

Theoretical Study of Stability, Tautomerism, Equilibrium Constants (pK_T) of 2-Thiouracil in Gas phase and Different solvents (water and Acetonitrile) by the Density Functional Theory Method.

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ABSTRACT: A density functional theory (DFT) calculations were carried out to investigate the relative energies, equilibrium constants and dipole movements of 2-thiouracil in the gas phase and in solutions with different polarities. Solvent effects were examined by means of the self-consistent reaction field (SCRF) method. All possible tautomers are optimized at the B3LYP/6-31++G (d,p). The relative energy value indicates that tautomer 2TU1 is the most stable tautomer in both gas and solution phase and to calculate the inter conversion of equilibrium constants for all tautomers. In addition to calculate the thermodynamic properties and the values of $\Delta\Delta G_i^0(\text{solvnet1-solvent2})$, determines the solvent effect on the position of the equilibrium.

Key words: 2-Thiouracil, DFT method, Tautomerism, relative stabilities, equilibrium constants, and solvent effects.

1. INTRODUCTION

Tautomerism interconversions[1] have been investigated by chemists during last decades.

Recently, study of tautomerism received renewed attention due to its importance on determination of compounds' properties and their area of applications. The importance of tautomerism is revealed more since in recent years the investigation about tautomerism has been the major topic in theoretical chemistry. For example, tautomerisms in keto-enol [2], imine-enamine [3] and many other systems [4] have been studied during past decades. Tautomerisation and proton transfer of the keto-enol tautomer of heterocyclic systems with several basic centers, N, O and S atoms, are of great interest to medicinal and biochemical applications. Also, understanding of the relative stabilities of heterocyclic tautomers and any subsequent conversions between tautomeric forms is very vital for both structural chemists and biologists [5]. Along this line, relative stabilities of various tautomeric structures of five-, six- and seven-member heterocyclic rings were investigated using both theoretical and experimental tools [6].

In recent years, uracil and its thio derivatives have already become the intense focus of research due to their biological, pharmacological, and spectroscopic activities. For example, a series of thiouracils, such as 2-thiouracil, 4-thiouracil, and 2,4-dithiouracil, have been identified as minor components of t-RNA and peptide nucleic acids, where the former two thiouracils have also been used as anticancer and antithyroid drugs and for the treatment of heart disease [7–11]. The inappropriate replacement of uracil by a thiouracil can be responsible for the misrecognition in mRNA[12]. Moreover, their various tautomeric forms seem to be important for explaining the mutation occurring during DNA duplication. Meanwhile, the complexes of thiouracil derivatives with transition metal ions of biological importance have been shown to exhibit anticancer and antimicrobial activity [13]. Additionally, thiouracils have also been proposed to be efficient metal corrosion inhibitors [14]. Thus, the properties and characteristics of thiouracils are of great interest in pharmaceutical researches and applications. In the present paper, the geometries, dipole moments, Mullikan charges and relative energies have been calculated, using the DFT method.

2. COMPUTATIONAL METHOD DETAILS

2-thiouracil has 6 keto– enol and enol–enol tautomeric forms altogether. Considering the orientation of the hydroxyl hydrogen and thio hydrogen (it is in the same or opposite direction with the C=N bond of the enol), the number of the tautomers ascends to 12, Fig. 1, illustrates the 12 tautomers. All the geometries of the tautomers have been fully optimized using the B3LYP method within the framework of density functional theory (DFT) in conjunction with the 6-311++G(d,p) basis set, i.e., Becke's three parameter non-local hybrid exchange potential with the non-local correlation functional of Lee, Yang, and Parr [15,16]. The B3LYP method has been

shown to yield reliable geometries for a wide variety of systems also including the relevant uracil species [17-19]. Following the geometry optimizations, analytical frequency calculations were proceeded at the DFT/6-311++G(d,p) level, using following standard procedures, to obtain the thermochemical properties. Solvent effect was considered when calculating the equilibrium constant. All these calculations were carried out on a Pentium V personal computer by means of GAUSSIAN09 program package and for our computations [20].

Thermodynamic properties such as: the enthalpy, the Gibbs free energy and the entropy were given according to the formulas [21]

$$H = E + RT \quad (1)$$

$$G = H - TS \quad (2)$$

E is the thermal energy

H is the enthalpy

G is the Gibbs free energy

In order to determine the kinetic parameters of the transformations, we calculated their tautomeric equilibrium constants by using the following relations [22].

$$K_T = \exp(-\Delta G/RT) \quad (3)$$

Where K_T is the equilibrium constant between the tautomers, the gas constant is R is 1.987×10^{-3} kcal.mol⁻³ and the temperature T is 298.15K. The quantity ΔG is the difference between the Gibbs free energies of the given tautomer with respect to stable one. The pK_T values of the studied molecules were calculated by the following equation [21]:

$$pK_T = -\log K_T \quad (4)$$

Calculated total energies (a.u), zero-point vibrational energies (ZPVE) (kcal mol⁻¹), thermal Enthalpy (H) (a.u), thermal free energy (G) (a.u), dipole moment (μ) (debye), molar heat capacity (C_v) ,enthalpy change (ΔH^0), free energy change (ΔG^0), entropy change (ΔS^0) equilibrium constants (K) and pK_T for various tautomers.

