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Ab initio study of 2,4-substituted azolidines. I. Tautomerism

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Abstract

Detailed investigation of the tautomerism of oxazolidines, thiazolidines and selenazolidines substituted at positions 2 and 4 by hydroxy and amino groups was carried out by calculations at HF and MP2 levels of theory and NMR spectroscopy. The relative stabilities of the tautomers of the heterocycles were calculated in gas phase and in solvents $CHCl_3$ and DMSO utilizing the PCM method. The ab initio calculations, in agreement with the available experimental data, predict that the azolidines substituted at positions 2 and 4 by a hydroxy and an amino group exist as amino form in solution, while 2,4-diamino-oxazolidine, -thiazolidine and -selenazolidine occur as mixtures of tautomers.

HF, MP2 and DFT GIAO ^{13}C chemical shifts for the thiazolidines were calculated using the 6-311+G(d,p) basis set. Since, the MP2 calculations gave the best agreement with the experimental data, GIAO ^{13}C chemical shifts for the other compounds were studied at this level.

Keywords: Heterocycles; Tautomerism; Oxazolidine; Thiazolidine; Selenazolidine

1. Introduction

Heterocyclic tautomerism has been studied extensively for the past two decades due to its biological importance and highly solvent-dependent nature. It has been shown that solute–solvent interactions can determine the relative stability of the tautomeric forms [1,2].

The prototropic tautomerism of oxazolidines and thiazolidines containing oxo or thioxo groups in positions 2 and 4 of the five-membered heterocyclic ring has been studied theoretically at ab initio [3–5] and DFT [6] levels, and by IR and NMR spectroscopy [3,7]. The quantum chemical calculations and the experimental data indicate that in these compounds the thioxo, dioxo or dithio tautomer is most stable.

It is now accepted that amino-thiazolidinones exist predominantly in the amino form when the amino group is in position 2, whereas in position 4 they adopt the imino form [7]. 2,4-Diaminothiazole has been isolated as a salt, but is unstable as a free base [8]. The tautomerism and structure of 2,4-diaminothiazoles have been investigated by IR and NMR spectroscopy [7,9] and it has been shown that 2-amino-4-imino-thiazolidine is the predominant tautomer. According to Davies et al. [8], the free base of 2,4-diamino-selenazole is too unstable to be isolated. To our knowledge, there are no theoretical or experimental studies on the tautomerism of selenazolidines so far.

Based on the results of ab initio calculations at a high level of theory, the relative energies of the structures participating in a tautomeric equilibrium can be inferred. The calculations of the tautomeric equilibrium are difficult because characteristically it is dependent on the solvents employed. However, a combination of theoretical calculations and NMR spectroscopy seems to be promising for investigating the tautomeric equilibrium. In addition, the comparison of calculated and experimentally determined chemical shifts can be used to find the most stable tautomeric form of the studied compounds.

In the present work, oxazolidine, thiazolidine and selenazolidine containing hydroxy and amino groups in positions 2 and 4 of the five-membered heterocyclic system are studied. Such compounds are of interest because

