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ORIGINAL PAPER

Theoretical studies on the tautomerism of tetrazole selenone

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Abstract The tautomerism of all possible forms of tetrazole selenone (**A**–**G**), induced by proton transfer, was studied, theoretically, in different environments including gas phase, continuum solvent and microsolvated environment with one or two explicit water or ammonia molecules. The calculations were performed using two different levels of theory including mPW2PLYP and DFT-B3LYP. The 6-311++G(d,p) basis set was used for C, H, O and N and the standard relativistic effective core pseudo potential LANL2DZ basis set was used for Se atom. It was found that the tetrazole selenone, in the form of **A**, is the most stable isomer in all of the environments considered in this work. The kinetics of proton transfer reaction was studied in both gas and solvent environments and it was concluded that the activation energy of the reaction increases with going from the gas phase to polar solvents. Moreover, the proton transfer reaction assisted by one or two water or ammonia molecules was investigated and it was found that the activation energy significantly reduces.

Keywords Imidazole selenone · Microsolvation · mPW2PLYP · Solvent effect · Tautomerism

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Introduction

Tetrazole compounds have a wide range of pharmaceutical applications [1]. They act as stimulants or sedatives on the central nervous system. These compounds have anti-inflammatory, antilipemic, antimicrobial, and antial-lergic activities [2]. Moreover, such compounds are useful as oxidizers and effective agents for regulating plant growth and as explosives and rocket propellants [3]. Furthermore, tetrazole compounds have a significant role in medicinal chemistry [4]. For example, tetrazoles are regarded as isosteres of the carboxylic acid functionality in medicinal chemistry and angiotensin II receptor blockers such as candesartan and losartan contain tetrazole functional group [5, 6].

Tautomerism is a prototropic rearrangement in which a hydrogen at the R-position to a carbon–heteroatom double bond, migrates to the heteroatom. Since the energy differences among some tautomers are very small, their thermal energy may be simply transformed from one tautomer to another at room temperature. Moreover, for the tautomers with relatively high energy differences, solvent molecules act as catalysts and facilitate the tautomerization process to form molecule–solvent clusters. This has been found to be very useful for studying the effects of a specific solvent on the structure and reactivity of biomolecules [7–9].

Selenium is predominantly present in the biological systems in the form of naturally occurring amino acids selenocysteine (Sec) and selenomethionine that are incorporated in some proteins with a relevant role in redox equilibria. In biology selenium was long considered as a toxic element until 1957 when its role as micronutrient for bacteria, mammals and birds was reported [10]. More recently many books, reviews and reports, appeared in the literature, describe the identification of various selenoproteins, involved in a wide number of biochemical processes, as well as the nutrient importance of selenium [11–16]. Selenones have been much less studied than their sulfur analogues and

are only infrequently used in organic synthesis [17]. Several selenones, including diphenyl selenone, have been crystallographically characterized [18–20]. Selenones have been studied as potential antitumor agents [21] and the biological reduction of dimethyl selenone has been reported [22–24].

As a continuation of our recent studies on proton shift reactions of heterocycles and the effect of different environments on their equilibriums [25–28], herein we report the results of calculations of tautomerism of tetrazole selenone compound. The subject of the current study, namely, tetrazole selenone, has been chosen so that to allow a direct comparison with the analogous tetrazole thion and 5-aminotetrazole [28, 29].

Computational details

All calculations were performed using the Gaussian 09 computational chemistry package [30]. The geometry of tetrazole selenone and its isomers were optimized at the DFT-B3LYP [31, 32], and mPW2PLYP [33] levels of theory, separately. The mPW2PLYP is a double hybrid functional which was proposed by Grimme and it is a combination of exact exchange with a second-order perturbation correction for nonlocal correlation effects. It has been stated that this method can predict geometrical parameters more accurately [34–38].

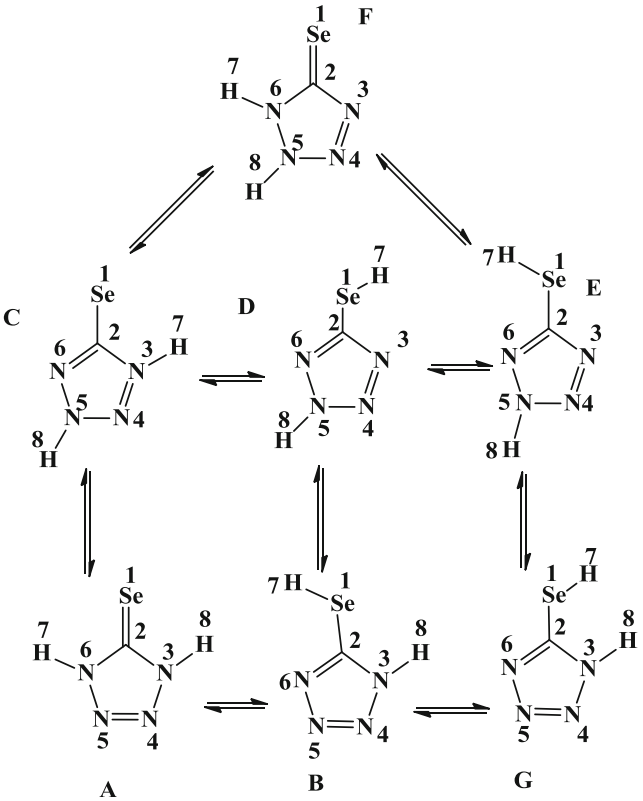
The 6-311++G(d,p) basis set was used for C, H, N, and O atoms and the relativistic effective core pseudo potential LANL2DZ which replaces the core electrons with an effective potential was used for selenium atom. Harmonic vibrational frequencies were computed at the same level of theory to verify the nature of minima. The effects of the polar medium (Benzene, THF, DMSO and water) on the relative stabilities and geometries of the tautomers were considered by using a relatively simple self-consistent reaction field (SCRF) method [39] based on polarizable continuum model (PCM) of Tomasi [40, 41] as implemented in the Gaussian software suite of program. The geometry of transition states of the proton transfer reactions for converting the tautomers to each other were determined using QST2 method at the mPW2PLYP level of theory. Similar calculations were performed on the complex of water and tautomers, at the same level of theory and basis set, to determine the transition state of proton transfer assisted by water or ammonia molecules.