These thermochemical parameters were obtained through the frequency calculation at DFT/6-311++G (d,p) level. The solvents (acetonitrile & water) effect on the tautomerism processes of 2-thiouracil was investigated by self-consistent reaction field (SCRF) method based on Onsager's reaction field theory.

3. RESULTS AND DISCUSSION

3.1. Energies and relative stability

The total and relative energies (at DFT/6-311++G(d,p) level) of 12 tautomers of 2-thiouracil are presented in Table 1, among the 12 tautomers, four are (2TU2, 2TU3, 2TU11, and 2TU12) thio-enols, four are (2TU4, 2TU5, 2TU9, and 2TU10) keto-enols, three are di-enols (keto-enol and thio-enol) and one is keto tautomer (2TU1). The most stable 2TU1 is taken as reference to obtain the relative energetic stability of other tautomers. It can be seen from the results that among four mono-enol tautomers two are thio-enol (2TU11 & 2TU12) and two are keto-enol (2TU9 & 2TU10) tautomers have highest energy, with relative energy about 20-25 kcal mol⁻¹, because of the possibility of migration of hydrogen atoms, and eliminating the simultaneous transfers little likely of more than atom, only the exchange of hydrogen atom between heteroatom spatially close and separate by more than two atoms can be carried out. Other mono and di-enol tautomers are less relative energy, except the tautomer 2TU5 (20.07 kcal/mole), with relative energy about 11-18 kcal mol⁻¹. The energy difference of the tautomers of same tautomeric form that differs in the orientations of hydroxyl hydrogens, varies for specific systems. The order of relative energies for tautomer in gas phase with respect to stable tautomer: 2TU2 > 2TU6 > 2TU7 > 2TU4 > 2TU3 > 2TU8 > 2TU5 > 2TU12 > 2TU9 > 2TU11 > 2TU10.

Solvent effects are relevant in tautomers stability phenomena, since polarity differences among tautomers can induce significant changes in their relative energies in solution. SCRF/B3LYP calculations were used to analyze the solvent effects on tautomerism of 2-thiouracil. The data presented in Table 1 show that polar solvents increase the stability of all 2-thiouracil tautomers in compare to gas phase. The difference between the total energies of 2-thiouracil and the other forms do not show a regular trend when changing from gas phase to most polar solvents (water). The solvent interactions have pronounced effect on the order of stability of the tautomers in the gas phase. The order of stability of 2-thiouracil in acetonitrile: 2TU5 > 2TU2 > 2TU3 > 2TU12 > 2TU6 > 2TU7 > 2TU11 > 2TU9 > 2TU8 > 2TU10 > 2TU4 and The order of stability in water: 2TU4 > 2TU5 > 2TU2 > 2TU3 > 2TU12 > 2TU6 > 2TU11 > 2TU7 > 2TU9 > 2TU8 > 2TU10.

The zero point vibrational energies (ZPVE), dipole movements (μ) and the molar heat capacities (C_V) have been calculated in different media, at the same basis set level and presented in table 2. It seems that the dipole moments (μ) increases by changing the gas phase to the solution as well as by increasing the solvent polarity. On going from gas phase to solution, dipole movements of all isomers are increased, as the solvent becomes much more polar. The increase in dipole movements implies that charges around the molecule are probably more developed due to the polarization induced by solvents.

3.2 The thermodynamic parameters

The thermodynamic parameters are presented in Table 3 in different media, the ΔH , ΔG and ΔS values are all positive for different solvents except 2TU1 $\leftrightarrow$ 2TU4 has negative ΔS value in all solvents. ΔH values are all positive, i.e endothermic reaction, ΔS usually is relatively small,

indicate that with no ring formation or other unusual changes in the constraints between the products and reactants.

The effect of the medium on the position of equilibrium can be considered from two points of view: (a) comparison of the gas-phase and solution equilibrium constants, and (b) comparison of the equilibrium constants for different solvents. These are primarily non-ionic reactions where the interaction between reacting molecules and solvent is relatively small. Let us consider a simple isomerization reaction $A \leftrightarrow B$ in the solvents I and II, whose abilities to solvate A and B are different. This corresponds to the Gibbs energy diagram shown in Fig. 2[23]. From Fig. 2, Eq. (5) can be immediately derived,

$$\Delta G^0(\text{II}) + \Delta G_t^0(A, \text{I} \rightarrow \text{II}) = \Delta G_t^0(B, \text{I} \rightarrow \text{II}) = \Delta G_t^0(B, \text{I} \rightarrow \text{II}) + \Delta G^0(\text{I}) \quad (5)$$

which, on rearrangement, leads to Eq.5

$$\begin{aligned} \Delta G^0(\text{II}) - \Delta G^0(\text{I}) &= \Delta G_t^0(B, \text{I} \rightarrow \text{II}) - \Delta G_t^0(B, \text{I} \rightarrow \text{II}) \\ &= \Delta \Delta G^0(\text{I} \rightarrow \text{II}) \end{aligned} \quad (6)$$

Since, for equilibria, the logarithm of the equilibrium constant is proportional to the standard molar Gibbs energy change, ΔG^0 , according to Eq. (7),

$$\Delta G^0 = -RT \ln K \quad (7)$$

It follows from Eqs. (6) and (7) that the difference in the molar transfer Gibbs energies of reactant A and product B, $\Delta \Delta G_t^0(\text{I} \rightarrow \text{II})$, determines the solvent effect on the position of this equilibrium.