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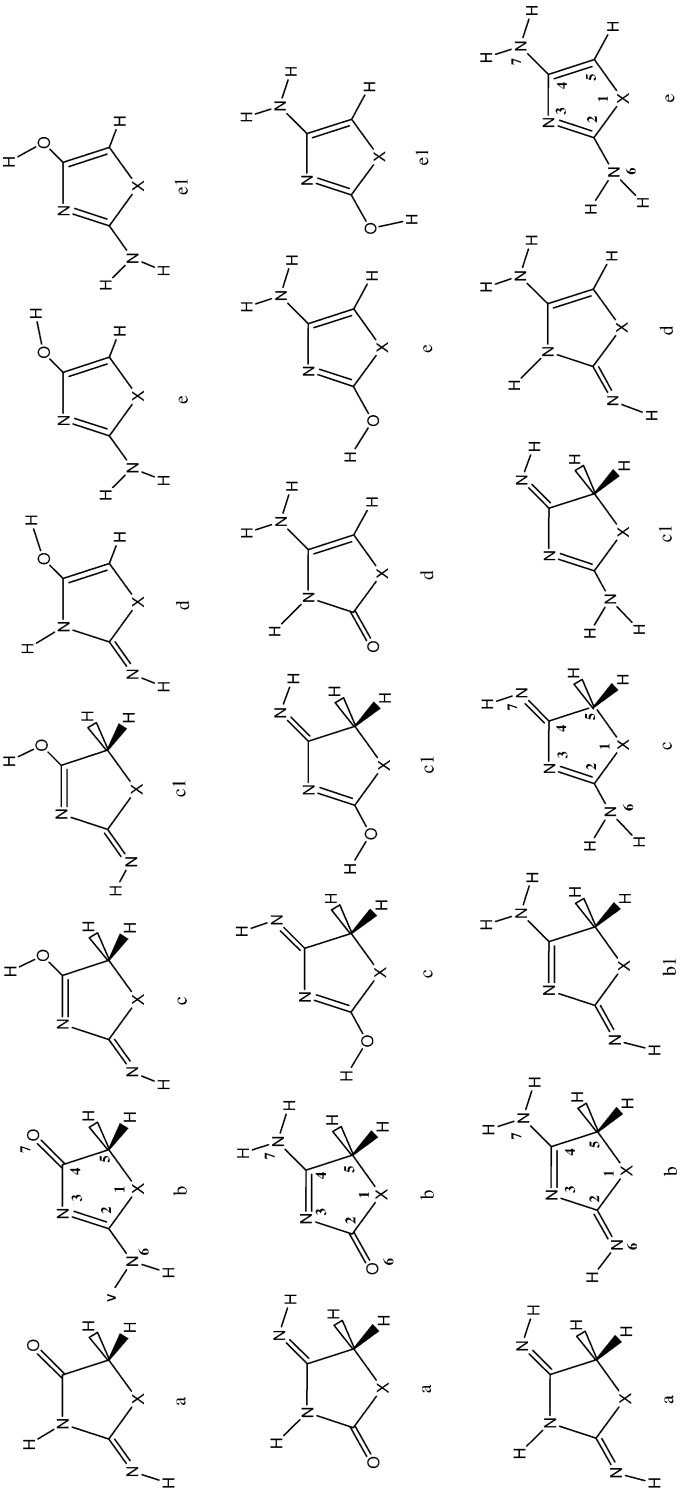

Fig. 1. The tautomeric and rotameric forms of compounds **1–9**.

incorporating a chalcogen atom into the five-membered ring is expected to influence its structure and properties.

2. Computational details

The calculations were carried out using the PC GAMESS version [10] of the GAMESS (US) quantum chemistry package [11]. The geometries of all possible tautomeric forms of the compounds **1–9**, shown in Fig. 1, were located at HF/6-31G(d,p) level without symmetry constraints (C_1 symmetry was assumed) by the gradient procedure. The default gradient convergence threshold (1×10^{-4} hartree Bohr^{-1}) was used. Selected structures were reoptimized at second order Møller–Plesset perturbation level of theory (MP2) using the 6-31+G(d,p) basis set. Local minima and transition states were verified by establishing that the Hessians have zero and one negative eigenvalues, respectively. The total energies were corrected using MP2/6-31+G(d,p) zero point energies.

To estimate the effect of the polar medium (chloroform and DMSO) on the relative stabilities of the tautomers of compounds **1–9**, we applied the polarizable continuum model (PCM) [12,13] as implemented in the GAUSSIAN 98 [14] suite of programs at MP2/6-31+G(d,p) level for the geometries optimized at the same level of theory (PCM/MP2/6-31+G(d,p)//MP2/6-31+G(d,p)).

^{13}C NMR chemical shieldings were calculated using the GIAO (gauge-including atomic orbitals) approach [15,16] implemented in GAUSSIAN 98 at HF, MP2 and DFT levels of theory using 6-31+G(d,p), 6-311+G(d,p) and 6-311++G(d,p) basis sets. In order to compare with experiment, the calculated absolute shieldings were transformed to chemical shifts using the reference compound tetramethylsilane (TMS): $\delta = \delta_{calc}(TMS) - \delta_{calc}$. Both $\delta_{calc}(TMS)$ and δ_{calc} were evaluated with the same method and basis set.