Results and discussion

The compound tetrazole selenone can exists mainly as five tatomeric forms (**A, B, C, D, F**), and two rotamers (**E,G**). Their structures and their arbitrary numbering have been presented in Scheme 1. Tautomer **A** has a symmetrical tetrazole selenone form that can be converted to **B** and **C** tautomers through a proton transfer reaction from N6 to Se1 and N5 positions, respectively. The **C** isomer is a zwitterionic form of tetrazole selenone and **B** is a selenol 2*H*-tetrazole tautomer. On the other hand, the **B** isomer, by a rotation around C-Se bond, is converted to **G** rotamer. The **D** tautomer is formed by transferring the proton from N3 to Se1. In addition, the **D** compound can be converted to **E** rotamer through the rotation of Se-H bond around C-Se single bond. This isomer can also be converted to **F** tautomer (a tetrazole selenone isomer).

Tautomeric equilibria in the gas phase and solution

The calculated relative stabilities, (ΔE), zero point corrected relative stabilities (ΔE + ZPE) and dipole moments (μ) of all seven isomers of tetrazole selenone compound, shown in Scheme I, have been tabulated in Table 1. It is revealed from Table 1 that the tetrazole selenone compound (**A**) is the most stable tautomer in both gas and solution phases. The order of stability in the gas phase was found to be **A**> **D**> **E**> **B**> **G**> **C**> **F** for both mPW2PLYP and B3LYP methods. Based on the mPW2PLYP results in the gas phase, the energy of **D**, **E**, **B**, **G**, **C** and **F** isomers are 6.97, 7.34, 9.93, 11.28, 15.82 and 26.41 kcal mol^{-1}, higher than **A** isomer, respectively.



Scheme 1 Isomerization for the tautomers and rotamers of tetrazole selenone compound

Table 1 Calculated stabilities of isomers relative to the **A** isomer, in gas phase and solution as well as the calculated dipole moments of all isomers at MPW2PLYP and B3LYP levels of theory using 6-311++G(d,p) basis function

MPW2PLYP		A	B	C	D	E	F	G
Gas	ΔE[a]	0 (**0**)	9.93 (**0**)	15.82 (**0**)	6.97 (**0**)	7.34 (**0**)	26.41 (**0**)	11.28 (**0**)
	ΔE+ZPE	0	6.80	16.11	4.37	4.73	25.77	8.05
	μ[b]	1.96	4.99	7.11	1.51	3.12	6.45	6.17
Benzene	ΔE	0 (**−4.05**)[c]	9.50 (**−4.48**)	13.15 (**−6.72**)	8.30 (**−2.73**)	8.60 (**−2.80**)	24.54 (**−5.92**)	10.56 (**−4.77**)
	ΔE+ZPE	0	6.38	13.41	5.50	5.77	23.60	7.62
	μ	2.66	5.88	8.76	1.67	3.62	9.73	7.20
THF	ΔE	0 (**−9.04**)	8.60 (**−10.36**)	10.35 (**−14.50**)	9.20 (**−6.81**)	9.38 (**−7.00**)	20.15 (**−9.37**)	9.10 (**−11.23**)
	ΔE+ZPE	0	5.40	10.64	6.22	6.37	19.06	6.04
	μ	3.28	6.68	10.17	1.80	4.11	12.09	8.33
DMSO	ΔE	0 (**−10.53**)	8.12 (**−12.33**)	8.87 (**−17.47**)	9.67 (**−7.83**)	9.77 (**−8.09**)	17.50 (**13.51**)	8.17 (**−13.64**)
	ΔE+ZPE	0	4.92	9.18	6.68	6.75	16.68	5.17
	μ	3.58	7.08	10.84	1.87	4.36	13.02	8.87
H_2O	ΔE	0 (**−12.60**)	7.44 (**−15.08**)	8.60 (**−19.82**)	8.98 (**−12.13**)	9.07 (**−10.86**)	17.13 (**15.95**)	7.36 (**−16.52**)
	ΔE+ZPE	0	4.26	8.95	6.03	6.10	16.34	4.41
	μ	3.60	7.11	10.88	1.87	4.38	13.10	8.92
B3LYP								
Gas	ΔE	0	10.45	15.81	7.59	7.92	25.64	11.32
	ΔE+ZPE	0	7.04	16.05	4.72	5.01	24.79	8.07
	μ	1.55	5.04	6.47	1.62	2.8787	6.1456	5.93
Water	ΔE	0	8.17	8.69	9.87	9.98	16.58	8.00
	ΔE+ZPE	0	4.81	9.02	6.70	6.78	15.80	4.83
	μ	3.08	7.37	10.27	2.07	4.0728	12.5359	8.75

[a] Relative stabilities in kcal mol^{-1}

[b] Dipole moments in Debye

[c] The bolded values are the relative stability of isomers in different solvents

Inclusion of zero point vibrational energy did not changed the order of stability but reduced the energy difference between **A** and **D**, **E**, **B**, **G**, and **F** to 4.37, 4.73, 6.80, 8.05 and 25.77 kcal mol^{-1}, respectively. For the **C** tautomer, the addition of ZPE causes its instability of about 16.11 kcal mol^{-1}.

Dipole moment is the first derivative of the energy with respect to an applied electric field and is a measure of the asymmetry in the molecular charge distribution. The results of the calculated dipole moments of tetrazole selenone isomers in the range of 1.51–7.11 Debye have been reported in Table 1. The order of dipole moments was found as **C > F > G > B > E > A > D.** A similar trend was observed when the DFT-B3LYP level of theory is used in the gas phase.