In studying solvent effects on equilibria, it is, in principle, not sufficient to investigate the ΔG^0 changes alone, because this term is determined by both an enthalpy and an entropy term according to Eq. (8).

$$\Delta G^0 = \Delta H^0 - T\Delta S^0 \quad (8)$$

Transfer functions can also be defined for the thermodynamic state functions ΔH^0 and ΔS^0 . If both transfer Gibbs energies and transfer enthalpies are available, it should be possible to achieve a complete dissection of the effect of solvents on the various thermodynamic parameters. The values of $\Delta \Delta H^0$ and $T \Delta \Delta S^0$ were presented in table 4 in all the solvents. From the table four types of reaction control can be recognized:

(a) Cooperative effects, with $\Delta \Delta H^0$ and $T \Delta \Delta S^0$ having opposite signs. Then these two terms will be additive; (b) Enthalpy-controlled effects, in which the two terms are opposed, but the enthalpy term is larger; (c) Entropy-controlled effects, in which the two terms are opposite but the $\Delta \Delta S^0$ is larger; and (d) Compensating effects, in which the two terms are opposed but nearly equal.

3.3. Equilibrium constants

In order to determine the kinetic parameters of the transformations, we calculated their tautomeric equilibrium constants by using the relation [21]. The constants were calculated by considering that all the tautomers can be in the equilibrium with the most stable tautomer. Table 4 contained the equilibrium constants (K) and the pK_T values in different solvents, calculated from tautomeric most stable which was 2TU1. All pK_T values in gas phase and the two solvents were positive and this confirmed the fact that 2TU1 tautomer is most stable.

We can return to our diagram of interconversion, to evaluate in a more realistic way the constants of equilibrium as presented in Fig 3. Table 6. Contained the pK_T of the equilibrium constants calculated from the general outline of interconversion. Some pK_T were positive and other negative; that determine the privileged direction of equilibrium. If the pK_T was positive, equilibrium moved from right towards the left and when it was negative, equilibrium moved from left towards the right.

4. Conclusion

For 2-thiouracil, tautomerization in gas phase and solution was studied using DFT at the B3LYP/6-31++G(d,p) basis set. In this work we calculated relative stability, the constants of equilibrium for different tautomers of 2-thiouracil. According to our calculations, the most stable form is di ketone form (2TU1) and the order of energies; acetonitrile > water > gas, the dipole movements are order: Gas > acetonitrile > water, because of polarity increasing. In addition the equilibrium constants and inter conversation equilibrium constants also calculated. From this we observed some pK_T were positive and other negative; that determine the privileged direction of equilibrium.

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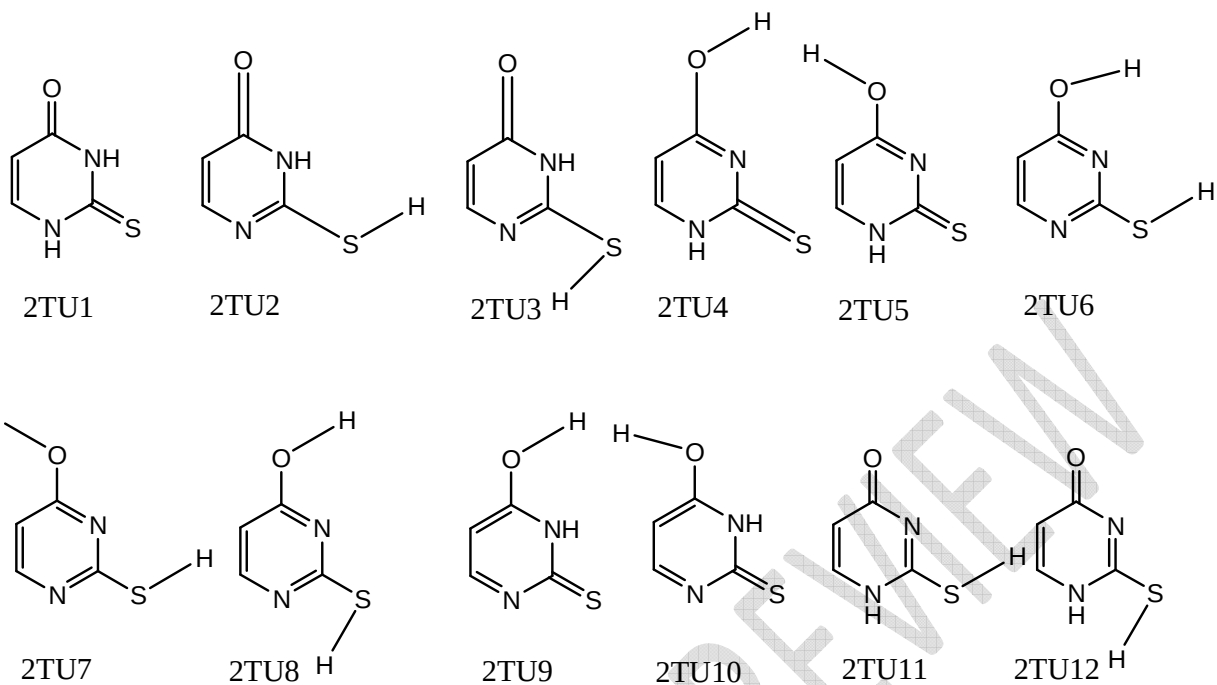