3. Experimental

The NMR spectra were recorded on a Bruker DRX-250 spectrometer, operating at 250.13 MHz for ^{1}H and 62.9 MHz for ^{13}C, using a 5 mm dual ^{1}H/^{13}C probe head. For all compounds, the power gated decoupling technique was used to obtain decoupled ^{13}C NMR spectra with signals enhanced by the NOE. For the hydrochloride of compound **8**, the gated decoupling technique was used to obtain the ^{13}C spectrum coupled to protons while retaining the NOE for sensitivity enhancement. To avoid heating of the sample, a composite pulse decoupling with the WALTZ16 pulse sequence was applied. The digital resolution for the decoupled ^{13}C spectra was 0.66 Hz/pt. Exponential multiplication with a line broadening factor of 1 Hz was applied to the FID in order to reduce the noise level. The NMR spectra in $CDCl_3$ and DMSO-d_6 were calibrated relative to TMS used as an internal standard.

2,4-Diamino-thiazole hydrochloride, its free base **8**, and 2-amino-thiazolidine-4-one **2** were synthesised according to Davies et al. [8]. 4-Amino-thiazolidine-2-one **5** was prepared according to Komaritsa [17].

4. Results and discussion

4.1. Gas phase results

All five tautomers and their possible rotameric structures of compounds **1–9**, presented in Fig. 1, were considered in our study. Data on the relative stabilities of the isolated forms are collected in Table 1. Geometry optimizations were carried out at HF/6-31G(d,p) level of theory for all species. The calculations show that for the compounds **2–4**, tautomers **a** (2-imino-thiazolidine-4-one **2a**, 2-imino-selenazolidine-4-one **3a** and 4-imino-oxazolidine-2-one **4a**) are most stable while for **1**, **5** and **6** tautomers **b** (2-amino-oxazole-4-one, **1b**, 4-amino-thiazole-2-one **5b** and 4-amino-selenazole-2-one **6b**) are preferred (Table 1). The energy differences between tautomers **a** and **b** are in the range 0.38–1.75 kcal mol^{-1} and the energy differences between the most stable tautomer and the rest of the tautomers are larger than 11 kcal mol^{-1}. For compounds **7–9**, tautomers 2-amino-4-imino-oxazole **7c**, 2-amino-4-imino-thiazole **8c** and 2-imino-4-amino-selenazole **9b** are favoured. The energy differences between tautomers **b** and **c** of compounds **8** and **9** are very small—only 0.18–0.28 kcal mol^{-1}. However, for **7** this value is 5.24 kcal mol^{-1}. Tautomers **a** and **e** are also near in energy to the most stable tautomeric form for compounds **8** and **9**. Tautomeric form **d** is quite high in energy.

Tautomeric forms **a** and **b** of compounds **1–6**, and **a–c** and **e** of compounds **7–9** were reoptimized at MP2/6-31+G(d,p) level. The relative stabilities are listed in Table 1. The energy differences between tautomers **a** and **b** for compounds **1–3** decrease in comparison with the results obtained at HF/6-31G(d,p) level. The opposite tendency is observed for compounds **4–6**—for **4**, tautomer **4b** (4-amino-oxazole-2-one) even becomes more stable. Inclusion of ZPE correction in the relative stabilities does not change the tendencies mentioned above. At MP2/6-31+G(d,p)+ZPE level, the amino tautomer **b** for compounds **1** and **4–6** is found to be more stable, while for selenazolidine **3** the imino form **a** is preferred. In the case of pseudothiohydantoin tautomeric forms **2a** and **2b** become isoenergetic.

The intramolecular proton transfer barriers between tautomers **a** and **b** for compounds **1–6** were calculated. The results of these calculations are listed in Table 2. The barrier heights in the thiazolidines and selenazolidines are lower than those in the oxazolidines. The barriers of tautomerization in sulphur- and selenium-containing rings have closer values and differ by 0.28 and 1.83 kcal mol^{-1} for compounds **1–3** and **4–6**, respectively. In all cases,

Table 1
Relative energies (kcal mol^{-1}) calculated at HF/6-31G(d,p) and MP2/6-31+G(d,p) levels of theory for compounds **1–9** shown in Fig. 1