Solvent effects are important in the tautomer stability phenomena, since polarity differences among tautomers can induce significant changes in their relative energies in solutions. For this purpose we used PCM model to analyze the solvent effects on the tautomerism of tetrazole selenone in different solvents including water, DMSO, THF and benzene. The calculated values of ΔE, ΔE + ZPE and μ of considered isomers have been presented in Table 1. The comparison of the results obtained from gas phase with those of the solution, confirms that the energies of all tautomers decrease with the increase in the polarity of solvent. The bolded values, presented in the Table 1, show the stability of each compound relative to its structure in the gas phase.

The results of calculations showed that with going to more polar solvents significant changes in the order of stability is observed. Although in the THF the order of stability was the same as in the gas phase, the order of stability changed to **A> B > G >D >E >C >F** in the more polar solvent DMSO, whereas the difference between **A** as the most stable and **B** as the second stable isomer reached 4.92 kcal mol^{-1}. Interestingly, with going to the water as the most polar solvent, the order of stability changed again and it was found that **G** is the second stable isomer. It is notable that with addition of ZPE correction the order of stability is the same as in the DMSO solvent. Similar results were obtained when the B3LYP/6-311++G(d,p) level was used for the isomers in the water (see Table 1). Table 1 also reveals that the dipole moments are affected by solvents and with going to more polar solvents a regular increase in the dipole moments was observed. Figure 1 shows the effect of various solvents on the dipole moment of tautomers of tetrazole selenone compound.

In the next stage, the proton transfer reaction in the interconversion of isomers in the gas phase and the effect of various solvents on this process are investigated. The values of activation energies (Ea) and free activation energies ($\Delta G^{\#}$) of transformations, calculated using QST2 method, have been listed in Table 2. The activation energy and free activation energy for the conversion of **A → B** reaction was found to be 33.09 and 32.31 kcal mol^{-1}, respectively. These values for the

Table 2 Activation energies and free energies of activation for interconversion of the isomers at the MPW2PLYP level of theory

		A → B	**B → D**	**B → G**	**G → E**	**A → C**	**F → C**
Gas	E_a	33.09	52.80	1.35	51.75	68.05	43.87
	$\Delta G^{\#}$	32.31	49.38	1.89	47.78	64.05	40.38
	Δ(E+ZPE)	31.73	49.00	1.25	48.06	64.03	40.34
	υ	−1609.31	−1730.99	−88.69	−1722.80	−1773.58	−1732.13
Benzene	E_a	35.17	54.40	1.10	54.58	68.03	45.26
	$\Delta G^{\#}$	34.23	51.93	1.54	50.49	63.90	42.28
	Δ(E+ZPE)	33.64	51.52	0.92	50.49	63.88	42.07
	υ	−1669.40	−1753.82	−183.85	−1747.10	1802.23	−1742.21
THF	E_a	37.61	57.38	1.15	56.97	67.29	48.18
	$\Delta G^{\#}$	36.07	53.39	1.27	53.17	63.17	45.51
	Δ(E+ZPE)	36.14	53.62	1.26	53.04	63.15	45.15
	υ	−1730.86	−1763.72	−144.16	−1758.39	−1809.18	−1740.64
DMSO	E_a	38.82	58.33	1.17	58.26	66.74	49.75
	$\Delta G^{\#}$	37.28	54.34	1.22	54.40	62.60	46.63
	Δ(E+ZPE)	37.35	54.57	1.23	54.30	62.58	46.45
	υ	−1763.05	−1766.99	−240.23	−1761.99	−1809.22	−1735.75
Water	E_a	39.59	57.96	1.09	58.00	66.25	49.58
	$\Delta G^{\#}$	38.06	53.78	1.17	54.16	62.13	46.47
	Δ(E+ZPE)	38.11	54.08	1.17	54.00	62.11	46.29
	υ	−1766.54	−1754.79	−210.81	−1750.44	−1798.05	−1733.64

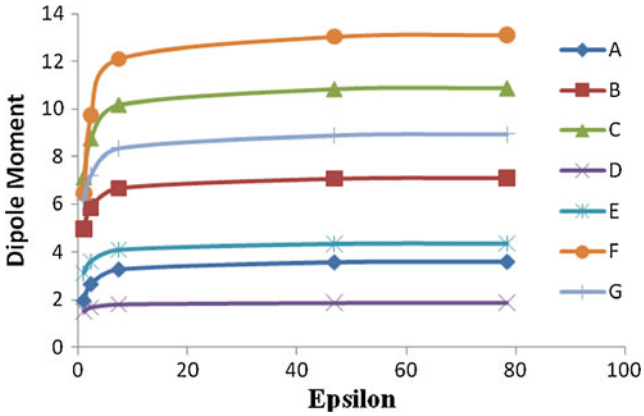


Fig. 1 the effect of solvents on the dipole moments of tetrazole selenone isomers

B → D reaction were found to be 52.8 and 49.38 kcal mol^{-1}, respectively. In addition for the **D → E**, **G → E, A → C** and **F → C** processes the activation energy values were found as 52.76, 51.75 68.05 and 43.87 kcal mol^{-1}, respectively. These values are comparable with the values previously reported for proton transfer reaction between Se–H bond and N atom in the selenourea compound (95 kJ mol^{-1}), studied by Rostkowska et al. [42]. In addition, the activation energy of proton transfer for 2-pyridineselenol is about 24.7 kcal mol^{-1} calculated at B3LYP/6-311+G(d,p) level of theory [43]. Besides for the proton transfer reaction of imidazole selenone tautomers the values were found in the range of 25.3 to 44.3 kcal mol^{-1} at MP2/6-31++G(d,p) method [44]. In addition, the values for the 5-amino tetrazole and tetrazole thion have been reported in the range of 49.52–69.02 and 41.6–55.94 kcal mol^{-1} respectively [28, 29]. It is notable that the energy barrier for rotation around the Se-C bond in **D → E** transformation is 5.0 kcal mol^{-1} in the gas phase. The calculate transition states of proton transfer reactions of tetrazole selenone isomers have been presented in Fig. 2. The effect of various solvents on the activation energy of the proton transfer reactions of tetrazole selenone tautomers was also investigated. According to the results shown in Table 2, the activation energy of A → B reaction increases from 33.09 to 39.59 kcal mol^{-1} with going from the gas phase to water as the most polar solvent. On the other hand, the activation energy of the **B → D** reaction in which 1*H* tautomer converted to 2*H* isomer of tetrazole selenol, increases from 52.80 to 57.96 kcal mol^{-1} with going to more polar solvents.