Fig. 1. Tautomers of 2-thiouracil

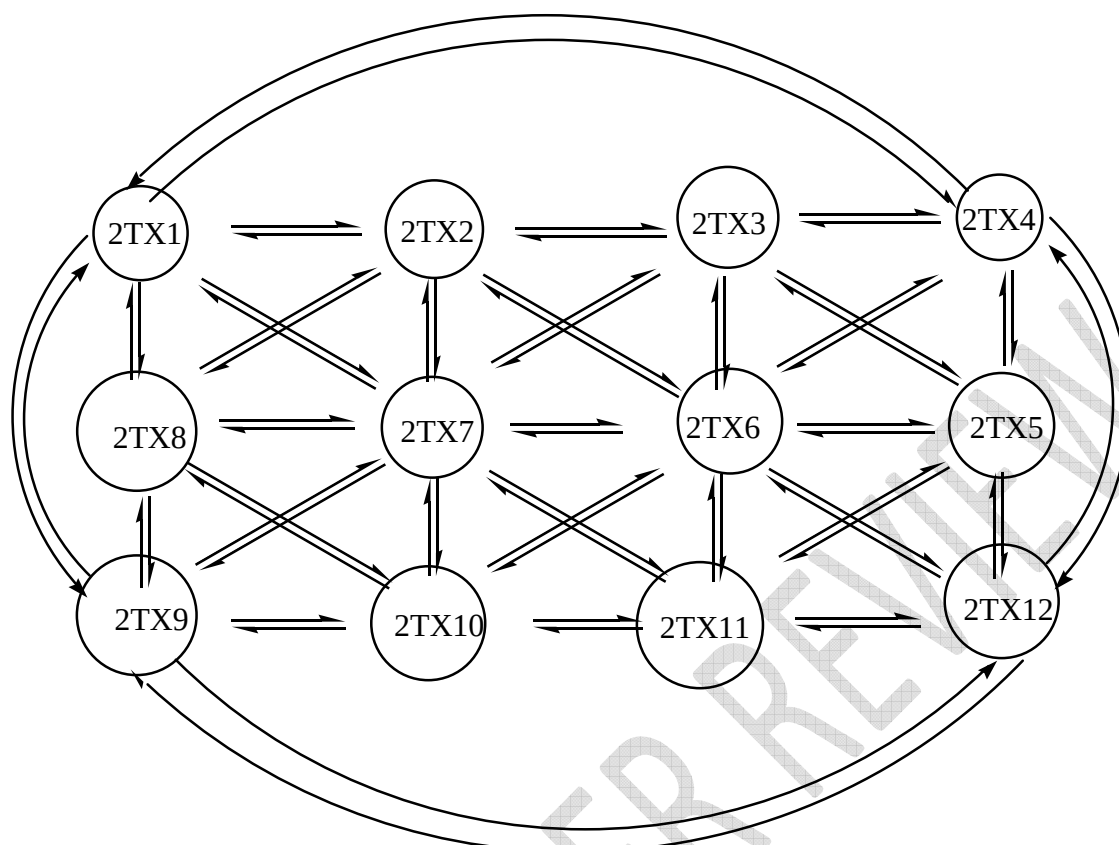


Fig.3. Diagram of interconversion of 2-thiouracil

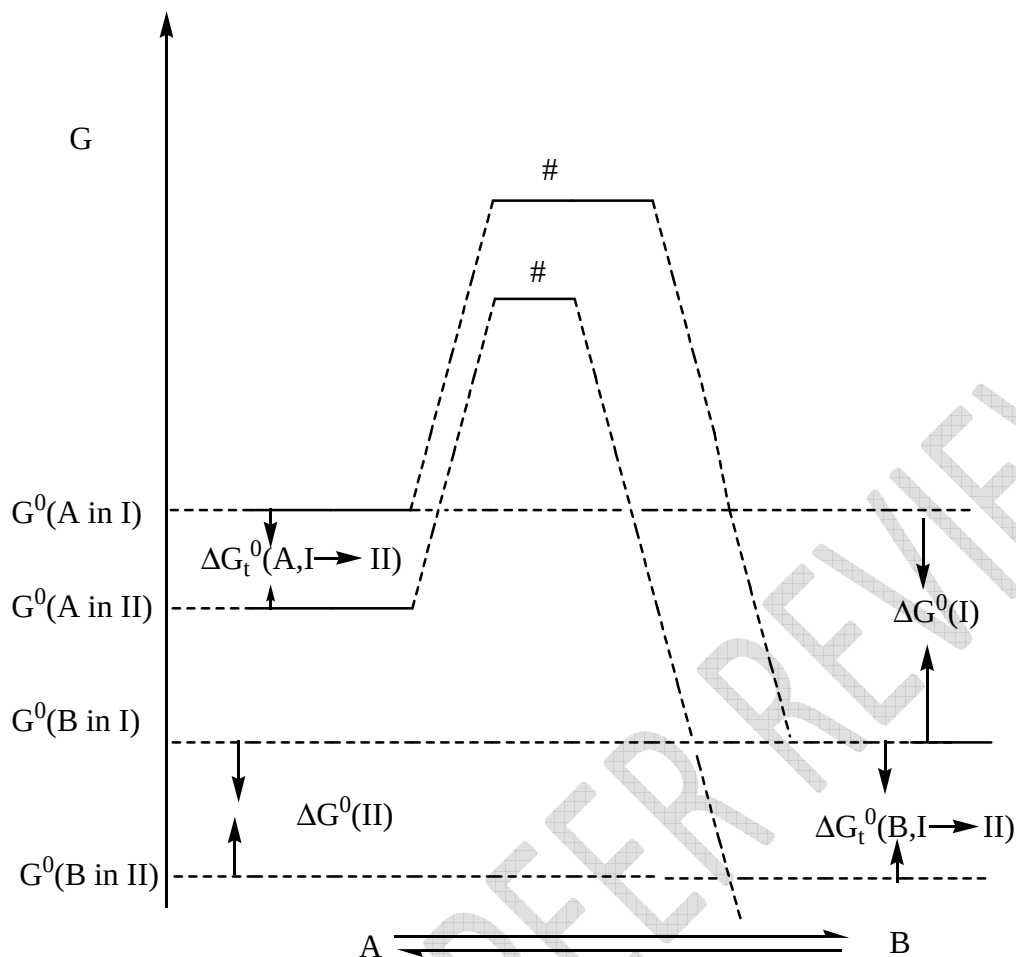


Fig.2. One-dimensional Gibbs energy diagram for an equilibrium reaction $A \leftrightarrow B$ in the solvents I and II. Ordinate: standard molar Gibbs energies of the reactants A and B in solvents I and II; Abscissa: not defined. $\Delta G_{\text{r}}^0(\text{I})$ and $\Delta G_{\text{r}}^0(\text{II})$: standard molar Gibbs energies of reaction in solvents I and II, respectively; $\Delta G_{\text{t}}^0(\text{A, I} \rightarrow \text{II})$ and $\Delta G_{\text{t}}^0(\text{B, I} \rightarrow \text{II})$: standard molar Gibbs energies of transfer of the solutes A and B from solvent I to solvent II, respectively [$\Delta G_{\text{t}}^0(\text{A, I} \rightarrow \text{II}) = G^0(\text{A in I}) - G^0(\text{A in II})$], and [$\Delta G_{\text{t}}^0(\text{B, I} \rightarrow \text{II}) = G^0(\text{B in I}) - G^0(\text{B in II})$], # = transition state.

Table 1. The energies of tautomers(a.u) at DFT/6-311++G(d,p) level in different media and the relative energies compared to the most stable isomer 2TU1. The relative energies in brackets in kcal mol⁻¹ (in brackets Kcal/mole).

