significantly among all conformers (no more than 0.008 Å for bond lengths and no more than 2° for bond angles). Noticeable differences appear only for nonbonding internuclear distances corresponding to the arrangement of the ethyl fragments. The main equilibrium parameters averaged for all conformers are given in Table 1. All other equilibrium (r_e) and thermally averaged (r_g, r_a) distances, vibrational corrections and mean amplitudes (u) for internuclear distances in all conformers are collected in Tables S9–S16.

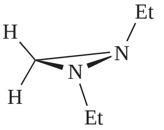
Table 2 presents for comparison the main geometric parameters obtained in the GED experiment for TEDA **1** and other similar monocyclic diaziridine derivatives, namely, 1,2,3-trimethyldiaziridine (1,2,3-TMDA)[17] **2**, 1,2-diethyldiaziridine (1,2-DEDA)[18] **3** and *meso*-tetramezine[3] **4**.



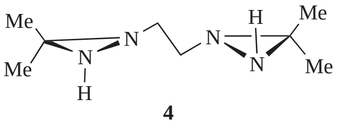
1



2



3



4

As can be seen, the data of the GED experiment (see Table 1) are in good agreement with the calculated ones,[21] except for the values of the bond lengths C(3)−N(1), C(4)−N(1) and C(5)−N(2): the experimental values are 0.020–0.025 Å less than the corresponding calculated values obtained in the MP2/cc-pVTZ approximation. Since the published data for related molecules mostly refer not to the equilibrium geometry (parameters r_e), but to the thermally averaged parameters r_g or r_{h1}, various vibrational corrections should be taken into account. Table 2 presents the r_g parameters for the TEDA molecule. Comparing the obtained values of thermally averaged parameters for TEDA with those for 1,2,3-TMDA, 1,2-DEDA and tetramezine molecules similar in structure, one can note slight differences in endocyclic N−C_{cyc} and exocyclic N−C_{alk} bonds, but within three standard deviations, these parameters do not differ statistically. However, the length of the endocyclic N−C_{cyc} bond in TEDA is shorter than in 3-methyldiaziridine[19] [1.489(9) Å] by 0.04 Å. If we consider the ratio of N–N bond lengths in these molecules, we can see the opposite trend: 1.444(13) Å in 3-methyldiaziridine *vs.* 1.496(17) Å in TEDA. Apparently, this effect is due to steric interactions of ethyl substituents. On the contrary, the N–N bond length in TEDA is somewhat shorter than in tetramezine. The interaction of electron orbitals $n_{N(2)} \rightarrow \sigma^*_{C(6)-C(9)}$ here probably plays a key role.

Since the TEDA molecule is asymmetric, the exocyclic bond angles C(3)−N(1)−C(4) and C(3)−N(2)−C(5) differ slightly in

Table 2 Experimental thermally averaged geometric parameters of some alkyl-substituted diaziridines: TEDA **1**, 1,2,3-TMDA **2**, 1,2-DEDA **3** and *meso*-tetramezine **4**.

Diaziridine	TEDA[a]	1,2,3-TMDA[b]	1,2-DEDA[c]	*meso*-Tetramezine[d]
		Bond lengths / Å		
Parameter	r_g^e	r_g/r_{h1}	r_{h1}	r_g
N−N	1.496(17)	1.479(15) / 1.480(15)	1.492(5)	1.526(9)
N−C_{cyc}^{f}	1.435(6)^{g}	1.450(15) / 1.448(15)^{g}	1.446(4)	1.442(3)^{g}
N−C_{alk}^{h}	1.449(6)^{g}	1.461(18) / 1.462(24)^{g}	1.459(6)^{g}	1.451(3)
		Bond angles / deg		
N−C−N	62.8^{i}	61.5(9)	62.1^{j}	63.8^{i}
C_{cyc}−N−C_{alk}^{f,h}	118.5(11) 115.1(11)	117.7(15)	114.7(6)	118.0(2)

[a] This work. [b] Reference 17. [c] Reference 18. [d] Reference 3. [e] Averaged values for 8 conformers. [f] The C_{cyc} atom belongs to the diaziridine cycle. [g] Average value. [h] The C_{alk} atom belongs to the alkyl substituent. [i] Calculated from refined Cartesian coordinates. [j] Taken from MP2/cc-pVTZ calculations.

values, about 3°, but are somewhat close in magnitude to the corresponding angles in the compared molecules (see Table 2).