The values of imaginary frequencies associated with transition states of proton transfer reactions of tetrazole selenone derivatives have also been included in Table 2. As known, the magnitude of the imaginary frequency is a measure of the curvature of the transition state region along the reaction coordinate. Therefore, for a series of related reactions, a small imaginary frequency should correspond to a low barrier and a large imaginary frequency to a high barrier. In other words, for low barriers the transition region may be relatively flat. According to calculated imaginary frequencies in Table 2, with going from gas phase to polar solvents a regular increase in the values of imaginary frequencies was observed. The optimized structures of transition states of interconversion of tetrazole selenone isomers presented in Fig. 2.

Vibrational analysis

The infrared spectrum of tetrazole and its derivatives have been investigated by experimental and theoretical methods [45–48]. Wilson studied the vibrational spectra of tetrazole and carried out a normal coordinate analysis using a Urey-Bradley force field [45]. Sokolova and coworkers recorded the infrared spectra of the compound and some of its simple substituted derivatives [46]. They also calculated the vibrational frequencies using the classical GF matrix method. Sushko et al. recorded the infrared spectrum of tetrazole and N-deuterotetrazole and calculated the vibrational frequencies using the semiempirical MNDO method [47].

In order to obtain the infrared spectroscopic properties of imidazole selenone and its isomers, the frequency calculation analysis was performed. Calculations were carried out for a free molecule in vacuum using mPW2PLYP method. The frequency calculations were performed only on the optimized geometries of most important **A**, **B**, and **D** isomers at the same level of theory. The results of calculations and their assignments have been collected in the Table 3.

The symmetrical and asymmetrical N–H stretching modes for the tetrazole selenone form (**A** isomer) were found at 3691.9, and 3690.1 cm^{-1}, respectively. In addition the C = S stretching mode for the **A** was found at 376.7 cm^{-1}. However, the symmetrical and asymmetrical out of plane bending of N–H bonds appear at 488.8 and 344.8 cm^{-1}, respectively. The important vibrational modes for the **B** tautomer are assigned as follows: The N–H and Se–H stretching mode were found at 3685.8 and 2484.6 cm^{-1}, respectively. Besides, the C–Se stretching mode, in-plane and out of plane bending of Se–H were found at 344.8, 829.8 and 88.2 cm^{-1}, respectively. For the **D** isomer as the 2*H* tautomer of selenol form, the N–H and Se–H stretching mode was found at 3673.6 and 2481.5 cm^{-1}, respectively. In addition the C–Se stretching mode appears at 348.6 cm^{-1}. In addition, the in-plane and out of plane bending of Se–H bond was found at 230.6 and 128.1 cm^{-1}, respectively. It is notable that the vibrational analysis via matrix isolation infrared spectroscopy for the selenourea compound that is structurally similar to the tetrazole selenone has been reported in ref. [42]. The stretching mode of C = Se bond in selenourea appears at 611 cm^{-1}. Moreover, the Se–H stretching mode, calculated at the B3LYP/6-311++G(2d,p) level of theory, for selenourea is 2361 cm^{-1}.

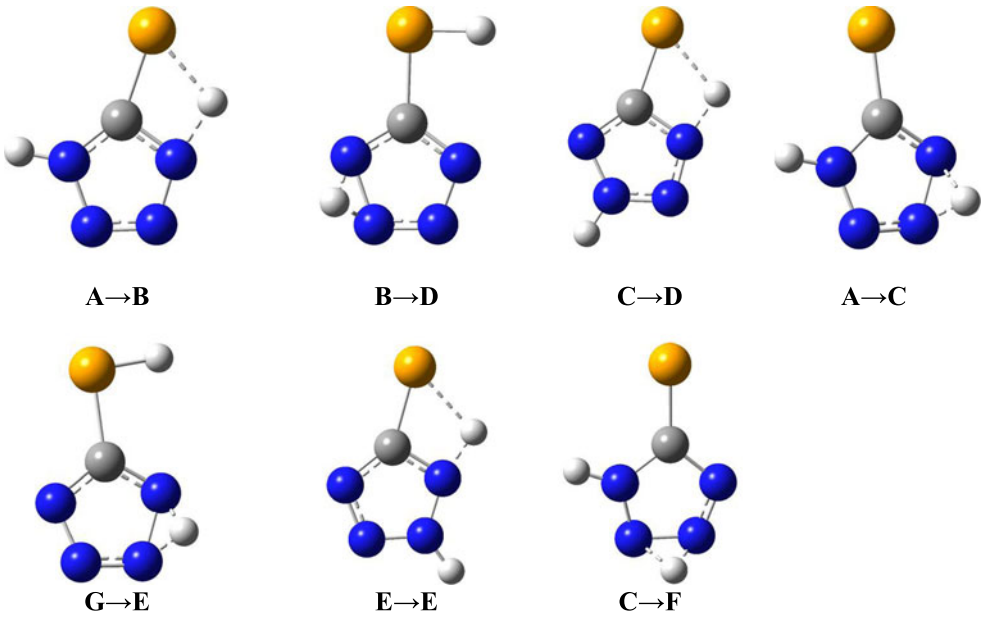


Fig. 2 Optimized structures of the transition states of proton transfer reactions of tetrazole selenone isomers in the gas phase

Microsolvation

Protic solvents such as water or alcohols, as a strong hydrogen bond donor/acceptor, can accept a proton from the donor site of the solute molecule or give another proton to the proper sites of the solute. Water-assisted proton transfer mechanism studies have shown that the assistance of a water molecule significantly lowers the free energy barriers in proton-transfer related reactions [44, 49–51]. In this case, an explicit interaction with a limited number of protic solvent molecules could influence the whole reaction path by lowering the energy barrier due to the direct participation of molecules in the proton transfer process. Selecting the hydrophilic centers on the tetrazole selenone, we searched the most stable monohydrated forms for all tautomers. All geometries were fully optimized using mPW2PLYP method.