Compound	a	b	b1	c	c1	d	e	e1
1								
HF/6-31G(d,p)	1.75	0.00		26.07	25.25	36.99	24.89	21.79
MP2/6-31+G(d,p)	1.38	0.00						
MP2/6-31+G(d,p)+ZPE	1.20	0.00						
2								
HF/6-31G(d,p)	0.00	0.85		23.43	20.29	27.94	19.54	16.35
MP2/6-31+G(d,p)	0.00	0.21						
MP2/6-31+G(d,p)+ZPE	0.00	0.00						
3								
HF/6-31G(d,p)	0.00	1.60		23.42	20.28	27.87	21.31	18.04
MP2/6-31+G(d,p)	0.00	1.18						
MP2/6-31+G(d,p)+ZPE	0.00	0.73						
4								
HF/6-31G(d,p)	0.00	0.38		20.24	15.39	15.50	23.48	25.75
MP2/6-31+G(d,p)	0.08	0.00						
MP2/6-31+G(d,p)+ZPE	0.15	0.00						
5								
HF/6-31G(d,p)	0.84	0.00		19.69	15.50	13.11	19.07	23.05
MP2/6-31+G(d,p)	1.05	0.00						
MP2/6-31+G(d,p)+ZPE	1.33	0.00						
6								
HF/6-31G(d,p)	0.81	0.00		20.11	15.97	11.10	19.81	24.95
MP2/6-31+G(d,p)	1.41	0.00						
MP2/6-31+G(d,p)+ZPE	1.48	0.00						
7								
HF/6-31G(d,p)	5.32	5.24	5.89	0.00	5.30	22.33	9.53	
MP2/6-31+G(d,p)	5.04	4.31	4.43	0.00	4.34		4.05	
MP2/6-31+G(d,p)+ZPE	4.79	4.19	4.26	0.00	4.23		3.89	
8								
HF/6-31G(d,p)	3.10	0.18	2.99	0.00	4.80	16.71	5.41	
MP2/6-31+G(d,p)	4.09	1.68	3.06	0.60	4.42		0.00	
MP2/6-31+G(d,p)+ZPE	4.37	1.79	3.23	0.78	4.52		0.00	
9								
HF/6-31G(d,p)	2.77	0.00	2.75	0.28	5.01	14.10	5.35	
MP2/6-31+G(d,p)	2.62	0.32	1.22	0.09	3.55		0.00	
MP2/6-31+G(d,p)+ZPE	2.75	0.40	1.40	0.00	3.43		0.05	

the values of the proton transfer barriers are quite large and tautomerization should not occur.

Calculations at MP2/6-31+G(d,p)+ZPE level predict tautomer **7c** as most stable and the energy difference between tautomers **c** and **e** is 3.89 kcal mol^{-1}. For compound **8**, the preferred tautomer is **e**. However, the energy differences between tautomers **e** and **c** and **e** and **b** are small—0.78 and 1.79 kcal mol^{-1}, respectively. Similar results were obtained for **9**, where tautomers **c** and **e** are predicted to be almost isoenergetic (0.05 kcal mol^{-1}); the energy difference between **c** and **b** was found to be only 0.40 kcal mol^{-1}.

4.2. Tautomeric equilibrium in solution

Table 3 shows the total energies in solution of the low energy tautomers of each molecule calculated using PCM method with solvents $CHCl_3$ ($\varepsilon=4.9$) and DMSO ($\varepsilon=46.7$) at MP2/6-31+G(d,p) level. The gas-phase- and PCM-calculated relative stabilities of tautomers **a** and **b** of compounds **1–6** and tautomers **a–c** and **e** of compounds **7–9**, obtained at MP2/6-31+G(d,p) level, are presented in Table 4.

For compounds **1–6**, tautomeric forms **b** are found as the most stable. The energy differences between the two tautomers increase on going from gas-phase to solvent $CHCl_3$ and to the more polar DMSO. This is in agreement with the expectation that the polar species

Table 2
MP2/6-31+G(d,p) calculated activation barriers (kcal mol^{-1}) of tautomerization at 0 K for compounds **1–6** (Fig. 1)

Compound	$\Delta H_0^{\#}$	$\nu^{\#}$
2-Amino-oxazole-4-one, **1**	50.51	1939*i*
2-Amino-thiazole-4-one, **2**	45.17	1935*i*
2-Amino-selenazole-4-one, **3**	44.89	1935*i*
4-Amino-oxazole-2-one, **4**	50.72	1960*i*
4-Amino-thiazole-2-one, **5**	47.15	1942*i*
4-Amino-selenazole-2-one, **6**	45.32	1935*i*

The imaginary frequencies are given in cm^{-1}.