Thus, for the first time, the equilibrium geometric parameters and the conformational composition of the TEDA molecule in the gas phase were experimentally determined by the GED method. The enthalpy of formation of the TEDA molecule $\Delta_f H^0_{298} = 92.2 \pm 1.7$ kJ mol^{-1} was also calculated for the first time, corrected for its conformational composition for a mixture of eight conformers. It should be noted that the R_f value was minimal for a mixture of four conformers **1a–d** and equaled 4.6, but in this case, the remaining four conformers **1e–h**, the total content of which is about 25%, are excluded from consideration, which is not entirely correct. Therefore, based on rather close and relatively low values of the disagreement factor R_f, it can be assumed that, under normal conditions, the TEDA molecule in the gas phase probably exists as a mixture of 6–8 conformers. The exact determination of all eight conformers is at the limit of sensitivity of the GED method and cannot be carried out unambiguously.

Online Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.mencom.2023.06.024.

References

1 N. N. Makhova, L. I. Belen’kii, G. A. Gazieva, I. L. Dalinger, L. S. Konstantinova, V. V. Kuznetsov, A. N. Kravchenko, M. M. Krayushkin, O. A. Rakitin, A. M. Starosotnikov, L. L. Fershtat, S. A. Shevelev, V. Z. Shirinian and V. N. Yarovenko, *Russ. Chem. Rev.*, 2020, **89**, 55.

2 S. Ravindra, C. P. Irfana Jesin, A. Shabashini and G. C. Nandi, *Adv. Synth. Catal.*, 2021, **363**, 1756.

3 L. S. Khaikin, I. V. Kochikov, A. N. Rykov, O. E. Grikina, G. G. Ageev, I. F. Shishkov, V. V. Kuznetsov and N. N. Makhova, *Phys. Chem. Chem. Phys.*, 2019, **21**, 5598.

4 A. O. Chagarovskiy, V. S. Vasin, V. V. Kuznetsov, O. A. Ivanova, V. B. Rybakov, A. N. Shumsky, N. N. Makhova and I. V. Trushkov, *Angew. Chem., Int. Ed.*, 2018, **57**, 10338.

5 T. Sarkar, K. Talukdar, S. Roy and T. Punniyamurthy, *Chem. Commun.*, 2020, **56**, 3381.

6 H. Hu, J. Xu, F. Wang, S. Dong, X. Liu and X. Feng, *Org. Lett.*, 2020, **22**, 93.

7 A. P. Molchanov, M. M. Efremova, M. A. Kryukova and M. A. Kuznetsov, *Beilstein J. Org. Chem.*, 2020, **16**, 2679.

8 J. Cortes Vazquez, J. Davis, V. N. Nesterov, H. Wang and W. Luo, *Org. Lett.*, 2021, **23**, 3136.

9 A. A. Penney, M. M. Efremova, A. P. Molchanov, M. A. Kryukova, A. Yu. Kudinov, A. S. Bunev, V. M. Keresten and M. A. Kuznetsov, *ChemistrySelect*, 2022, **7**, e202202627.

10 A. V. Shevtsov, V. Yu. Petukhova, Yu. A. Strelenko, K. A. Lyssenko, N. N. Makhova and V. A. Tartakovsky, *Russ. Chem. Bull.*, 2005, **54**, 1021 (*Izv. Akad. Nauk, Ser. Khim.*, 2005, 997).

11 M. Komatsu, N. Nishikaze, M. Sakamoto, Y. Ohshiro and T. Agawa, *J. Org. Chem.*, 1974, **39**, 3198.

12 M. Kamuf and O. Trapp, *Chirality*, 2011, **23**, 113.

13 N. N. Makhova, V. Y. Petukhova, A. V. Shevtsov, V. V. Novakovskiy and V. V. Kuznetsov, *Patent WO 2013/121334 A2*, 2013.