Table 3 Harmonic vibrational frequencies (cm^{-1}) of the most important isomers of imidazole selenone, calculated at mPW2PLYP level of theory, in the gas phase

	A		B		D	
1	196.8	$\Gamma_{SeCN4N5}+\Gamma_{SeCN7N6}$	88.2	$\Gamma_{N6CSeH7}+\Gamma_{N3CSeH7}$	128.1	$\Gamma_{N3CSeH7}+\Gamma_{N6CSeH7}$
2	264.9	$\rho_{SeCN4}+\rho_{SeCN7}$	216.9	$\Gamma_{SeCN3N4}+\Gamma_{SeCN6N5}$	230.6	$\Gamma_{SeCN3N4}+\Gamma_{SeCN6N5}$
3	376.7	ν_{SeC}	240. 8	$\rho_{SeCN3}+\rho_{SeCN6}$	248.4	$\rho_{SeCN3}+\rho_{SeCN6}$
4	486.6	$(\tau_{N7H2}+\tau_{N4H8})$asym	344.8	ν_{SeC}	348.6	ν_{SeC}
5	541.8	$(\tau_{N7H2}+\tau_{N4H8})$sym	488.8	$\Gamma_{SeCN3H8}+\Gamma_{N6CN3H8}$	560.7	$\Gamma_{N3N4N5H8}+\Gamma_{CN6N5H8}$
6	669.2	$\Gamma_{SeCN4H8}+\Gamma_{SeCN7H2}$	697.1	$\Gamma_{N5N4N3H8}+\Gamma_{N6CN3H8}$	719.8	$\Gamma_{CN6N5H8}$
7	713.22	$\Gamma_{N6N5N4H8}+\Gamma_{N5N6N7H2}$	718.7	$\Gamma_{N3N4N5N6}+\Gamma_{CN3N4N5}$	738.2	$\Gamma_{N6CN3N4}+\Gamma_{CN3N4N5}$
8	1022.3	$\nu_{CN4}+\nu_{CN7}+\nu_{N4N5}+\nu_{N6N7}$	829.8	ρ_{CSeH8}	845.0	ρ_{CSeH7}
9	1039.6	$\nu_{N4N5}+\nu_{N6N7}+\rho_{N4N5N6}+\rho_{N5N6N7}$	999.7	ν_{N5N6}	1024.7	$\nu_{N5N6}+\rho_{CN6N5}$
10	1052.3	$\rho_{CN4N5}+\rho_{CN7N6}$	1048.4	$\nu_{N3N4}+\rho_{N4N2H8}$	1057.3	$\rho_{CN3N4}+\rho_{N3N4N5}$
11	1097.9	$\nu_{N4N5}+\nu_{N6N7}$	1057.0	$\nu_{N3N4}+\rho_{CN3H8}$	1149.3	$\nu_{SeC}+\rho_{N6N5H8}$
12	1169.6	$\nu_{SeC}+\rho_{N5N4H8}+\rho_{H2N7N6}$	1085.7	$\nu_{N5N6+}\rho_{N3N4N5}$	1180.7	$(\nu_{N3N4}+\nu_{N5N6})$ asym
13	1300.1	$\nu_{CN4}+\nu_{CN7}$	1252.9	$\rho_{CN3H8}+\rho_{H2N7H6}$	1251.6	$(\nu_{N3N4}+\nu_{N5N6})$ sym
14	1401.3	ν_{N4-N5}	1324.7	$\rho_{CN3H8}+\nu_{N4N5}$	1297.6	ν_{CN3}
15	1403.3	$\rho_{N5N4H8}+\rho_{H2N7N6}$	1407.5	$\nu_{CN3}+\nu_{CN6}$	1407.1	$\nu_{CN6}+\rho_{N4N5H8}$
16	1554.7	$\rho_{CN4H6}+\rho_{N5N4H8}+\rho_{CN7H2}+\rho_{H2N7N6}$	1515.1	$\rho_{N4N3H8}+\rho_{N2N3H8}$	1509.2	$\rho_{N4N5H8}+\rho_{N6N5H8}$
17	3690.1	$\nu_{N-H}+\nu_{N-H}$ asym	2484.6	ν_{SeH}	2481.5	ν_{SeH}
18	3691.9	$\nu_{N-H}+\nu_{N-H}$ sym	3685.8	ν_{N3H8}	3673.6	ν_{N5H8}

Subscript definitions: asym (asymmetric); sym (symmetric); υ (stretching); ρ (in-plane bending); τ out of plane bending, Γ Torsional vibration