Isomers	$\Delta E(\text{gas})$	$\Delta E(\text{Acetonitrile})$	$\Delta E(\text{water})$
2TU1	-737.89947302(0.0000)	-737.915900370(0.0000)	-737.91633658(0.0000)
2TU2	-737.88090388(11.6523)	-737.89321425(14.2358)	-737.89353095(14.3107)
2TU3	-737.87768488(13.6723)	-737.89229300(14.8138)	-737.89233375(15.0620)
2TU4	-737.87925325(12.6881)	-737.86856173(29.7054)	-737.89911925(10.8040)
2TU5	-737.86747854(20.0768)	-737.89418033(13.6295)	-737.89378865(14.1490)
2TU6	-737.88025401(12.0601)	-737.88784348(17.6060)	-737.88803863(17.7572)
2TU7	-737.87957496(12.4862)	-737.88773617(17.6733)	-737.88785780(17.8707)
2TU8	-737.87169145(17.4332)	-737.88454688(19.6746)	-737.88478499(19.7989)
2TU9	-737.86363640(22.4878)	-737.88693953(18.1732)	-737.88764167(18.0063)

292	2TU10	-737.85926764(25.2293)	-737.88366617(20.2273)	-737.88308063(20.8684)
293	2TU11	-737.86186485(23.5995)	-737.88715114(18.0404)	-737.88792579(17.8280)
294	2TU12	-737.86670631(20.5614)	-737.88836509(17.2786)	-737.88899187(17.1591)

295
 296 Table 2. The zero point vibrational energies (ZPVE) in kcal/mol, dipole movements(μ) in Debye, the
 297 molar heat capacities(CV) in Cal/Mol-Kelvin, for the tautomers at DFT/6-311++G(d,p) level in different
 298 media.