Table 3
MP2/6-31+G(d,p) calculated total energies (E_T), zero-point energies (ZPE), total energy in solution (E_{sol}) (a.u.) and dipole moment μ (Debye) for the compounds shown in Fig. 1

Species	Isolated molecule			E_{sol}	
	E_T	ZPE	μ	$CHCl_3$	DMSO
1a	−375.589536	0.080982	1.63	−375.673105	−375.674426
1b	−375.591449	0.081276	5.50	−375.678004	−375.680421
2a	−698.194221	0.077937	2.25	−698.275419	−698.277004
2b	−698.194216	0.077647	5.17	−698.277595	−698.280280
3a	−2698.304330	0.077092	2.46	−2698.350879	−2698.351010
3b	−2698.303161	0.076374	5.11	−2698.351483	−2698.358259
4a	−375.593243	0.081146	3.69	−375.678706	−375.680814
4b	−375.593478	0.081032	7.78	−375.682498	−375.686064
5a	−698.195083	0.078268	3.79	−698.277123	−698.278980
5b	−698.197201	0.077836	7.26	−698.282186	−698.285429
6a	−2698.304630	0.077083	3.77	−2698.351422	−2698.351725
6b	−2698.306980	0.077836	7.05	−2698.356711	−2698.358259
7a	−355.811811	0.093322	3.17	−355.815083	−355.816790
7b	−355.812970	0.093519	6.74	−355.819692	−355.822807
7c	−355.819836	0.093714	4.02	−355.822814	−355.824347
7e	−355.813386	0.093462	2.44	−355.816272	−355.817997
8a	−678.413488	0.090584	3.30	−678.417253	−678.419162
8b	−678.417321	0.090311	6.93	−678.423104	−678.425804
8c	−678.419056	0.090440	4.43	−678.422586	−678.424353
8e	−678.420004	0.090143	2.32	−678.423461	−678.425430
9a	−2678.523584	0.089436	3.97	−2678.493503	−2678.493990
9b	−2678.527260	0.089368	6.15	−2678.498870	−2678.499970
9c	−2678.527620	0.089086	3.87	−2678.497521	−2678.497890
9e	−2678.527767	0.089313	2.56	−2678.497641	−2678.498195

are stabilized more in a polar solvent than in a non-polar one. For compound **5**, the amino form **5b** is predicted as most stable in the gas phase and in $CHCl_3$ and DMSO solutions (Table 4), in contradiction to the NMR and IR results of Elguero et al. [7]. On the other hand, our calculated chemical shifts of **5b** are in accordance with the experimentally obtained values (Table 5), while the calculated ^{13}C chemical shifts for **5a** are C2: 170.2 ppm, C4: 162.4 ppm and C5: 37.5 ppm.

The stabilities of tautomers **b**, **c** and **e** of compounds **7–9** change on inclusion of the solvent effect. The polarities of tautomers **e** and **c** of compounds **7–9** are close, while the dipole moment of tautomer **b** is higher (6.15–6.93 D). For compound **7**, the energy difference between **b** and **c** decreases on going from gas phase to solvent $CHCl_3$ and to DMSO. For compounds **8** and **9**, tautomers **8b** and **9b** are preferred in solvent DMSO. In the case of compound **8**, the energy difference between **8b** and **8e** is 0.13 kcal mol^{-1} only, while that between **9b** and **9e** is 1.08 kcal mol^{-1}.