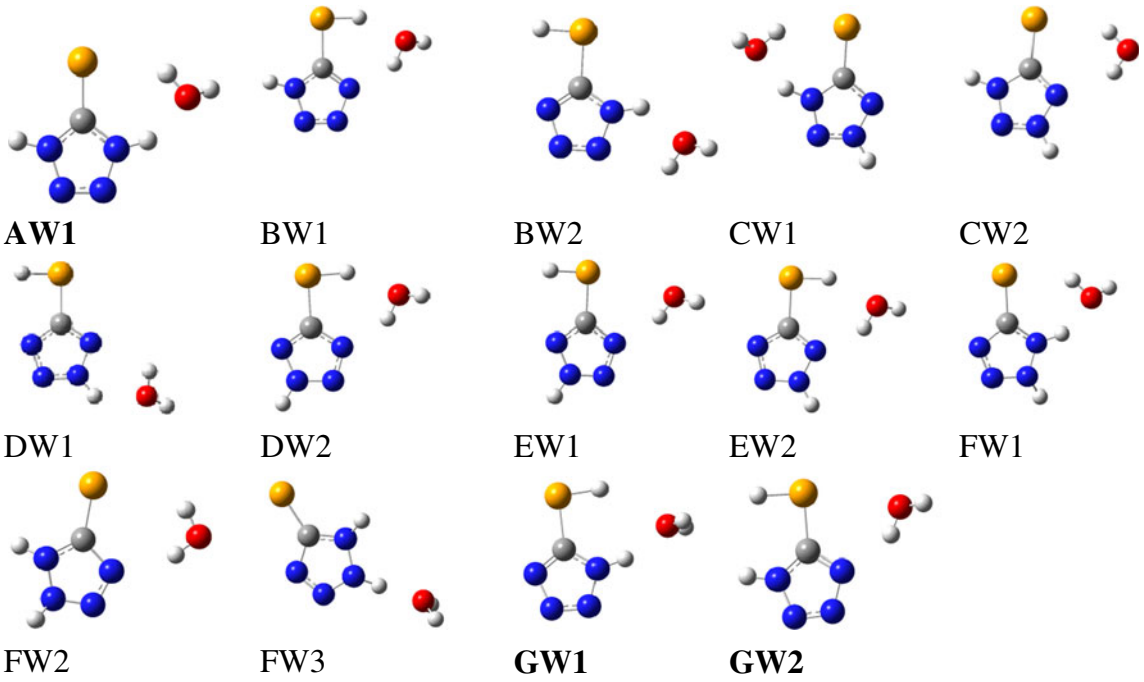


Fig. 3 Optimized structures of monohydrated isomers of tetrazole selenone at mPW2PLYP level in the gas phase

The optimized microsolvated structures of complexes are shown in Fig. 3. In addition, the results of total energies, relative stabilities of monohydrate complexes and hydrogen bond distances in the gas phase are collected in Table 4. The interaction energies were obtained by subtracting the energy of fully optimized tetrazole selenone tautomers and water molecule from the energy of the optimized microsolvated structures of complexes (Eq. 1):

$$E_{\text{int}} = E_{complex} - (E_{tetrazole} + E_{water}) \quad (1)$$

where E $_{\text{tetrazole}}$, E $_{\text{water}}$ and E $_{\text{complex}}$ are the electronic energies of tetrazole selenone molecule, water molecule and the complex, respectively. It is evident from Table 4 that the most stable form is the **AW1**, in which water molecule acts as hydrogen acceptor. The second stable aggregates are **DW1** and **DW2** complexes with 10.55 and 10.87 kcal mol^{-1} instability relative to **AW1** in the gas phase, respectively. The order of stability of monohydrated complexes was found to be **AW1**> **DW1**> **DW2**> **BW1**> **BW2**> **EW2**> **GW1**> **CW1**> **EW1**> **GW2**> **FW1**> **FW3**> **FW2**> **CW2**. In the next step we analyzed the hydrogen bonding strength in the complexes.

The calculated results presented in Table 4 show that the strongest hydrogen bond was found for the **CW1** complex with 14.78 kcal mol^{-1} where water acts as a proton acceptor from the **C** tautomer. In addition, for the **FW1** and **AW1** isomers, the hydrogen bond strength was found to be 14.10 and 12.73 kcal mol^{-1}, respectively.

For evaluating the effect of explicit small molecules on the proton transfer reaction, the transition state of **A** → **B** and **B** → **D** reactions assisted by one or two water and ammonia molecules in the gas phase were calculated. The optimized structures and activation energies are presented in Fig. 4. As seen, the inclusion of one water or ammonia molecule causes the activation energies to significantly decrease. For example, for the **A** → **B** reaction that tetrazole selenone compound

Table 4 The calculated relative stabilities, hydrogen bond strengths and hydrogen bond distances of mono hydrated tautomers of tetrazole selenone in the gas phase at the mPW2PLYP level of theory

Tautomer	ΔE[a]	HB distance[b]	HB strength[c]
AW1	0	1.820	12.73
BW1	11.92	1.980	10.74
BW2	12.38	1.943	9.94
CW1	13.78	1.763	14.78
CW2	37.81	2.290	9.26
DW1	10.55	1.980	9.16
DW2	10.87	2.009	8.84
EW1	13.88	2.007	6.20
EW2	13.17	2.076	6.92
FW1	25.04	1.756	14.10
FW2	32.96	2.195	6.19
FW3	27.9	1.776	11.27
GW1	13.27	1.882	10.84
GW2	16.48	1.991	7.54

[a] Relative energies in kcal mol^{-1}

[b] Hydrogen bond distance in angstrom

[c] bond strength in kcal mol^{-1}

converts to 1*H*-selenol form, the activation energy of proton transfer reaction decreases from 33.09 to 19.40 and 14.32 kcal mol^{-1} for the water or ammonia assisted reaction, respectively. In addition, for the **B** → **D** reaction that 1*H* tautomer can be converted to 2*H*, the activation energy in the gas phase decreases from 52.8 to 27.29 and 15.52 kcal mol^{-1} for the water and ammonia assisted reaction, respectively. As seen, the ammonia molecule can decrease the activation energy more effectively than water molecule.