299	Isomers	Gas	Water	Acetonitrile						
300		ZPVE	μ	CV	ZPVE	μ	CV	ZPVE	μ	CV
301	2TU1	52.9573		4.7462	24.486	53.0378		6.6964	24.306	53.0371
302	2TU2	50.4328		2.9654	25.594	50.4076		4.1644	25.479	50.4106
303	2TU3	50.2700		2.1055	25.748	50.3244		2.8698	25.677	50.3742
304		25.543								3.0960
305	2TU4	52.7666		5.7112	24.456	52.8240		9.0025	24.365	52.8239
306	2TU5	52.3795		8.5147	25.017	52.5309		12.0860	24.811	52.6969
307		12.6761		24.602						
308	2TU6	50.5809		1.3385	25.318	50.3517		1.9524	25.523	50.3596
309	2TU7	50.5476		2.1036	25.368	50.3830		2.8607	25.526	50.3563
310		25.517								2.9737
311	2TU8	50.3539		4.1486	25.632	50.2753		5.5645	25.727	50.2865
312	2TU9	52.2015		8.1244	25.059	52.4377		12.6227	24.782	52.4413
313		12.4880		24.778						
314	2TU10	51.8934		6.5580	25.432	52.2415		9.5422	25.067	52.5578
315		10.3299		24.707						
316	2TU11	49.9025		8.3876	26.411	50.3364		12.3290	25.757	50.3231
317		12.2103		25.779						
318	2TU12	50.1098		6.7169	26.231	50.4469		9.9378	25.649	50.4382
319										9.8397
320										25.667

323 Table 3. The enthalpy (ΔH), Gibbs free energy(ΔG) values in kcal/mol and entropy(ΔS) in kcal/mol Kelvin ,
 324 for the tautomers at DFT/6-311++G(d,p) level in different media.

325	Isomers	Gas	Water	Acetonitrile						
326		ΔH	ΔG	ΔS	ΔH	ΔG	ΔS	ΔH	ΔG	ΔS
327	2TX1 $\leftrightarrow$ 2TX2	9.3618	8.9859	0.00126			11.9327		11.5054	0.00143
328		11.8606		11.4357		0.0013				
329	2TX1 $\leftrightarrow$ 2TX3	11.3435		10.5886		0.00253		12.6688		12.0865
330		0.00195		12.4611		11.8744		0.0025		
331	2TX1 $\leftrightarrow$ 2TX4	12.4598		12.5471		-0.00029		10.5685		10.6438
332		0.00025		10.6444		10.7210		-0.0003		-
333	2TX1 $\leftrightarrow$ 2TX5	19.5827		19.4214		0.00054		13.7230		13.5818
334		0.00047		13.3214		13.2907		0.0005		
335	2TX1 $\leftrightarrow$ 2TX6	9.7885	9.7440	0.00015		15.2704		15.0182		0.00085
336		15.1249		14.8789		0.0001				
337	2TX1 $\leftrightarrow$ 2TX7	10.1977		10.1236		0.00025		15.4204		15.1575
338		0.00088		15.1914		14.9404		0.0002		

339	2TX1 $\leftrightarrow$ 2TX8	15.0006	14.8387	0.00054	17.2935	16.9290
340		0.00122	17.1567	16.8430	0.0005	
341	2TX1 $\leftrightarrow$ 2TX9	21.8235	21.6641	0.00053	17.4843	17.3833
342		0.00034	17.6525	17.5571	0.0005	
343	2TX1 $\leftrightarrow$ 2TX10	24.3863	23.9621	0.00142	20.2209	19.9636
344		0.00086	19.7929	19.7709	0.0014	
345	2TX1 $\leftrightarrow$ 2TX11	21.0642	19.9109	0.00387	15.4876	14.7527
346		0.00246	15.6946	14.9410	0.0039	
347	2TX1 $\leftrightarrow$ 2TX12	18.1168	17.3136	0.00269	14.8713	14.2871
348		0.00196	14.9868	14.3938	0.0027	

349
350 Table 4. $\Delta\Delta H_0$ (solvnet1-solvent2), and $T\Delta\Delta S_0$ (solvnet1-solvent2), values in kcal/mole for the
351 tautomers at DFT/6-311++G(d,p) level in different media.

352	Isomers	$\Delta\Delta H_0(G\rightarrow A)$	$T\Delta\Delta S_0(G\rightarrow A)$	$\Delta\Delta H_0(G\rightarrow W)$	$T\Delta\Delta S_0(G\rightarrow W)$	$\Delta\Delta H_0(A\rightarrow W)$	$T\Delta\Delta S_0(A\rightarrow W)$
353	2TX1 $\leftrightarrow$ 2TX2	-2.4988	-0.01193	-2.5709	-0.05069	-0.0721	-0.03876
354	2TX1 $\leftrightarrow$ 2TX3	-1.1176	0.008945	-1.3253	0.172927	-0.2077	0.163983
355	2TX1 $\leftrightarrow$ 2TX4	1.8154	0.002981	1.8913	-0.01193	0.0759	-0.01491
356	2TX1 $\leftrightarrow$ 2TX5	6.2613	0.011926	5.8597	0.020871	-0.4016	0.008945
357	2TX1 $\leftrightarrow$ 2TX6	-5.3364	0.014908	-5.4819	-0.20871	-0.1455	-0.22361
358	2TX1 $\leftrightarrow$ 2TX7	-4.9937	0.014908	-5.2227	-0.18783	-0.229	-0.20274
359	2TX1 $\leftrightarrow$ 2TX8	-2.1561	0.011926	-2.2929	-0.20274	-0.1368	-0.21467
360	2TX1 $\leftrightarrow$ 2TX9	4.171	0.008944	4.3392	0.056649	0.1682	0.047704
361	2TX1 $\leftrightarrow$ 2TX10	4.5934	0.005963	4.1654	0.166964	-0.428	0.161001
362	2TX1 $\leftrightarrow$ 2TX11	5.3696	-0.00894	5.5766	0.420392	0.207	0.429336
363	2TX1 $\leftrightarrow$ 2TX12	3.13	-0.00298	3.2455	0.21765	0.1155	0.220631