14 X. Zhang, L. Shen, Y. Luo, R. Jiang, H. Sun, J. Liu, T. Fang, H. Fan and Z. Liu, *Ind. Eng. Chem. Res.*, 2017, **56**, 2883.

15 V. Yu. Petukhova, Yu. A. Strelenko, K. A. Lyssenko and N. N. Makhova, *Russ. Chem. Bull.*, 2007, **56**, 1550 (*Izv. Akad. Nauk, Ser. Khim.*, 2007, 1491).

16 G. V. Shustov, S. N. Denisenko, I. I. Chervin, N. L. Asfandiarov and R. G. Kostyanovsky, *Tetrahedron*, 1985, **41**, 5719.

17 I. I. Marochkin, V. V. Kuznetsov, A. N. Rykov, N. N. Makhova and I. F. Shishkov, *Struct. Chem.*, 2019, **30**, 457.

18 I. I. Marochkin, V. V. Kuznetsov, Z. Li, A. N. Rykov, N. N. Makhova and I. F. Shishkov, *J. Mol. Struct.*, 2021, **1225**, 129066.

19 V. S. Mastryukov, O. V. Dorofeeva, L. V. Vilkov and A. V. Golubinskii, *J. Mol. Struct.*, 1976, **32**, 161.

20 E. P. Altova, V. V. Kuznetsov, I. I. Marochkin, A. N. Rykov, N. N. Makhova and I. F. Shishkov, *Struct. Chem.*, 2018, **29**, 815.

21 L. S. Khaikin, G. G. Ageev, O. E. Grikina, I. F. Shishkov, V. V. Kuznetsov and N. N. Makhova, *Russ. J. Phys. Chem. A*, 2020, **94**, 1836 (*Zh. Fiz. Khim.*, 2020, **94**, 1372).

22 C. Møller and M. S. Plesset, *Phys. Rev.*, 1934, **46**, 618.

23 T. H. Dunning, Jr., *J. Chem. Phys.*, 1989, **90**, 1007.

24 E. P. Altova, A. N. Rykov, N. Vogt and I. F. Shishkov, *Mendeleev Commun.*, 2021, **31**, 81.

25 D. M. Kovtun, I. V. Kochikov and Y. I. Tarasov, *J. Phys. Chem. A*, 2015, **119**, 1657.

26 I. V. Kochikov and Y. I. Tarasov, *Struct. Chem.*, 2003, **14**, 227.

27 L. S. Khaikin, I. V. Kochikov, O. E. Grikina, D. S. Tikhonov and E. G. Baskir, *Struct. Chem.*, 2015, **26**, 1651.

28 I. V. Kochikov, Yu. I. Tarasov, G. M. Kuramshina, V. P. Spiridonov, A. G. Yagola and T. G. Strand, *J. Mol. Struct.*, 1998, **445**, 243.

29 L. A. Curtiss, P. C. Redfern and K. Raghavachari, *J. Chem. Phys.*, 2007, **126**, 084108.

30 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, G. A. Petersson, H. Nakatsuji, X. Li, M. Caricato, A. Marenich, J. Bloino, B. G. Janesko, R. Gomperts, B. Mennucci, H. P. Hratchian, J. V. Ortiz, A. F. Izmaylov, J. L. Sonnenberg, D. Williams-Young, F. Ding, F. Lipparini, F. Egidi, J. Goings, B. Peng, A. Petrone, T. Henderson, D. Ranasinghe, V. G. Zakrzewski, J. Gao, N. Rega, G. Zheng, W. Liang, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, K. Throssell, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, T. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, J. M. Millam, M. Klene, C. Adamo, R. Cammi, J. W. Ochterski, R. L. Martin, K. Morokuma, O. Farkas, J. B. Foresman and D. J. Fox, *Gaussian 09, Revision C.01*, Gaussian, Inc., Wallingford, CT, 2016.

Received: 16th March 2023; Com. 23/7122