A question may be raised here: Can we reduce the activation energy of proton transfer reaction more by adding more solvent molecules around the tetrazole selenone isomers? For this propose a proton transfer reaction assisted by two water molecules, two ammonia or one ammonia and one water molecules for the **A** → **B** and **B** → **D** reactions were considered. The calculated transition states have been presented in Fig. 4. According to Fig. 4, in a microsolvated environment, the proton transfer reaction is carried out faster with lower activation energy. For example, for the **A** → **B** reaction, when the reaction assisted by two water molecule the activation energy decreased to16.94 kcal mol^{-1}. Furthermore, when water acts as hydrogen acceptor and ammonia acts as hydrogen donor to tetrazole selenone (**A** form) the activation energy reduced to 9.66 kcal mol^{-1}. Interestingly, when ammonia acts as proton acceptor and water as the proton donor to **A** the activation energy was found to be

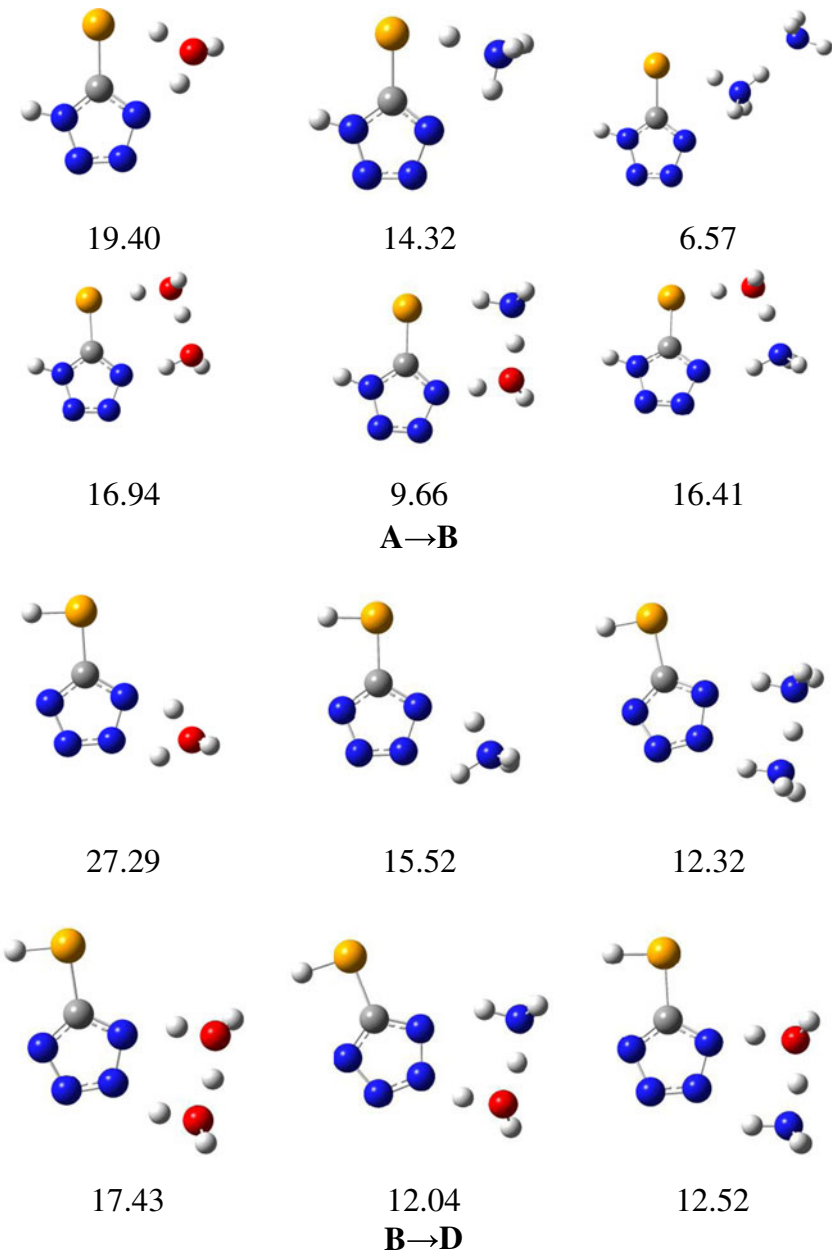


Fig. 4 Optimized structures and activation energies of proton transfer reaction of A → B and B → D reactions assisted by one or two molecules of water and ammonia in the gas phase calculated at

16.41 kcal mol^{-1}. In addition, for the **B** → **D** reaction, the activation energy of proton transfer reaction assisted by two water or ammonia molecules found 17.43 and 12.32 kcal mol^{-1}, respectively. When the water molecule acts as proton acceptor and ammonia as proton donor to the **B** tautomer the activation energy was found to be 12.52 kcal mol^{-1}. When ammonia molecule acts as proton acceptor and water as donor the activation energy was found to be 12.04 kcal mol^{-1}.

Conclusions

The main results of the present study can be summarized in the following manner:

1. This work represents an extension of the study of tautomerism of tetrazole selenone compound in the gas phase, solvent and microsolvated environment.
2. In the gas phase the tetrazole selenone compound (**A** form) is the most stable isomer and the order of stability is **A**> **D**> **E**> **B**> **G**> **C**> **F**.
3. This stability order depends on the polarity of solvent and with going to more polar solvents changes.
4. Proton transfer reaction was studied in the gas phase and solvent, separately, and the activation energies were found in the range of 33.09-68.05 kcal mol^{-1} in the gas phase.
5. Inclusion of one water or ammonia molecule decreases the activation energy significantly and it was found in the range of 14.32–27.29.
6. Inclusion of two solvent molecules causes the proton transfer reaction to take place with lower activation energy.