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365 Table 5. The equilibrium constants (K) and pKT values for the tautomers at DFT/6-311++G(d,p) level in
366 different media.

367	Isomers	Gas	Water	Acetonitrile				
368		K	pKT	K	pKT	K	pKT	
369	2TX1 $\leftrightarrow$ 2TX2	2.5859E-07		6.5874	3.67804E-09	8.4344	4.13702E-09	8.3833
370	2TX1 $\leftrightarrow$ 2TX3	1.72864E-08		7.7623	1.37919E-09	8.8604	1.97305E-09	8.7049
371	2TX1 $\leftrightarrow$ 2TX4	6.33821E-10		9.1980	1.57485E-08	7.8028	1.38244E-08	7.8594
372	2TX1 $\leftrightarrow$ 2TX5	5.78831E-15		14.2374		1.10522E-10	9.9566	1.80669E-10
373	2TX1 $\leftrightarrow$ 2TX6	7.19224E-08		7.1431	9.78253E-12	11.0095		1.23762E-11
374	2TX1 $\leftrightarrow$ 2TX7	3.78954E-08		7.4214	7.73274E-12	11.1117		1.11559E-11
375	2TX1 $\leftrightarrow$ 2TX8	1.32446E-11		10.8780		3.8876E-13	12.4103	4.4951E-13
376		12.3473						
377	2TX1 $\leftrightarrow$ 2TX9	1.31363E-16		15.8815		1.80569E-13	12.7434	1.34661E-13
378		12.8708						
379	2TX1 $\leftrightarrow$ 2TX10	2.71552E-18		17.5661		2.3178E-15	14.6349	3.20855E-15
380		14.4937						
381	2TX1 $\leftrightarrow$ 2TX11	2.53343E-15		14.5963		1.53138E-11	10.8149	1.11441E-11
382		10.9530						
383	2TX1 $\leftrightarrow$ 2TX12	2.03113E-13		12.6923		3.36052E-11	10.4736	2.80658E-11
384		10.5518						

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387 Table 6. The inter conversion equilibrium constants (K) and pKT values for tautomers at DFT/6-
 388 311++G(d,p) level in different media.