According to the relative stabilities calculated at MP2/6-31+G(d,p) level for the species **b**, **c** and **e** of compound **8** in DMSO, the populations of **b** and **e** are 50.3 and 40.3%. However, a minor fraction of the form **c** cannot be ruled out, since this tautomer is by 0.99 kcal mol^{-1} less

Table 4
MP2/6-31+G(d,p)+ZPE calculated relative stabilities (kcal mol^{-1}) for the tautomers of compounds **1–9** shown in Fig. 1 for isolated molecules and in $CHCl_3$ and DMSO solution

Compound	Gas phase				$CHCl_3$				DMSO			
	a	**b**	**c**	**e**	**a**	**b**	**c**	**e**	**a**	**b**	**c**	**e**
1	1.20	0.00			2.89	0.00			3.58	0.00		
2	0.00	0.00			1.55	0.00			2.24	0.00		
3	0.00	0.73			0.83	0.00			5.00	0.00		
4	0.15	0.00			2.45	0.00			3.37	0.00		
5	1.33	0.00			3.45	0.00			4.32	0.00		
6	1.48	0.00			3.38	0.00			4.16	0.00		
7	4.79	4.19	0.00	3.89	4.61	1.84	0.00	3.95	4.50	0.84	0.00	3.83
8	4.37	1.79	0.78	0.00	4.18	1.15	0.74	0.00	4.34	0.00	0.99	0.13
9	2.75	0.40	0.00	0.05	3.44	0.00	0.67	0.74	3.85	0.00	1.13	1.08

favored than **b** and the population of this tautomer in solution is 9.4%. In solvent $CHCl_3$, the populations were calculated to be **e**:**c**:**b** = 70:20:10%.

The differences in the relative energies of tautomers **8b**, **8c** and **8e** are very small—the PCM/MP2/6-31 + G(d,p)//MP2/6-31 + G(d,p) + ZPE energies differ by less than 1 kcal mol^{-1} (Table 4). This is in agreement with the experimental results. The ^{13}C NMR data in DMSO-d_6 show the presence of three tautomeric forms, one with a CH group for C5 and two with a CH_2 group. The differences between the calculated at MP2/6-311 + G(d,p) level and experimental chemical shifts for **8b**, **8c** and **8e** are about 4 ppm. Our results are in contradiction with a previously suggested structure of the predominant tautomer of compound **8** [7].

Similarly to compound **8**, in solution 2,4-diaminoselenazolidine should exist in three tautomeric forms—**b**, **c** and **e**. The populations in $CHCl_3$ are **b**:**e**:**c** = 55:25:20%, while in DMSO this ratio is **b**:**e**:**c** = 76.34:12.33:11.33%.

4.3. NMR spectra

Chemical shieldings were calculated at MP2/6-31 + G(d,p) optimized geometries. HF, MP2 and DFT B3LYP and B3PW91 functionals with the 6-311 + G(d,p) and 6-31 + G(d,p) basis sets were employed. The B3LYP/6-311 + G(d,p) and B3PW91/6-311 + G(d,p) calculations of compounds **2** and **5** do not result in reliable ^{13}C NMR spectrum prediction, with a relatively high average deviation of about 10 ppm for **2** and 7 ppm for **5**. To check the basis set effect, GIAO calculations of ^{13}C chemical shifts of **2** and **5** were performed with 6-31 + G(d,p) and 6-311 + G(d) basis sets at HF and MP2 level of theory. Results at MP2/6-311 + G(d,p) level showed best agreement with the experimental values, hence the chemical shieldings of **1**–**9** were calculated at this level.

The ^{13}C chemical shifts calculated at HF and MP2 levels of theory with 6-311 + G(d,p) basis set are presented in Table 5. The MP2 chemical shifts are closer to the experimental data for compounds **2** and **5**. The most noticeable disagreement between calculated and experimental chemical shifts concerns C5 ($\Delta\delta = 6.2$ ppm for **2**), while the values for C2 and C4 are predicted more accurately. The average deviation between calculated and experimental ^{13}C NMR spectrum is 2.7 ppm for **2** and **5**.

The assignment of the C2 and C4 signals of the hydrochloride of **8** is not straightforward. To assign these signals, the spin–spin coupling constants of C2 ($^3J_{CH}$) and C4 ($^2J_{CH}$) with the methylenic protons were measured, obtaining the values of 2.6 and 4.6 Hz. For this compound, Elguero et al. [7] reported a coupling constant of ≤ 2 Hz and another constant of ≤ 1 Hz and assigned the signal with $^3J_{CH} \leq 2$ Hz at 182.4 ppm as C2 and the signal with $^2J_{CH} \leq 1$ Hz at 185.8 ppm as C4. For ring systems, it is commonly accepted that $^2J_{CH} < {}^3J_{CH}$ [18]; however, this dependence is usually strictly valid for aromatic systems, while for nonaromatic rings and especially in the presence of heteroatoms the differences in the values of $^2J_{CH}$ and $^3J_{CH}$ constants are not characteristic. Due to the presence of a methylene group in the heterocycle, the hydrochloride of **8** cannot be considered as an aromatic system. Considering the explanations given above the J constants measured from the NMR spectrum cannot be used to unambigously assign the signals of C2 and C4 only on the basis of their values. We regard the theoretically calculated chemical shifts for C2 and C4 (Table 4) as more reliable and assign the signal at 196.2 ppm as C2 and the signal at 186.4 ppm as C4. The difference between the calculated and the assigned