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References

1. Gilchrist TL (1992) Heterocyclic chemistry, 2nd edn. Wiley, New York
2. Herr RJ (2002) Bioorg Med Chem 10:3379–3393
3. John EO, Kirchmeier RL, Shreeve JM (1989) Inorg Chem 28:4629–4633
4. Butler RN (1996) In: Katritzky AR, Rees CW, Scriven EFV (eds) Comprehensive heterocyclic chemistry II, vol 4. Pergamon Press, New York
5. Kubo K, Kohara Y, Imamiya E, Sugiura Y, Inada Y, Nishikawa K, Naka T (1993) J Med Chem 36:2182–2195
6. Noda K, Saad Y, Kinoshita A, Boyle TP, Graham RM, Husian A, Karnik SS (1995) J Biol Chem 270:2284–2289
7. Smith MB, March J (2001) Advanced organic chemistry, 5th edn. Wiley, New York, pp 1218–1223
8. Robertson EG, Simons JP (2001) Phys Chem Chem Phys 3:1–18
9. Xu S, Niles JM, Bowen KH Jr (2003) J Chem Phys 119:10696–10701
10. Scharz K, Foltz CM (1975) J Am Chem Soc 79:3292
11. Levander OA (1986) Selenium. In: Mertz W (ed) Trace elements in human and animal nutrition, vol 2. Academic, Orlando, p 209
12. Levander OAA (1987) Rev Nutr 7:227–250
13. Nève J Biological Functions of Selenium (1988) In: Nève J, Favier A (eds) Selenium in medicine and biology. W de Gruyter, Berlin, p 97
14. Ganther HE (1999) Carcinogenesis 20:1657–1666
15. Köhrle J (1999) Biochimie 81:527–533
16. Jacob C, Giles GI, Giles NM, Sies H (2003) Angew Chem Int Ed 42:4742–4758
17. Noureldin NA, McConnell WB, Lee DG (1984) Can J Chem 62:2113–2116
18. Krief A, Dumont W, Denis J N, Evrard G, Norberg B (1985) Chem Commun 569–570
19. Hoier H, Carrell HL, Glusker JP, Spears CP (1993) Acta Crystallogr C49:520–523
20. Nakayama J, Matsui T, Sugihara Y, Ishii A, Kumakura S (1996) Chem Lett 269–270
21. Kang SI, Spears CP (1990) J Med Chem 33:1544–1547
22. Zhang L, Chasteen TG (1994) Appl Organomet Chem 8:501–508
23. Yu R, Coffman JP, Van Fleet-Stalder V, Chasteen TG (1997) Environ Toxicol Chem 16:140–145
24. Chasteen TG, Bentley R (2003) Chem Rev 103:1–26
25. Chermahini AN, Teimouri A, Momenbeik F, Zarei A, Dalirnasab Z, Ghaedi A, Roosta M (2010) J Heterocycl Chem 47:913–922
26. Chermahini AN, Dabbagh AH, Teimouri A (2007) J Mol Struct (Theochem) 822:33–37
27. Chermahini AN, Teimouri A, Moadeli A (2011) Heteroat Chem 22:168–173
28. Chermahini AN, Teimouri A, Salimi Beni A (2011) Struct Chem 22:178–181
29. Zhang J-G, Feng L-N, Shu Y-J, Zhang S-W, Zhang T-L, Yang L, Wu M (2009) J Mol Model 15:67–77
30. Frisch MJ, Trucks GW, Schlegel HB, Scuseria GE, Robb MA, Cheeseman JR, Scalmani G, Barone V, Mennucci B, Petersson GA, Nakatsuji H, Caricato M, Li X, Hratchian HP, Izmaylov AF, Bloino J, Zheng G, Sonnenberg JL, Hada M, Ehara M, Toyota K, Fukuda R, Hasegawa J, Ishida M, Nakajima T, Honda Y, Kitao O, Nakai H, Vreven T, Montgomery JA Jr, Peralta JE, Ogliaro F, Bearpark M, Heyd JJ, Brothers E, Kudin KN, Staroverov VN, Kobayashi R, Normand J, Raghavachari K, Rendell A, Burant JC, Iyengar SS, Tomasi J, Cossi M, Rega N, Millam JM, Klene M, Knox JE, Cross JB, Bakken V, Adamo C, Jaramillo J, Gomperts R, Stratmann RE, Yazyev O, Austin AJ, Cammi R, Pomelli C, Ochterski JW, Martin RL, Morokuma K, Zakrzewski VG, Voth GA, Salvador P, Dannenberg JJ, Dapprich S, Daniels AD, Farkas Ö, Foresman JB, Ortiz JV, Cioslowski J, Fox DJ (2009) Gaussian09. Gaussian Inc., Wallingford
31. Becke AD (1993) J Chem Phys 98:5648–5652
32. Lee C, Yang W, Parr RG (1988) Phys Rev B 37:785–789
33. Schwabe T, Grimme S (2006) Phys Chem Chem Phys 8:4398
34. Antonov L, Kurteva V, Crochet A, Mirolo L, Fromm KM, Angelova S (2012) Dyes Pigment 92:714–723
35. Sameera WMC, Pantazis DA (2012) J Chem Theory Comput 8:2630–2645
36. Salimi Beni A, Jafari Chermahini Z (2013) Struct Chem doi:10.1007/s11224-013-0210-8
37. Fang HC, Li ZH, Fan KN (2011) Phys Chem Chem Phys 13:13358–13369
38. Antonov L, Kurteva V, Crochet A, Mirolo L, Fromm KM, Angelova S (2011) Dyes Pigment 92:714–723
39. Tomasi J, Persico M (1994) Chem Rev 94:2027–2094

40. Cance's E, Mennucci B, Tomasi J (1997) J Chem Phys 107:3032–3041
41. Barone V, Cossi M, Tomasi J (1998) J Comput Chem 19:404–417
42. Rostkowska H, Lapinski L, Khvorostov A, Nowak M (2004) J Chem Phys 298:223–232
43. Zhang YA, Monga V, Orvig C, Wang YA (2008) J Phys Chem A 112:3231–3238
44. Chermahini AN, Farookhpour H, Teimouri A, Pourmoghaddas F (2013) Struct Chem 24:1215–1227
45. Billes F, Endredi H, Keresztury G (2000) J Mol Struct (Theochem) 530:183–200
46. Sokolova MM, Melynikov VV et al (1975) Zh Obshch Khim 11:1744
47. Kyzhnyaev VN, Vereshchagin LI (2003) Russ Chem Rev 72:143–164
48. Markova N, Enchev V, Timtcheva I (2005) J Phys Chem A 109:1981–1988
49. Kyrychenko A, Waluk J (2006) J Phys Chem A 110:119 58–11967
50. Yepes D, Murray JS, Santos JC, Toro-Labbé A, Politzer P, Jaque P (2012) J Mol Mod. doi:10.1007/s00894-012-1475-3
51. Gorb L, Leszczynski J (1998) J Am Chem Soc 120:5024–5032