389	Isomers	Gas	Water	Acetonitrile				
390		K	pKT	K	pKT	K	pKT	
391	2TX1 $\leftrightarrow$ 2TX2	2.5857x10 ⁻⁷	6.5874	3.6781x10 ⁻⁹	8.4344	4.1370x10 ⁻⁹	8.3833	
392	2TX2 $\leftrightarrow$ 2TX3	6.6853x10 ⁻²	1.1749	3.7500x10 ⁻¹	4.2597x10 ⁻¹	4.7692x10 ⁻¹	3.2155x10 ⁻¹	
393	2TX3 $\leftrightarrow$ 2TX4	3.6669x10 ⁻²	1.4357	1.1418x10 ¹	-1.0576	7.0066	-8.4551x10 ⁻¹	
394	2TX4 $\leftrightarrow$ 2TX5	9.1314x10 ⁻⁶	5.0395	7.0179x10 ⁻³	2.1538	1.3069x10 ⁻²	1.8838	
395	2TX5 $\leftrightarrow$ 2TX6	1.2427x10 ⁷	-7.0944	8.8517x10 ⁻²	1.0530	6.8502x10 ⁻²	1.1643	
396	2TX6 $\leftrightarrow$ 2TX7	5.2685x10 ⁻¹	2.7831x10 ⁻¹	7.9045x10 ⁻¹	1.0212x10 ⁻¹	9.0140x10 ⁻¹		
397		4.5081x10 ⁻²						
398	2TX7 $\leftrightarrow$ 2TX8	3.4950x10 ⁻⁴	3.4566	5.0278x10 ⁻²	1.2986	4.0293x10 ⁻²	1.3948	
399	2TX8 $\leftrightarrow$ 2TX9	9.9178x10 ⁻⁶	5.0036	4.6446x10 ⁻¹	3.3305x10 ⁻¹	2.9957x10 ⁻¹	5.2350x10 ⁻¹	
400	2TX9 $\leftrightarrow$ 2TX10	2.0674x10 ⁻²	1.6846	1.2836x10 ⁻²	1.8916	2.3827x10 ⁻²	1.6229	
401	2TX10 $\leftrightarrow$ 2TX11		9.3295x10 ²	-2.9699	6.6064x10 ³	-3.8200	3.4732x10 ³	-3.5407
402	2TX11 $\leftrightarrow$ 2TX12		8.0168x10 ¹	-1.9040	2.1945	-3.4133x10 ⁻¹	2.5184	-4.0113x10 ⁻¹
403	2TX1 $\leftrightarrow$ 2TX8	1.3244x10 ⁻¹¹	1.0878x10 ¹	3.8879x10 ⁻¹³	1.2410x10 ¹	4.4951x10 ⁻¹³		
404		1.2347x10 ¹						
405	2TX8 $\leftrightarrow$ 2TX9	9.9178x10 ⁻⁶	5.0036	4.6446x10 ⁻¹	3.3305x10 ⁻¹	2.9957x10 ⁻¹	5.2350x10 ⁻¹	
406	2TX1 $\leftrightarrow$ 2TX7	3.7895x10 ⁻⁸	7.4214	7.7328x10 ⁻¹²	1.1112x10 ¹	1.1156x10 ⁻¹¹	1.0952x10 ¹	
407	2TX8 $\leftrightarrow$ 2TX6	5.4308x10 ³	-3.7349	2.5162x10 ¹	-1.4007	2.7533x10 ¹	-1.4398	
408	2TX2 $\leftrightarrow$ 2TX6	2.7816x10 ⁻¹	5.5570x10 ⁻¹	2.6597x10 ⁻³	2.5752	2.9916x10 ⁻³	2.5241	
409	2TX7 $\leftrightarrow$ 2TX3	4.5617x10 ⁻¹	3.4087x10 ⁻¹	1.7837x10 ²	-2.2513	1.7686x10 ²	-2.2476	
410	2TX3 $\leftrightarrow$ 2TX5	3.3483x10 ⁻⁷	6.4752	8.0128x10 ⁻²	1.0962	9.1569x10 ⁻²	1.0383	
411	2TX6 $\leftrightarrow$ 2TX4	8.8128x10 ⁻³	2.0549	1.6098x10 ³	-3.2068	1.1170x10 ³	-3.0481	
412	2TX6 $\leftrightarrow$ 2TX12	2.8238x10 ⁻⁶	5.5492	3.4349	-5.3592x10 ⁻¹	2.2677	-3.5559x10 ⁻¹	
413	2TX11 $\leftrightarrow$ 2TX5	2.2846E+00	-3.5881x10 ⁻¹	7.2175	-8.5839x10 ⁻¹	1.6212x10 ¹	-1.2098	
414	2TX7 $\leftrightarrow$ 2TX11	6.6857x10 ⁻⁸	7.1749	1.9802	-2.9671x10 ⁻¹	9.9894x10 ⁻¹	4.6001x10 ⁻⁴	
415	2TX10 $\leftrightarrow$ 2TX6	2.6486x10 ¹⁰	-1.0423x10 ¹	4.2206x10 ³	-3.6254	3.8572x10 ³	-3.5863	
416	2TX8 $\leftrightarrow$ 2TX10	2.0504x10 ⁻⁷	6.6882	5.9617x10 ⁻³	2.2246	7.1379x10 ⁻³	2.1464	
417	2TX9 $\leftrightarrow$ 2TX7	2.8849x10 ⁸	-8.4601	4.2823x10 ¹	-1.6317	8.2844x10 ¹	-1.9183	
418	2TX1 $\leftrightarrow$ 2TX9	1.3135x10 ⁻¹⁶	1.5882x10 ¹	1.8058x10 ⁻¹³	1.2743x10 ¹	1.3466x10 ⁻¹³		
419		1.2871x10 ¹						
420	2TX4 $\leftrightarrow$ 2TX12	3.2043x10 ⁻⁴	3.4943	2.1338x10 ⁻³	2.6708	2.0302x10 ⁻³	2.6925	
421	2TX1 $\leftrightarrow$ 2TX4	6.3387x10 ⁻¹⁰	9.1980	1.5748x10 ⁻⁸	7.8028	1.3824x10 ⁻⁸	7.8594	
422	2TX9 $\leftrightarrow$ 2TX12	1.5463x10 ³	-3.1893	1.8609x10 ²	-2.2697	2.0842x10 ²	-2.3189	
423	2TX2 $\leftrightarrow$ 2TX7	1.4655x10 ⁻¹	8.3401x10 ⁻¹	2.1024x10 ⁻³	2.6773	2.6966x10 ⁻³	2.5692	
424	2TX7 $\leftrightarrow$ 2TX10	7.1662x10 ⁻¹¹	1.0145x10 ¹	2.9974x10 ⁻⁴	3.5233	2.8761x10 ⁻⁴	3.5412	
425	2TX3 $\leftrightarrow$ 2TX6	4.1608E+00	-6.1918x10 ⁻¹	7.0927x10 ⁻³	2.1492	6.2726x10 ⁻³	2.2026	
426	2TX6 $\leftrightarrow$ 2TX11	3.5224x10 ⁻⁸	7.4532	1.5653	-1.9459x10 ⁻¹	9.0045x10 ⁻¹	4.5541x10 ⁻²	
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