Table 5
GIAO ^{13}C chemical shifts (ppm) calculated at HF/6-311 + G(d,p) and MP2/6-311 + G(d,p) levels using MP2/6-31 + G(d,p) optimized geometries

Compound	HF/6-311 + G(d,p)			MP2/6-311 + G(d,p)			Experimental		
	C2	C4	C5	C2	C4	C5	C2	C4	C5
1b	188.1	196.9	69.6	182.3	184.4	75.7			
2b	200.1	198.1	40.4	183.6	186.4	46.0	182.7 (183.0)[a]	187.7 (187.9)[a]	39.8 (40.0)[a]
3b	179.7	185.9	33.0	160.4	171.2	37.3			
4b	176.0	194.3	62.3	168.6	179.5	69.3			
5b	195.5	194.0	34.3	182.4	179.5	40.5	184.3 (184.4)[a]	181.9 (182.1)[a]	37.5 (37.7)[a]
6b	199.1	194.1	30.8	184.4	179.6	38.2			
7c	183.4	187.3	69.7	176.1	176.4	76.8			
7e	175.3	158.3	114.8	161.2	148.2	117.7			
8b	191.8	187.8	36.3	181.4	171.8	42.9	176.4	167.8	38.8
8c	192.2	190.0	39.3	174.3	180.3	45.5	180.9	186.1	42.9
8e	193.4	165.1	79.6	165.1	154.1	86.8	164.9	150.4	90.0
9b	195.1	187.1	32.7	183.2	171.0	40.2			
9c	195.3	190.8	37.4	173.4	181.0	44.5			
9e	203.8	164.6	79.0	171.3	153.7	88.9			
8 HCl	217.7	199.4	39.5	196.2	186.4	46.5	186.2	182.8	40.0
9 HCl	220.0	199.4	36.7	201.2	186.5	44.5			

Numbering of the atoms is given in Fig. 1.
[a] Ref. [7].

experimental chemical shifts for C4 and C5 is about 5 ppm, while the value for C2 is less accurately predicted ($\Delta\delta = 10.0$ ppm).

The MP2 calculations indicate a dependence of the C5 chemical shifts in all compounds on the type of the chalcogen atom. The difference between C5 chemical shifts in oxazolidines and thiazolidines is about 30 ppm, while the difference between C5 chemical shifts in thiazolidines and selenazolidines is about 5 ppm. The differences between C2 and C4 chemical shifts are small except for compounds **1**–**3** (a difference of 23.4 ppm for C2 and 14.2 ppm for C4) on going from thiazolidines to selenazolidines (**2b**–**3b**).

5. Conclusions

The relative stabilities of the investigated species are highly sensitive to basis set, electron correlation effects and inclusion of ZPE corrections. At MP2 level of theory without ZPE corrections, the **b** tautomer for compounds **1** and **4**–**6** is more stable. If ZPE correction is included tautomeric forms **2a** and **2b** become isoenergetic. In the case of compound **9**, the inclusion of ZPE correction makes tautomer **c** the most stable one.

Compounds **1**–**6** exist as amino form **b**, if weakly polar ($CHCl_3$) and polar (DMSO) solvents are used. Compounds **8** and **9** occur as a mixture of tautomers **b**, **c** and **e**.

The tautomeric equilibria of compounds **8** and **9** are strongly solvent-dependent. A combination of ab initio calculations and ^{13}C NMR can be employed to determine the position of these equilibria.

There is a good correspondence between the GIAO MP2/6-311+G(d,p) calculated chemical shifts of the most stable tautomeric forms of compounds **2**, **5** and **8** and the experimentally determined chemical shifts.

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