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Studies on tautomerism in tetrazole: comparison of Hartree–Fock and density functional theory quantum chemical methods

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Abstract

A comparison of the ab initio quantum chemical methods: Hartree–Fock (HF) and hybrid density functional theory (DFT)/B3LYP for the treatment of tautomeric equilibria both in the gas phase and in the solution is made. The solvent effects were investigated in terms of the self-consistent reaction field (SCRF). Ionization potentials (IP), calculated by DFT/B3LYP, are also compared with those calculated previously within the HF frame. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

There has been a continuing interest, both experimental [1–8] and theoretical [9–12], for tautomerism in tetrazole (Fig. 1). In the gas phase, microwave spectroscopy has disclosed that there exist two tautomeric forms of tetrazole [1]; however, mass spectroscopy [2] and photoelectron spectroscopy [3] results have demonstrated only the 2H tautomer. Ionization potentials (IP) and structural changes of cation radicals of both tautomers have been calculated by Mazurek and Osman in the Hartree–Fock (HF) frame to be compared with the experimental photoelectron spectra [3] and observed fragmentation in mass spectra [2]. Their results are consistent with the experimental data on the assumption that the

molecule exists in the 2H form. In a theoretical work, Fabian has used three semi-empirical methods [9]; other works have used HF methods including electron correlation at configuration interaction all doubles (CID) level [10], and quadratic configuration interaction ([QCISD(T)]) or MP2-MP4 level [11]. Their results showed that, at various theoretical levels, the 2H continues to be the lowest energy tautomer (except for HF/3-21G). At the HF/3-21G level, the 1H was predicted to be the more stable than the 2H tautomer and even inclusion of correlation at the 3-21G level could not reverse the incorrect preference. When better basis sets were used, this preference was reversed but the relative energy changed rather incoherently [11].

On the other hand, experimental data on solutions show tautomeric equilibria to be shifted strongly towards the 1H form [4]. Based on dipole moment measurements in benzene solution, it appears that the 1H tautomer is dominant [5]. Proton

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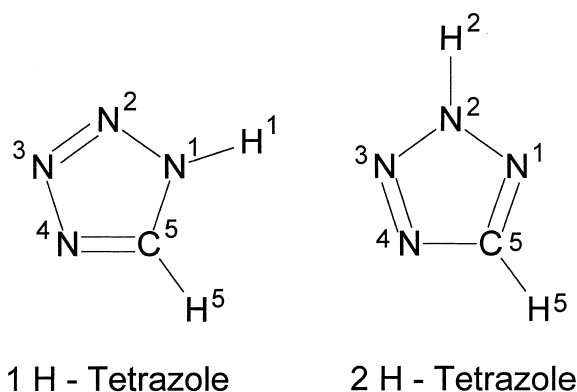


Fig. 1. Tautomeric forms of tetrazole.

magnetic resonance data [6] also suggest that this form is preferred in the DMF/H₂O solution. The results of the ¹³C NMR shift have indicated predominance of the 1H form in water, dimethylsulfoxide and dioxane [7]; in dimethylsulfoxide ¹⁵N NMR shift has confirmed this result [8].

In the solid state, X-ray diffraction data showed the occurrence of 1H tetrazole only which can exist in two different crystal structures [13,14].

These data can be accounted for by the suggestion that the tautomeric equilibrium is strongly influenced by the surrounding medium. Theoretical investigations on the influence of solvent on the tautomeric equilibrium of tetrazole have been carried out by Wong et al. by the HF method, but they took into account only a limited range of dielectric constants: $\epsilon = 2$ and $\epsilon = 40$, simulating non-polar and polar media, respectively. At $\epsilon = 2$, with the 6-31G* and 6-311+G** basis sets, the energy of tautomer 1H was lower than that of 2H; nevertheless, at the MP2/6-311+G** level, the sequence was reversed.

At $\epsilon = 40$, each of the three basis sets used gave the energy of 1H steadily lower than that of 2H [11].

Our goals in the present Letter are twofold. Firstly, we aim at comparing HF and hybrid density functional theory (DFT) results concerning tautomeric equilibria of tetrazole in the gas phase as well as its IP. Calculations by the latter method include electron correlation and are not so expensive as is MP2 or CI. Secondly, we investigate thoroughly tautomerism in relation to medium, carrying out isodensity polarizable continuum model (IPCM) calculations for solvents with varying dielectric constants. This model takes into consideration non-specific interactions between the solute molecule and the solvent, representable by a polarizable continuum. A comparison of DFT and SCF results allows to see if the relative energies and the structural parameters are strongly dependent on the method. Calculations with different basis sets up to 6-311++G**, including polarization and diffuse functions, especially adequate for the investigation on the lone-pair and open-shell systems, show dependence on the basis set.

2. Results

2.1. Tautomeric equilibria in the gas phase

Calculations were carried out by using GAUSSIAN98 programs [15]. The optimized structures by the semi-empirical AM1 method were adopted as initial geometries. The hybrid DFT method based on the B3LYP functional is used throughout with various basis sets.

Table 1
Energies and dipole moments of optimized tautomers of tetrazole

Basis set	Total energies (hartree)		Relative energy (kcal/mol)	Dipole moment (debye)	
	1H	2H		1H	2H
3-21G	−256.7873913	−256.7880281	0.40	5.44	2.33
6-31G	−258.1333471	−258.1362081	1.8	5.77	2.40
6-31G*	−258.2509047	−258.255384	2.8	5.34	2.27
6-31+G**	−258.2680498	−258.2725327	2.8	5.56	2.31
6-311++G**	−258.3242566	−258.3288958	2.9	5.55	2.31

The results of the energy comparison of two tautomers are given in Table 1. It can be seen that regardless of the basis set used, including 3-21G, the 2H tautomer has a lower energy than the 1H tautomer. The calculated dipole moments agree with the experimental values of 5.30 and 2.19 D obtained from microwave spectra for 1H and 2H tautomers, respectively [1], as well as with those calculated previously (5.63 and 2.24 D, HF with 6-31G** basis set) [10].

The optimized parameters of 1H tetrazole at the 6-311++G** level are presented in Table 2 and compared with two known polymorphs of tetrazole: the monoclinic form with two molecules in the unit cell [13], and the triclinic with one molecule of 1H tautomer in the unit cell [14]. It was previously found by using HF/6-31G that there was a good agreement between the structural parameters of the 1H tautomer and those measured in the crystal [10,13]. For a comparison with the HF results [10], parameters calculated by using the 6-31G basis set are given. It can be seen that the values obtained with B3LYP/6-31G agree not better with the experimental data than with HF/6-31G. Some improvement can be noticed in B3LYP/6-311++G** (e.g., for N1C5, N2N1, N4N3, and C5N4 dis-

tances), but the dependence of structural parameters on the basis set is rather small, as previously noticed [10]. Inclusion of electron correlation by Wong et al. [11] did not produce any substantial changes; the calculated molecular geometry of 1H-tetrazole at the MP2 level is also similar to our B3LYP/6-311++G** results.

Differences between data in the first three columns in Table 2 are not larger than the differences between experimental values reported for two different polymorphs (columns 4 and 5). So one can conclude that the most accurate calculations for the gas phase conformation fail to bring any better correlation with the solid-state parameters when the specific force fields operate, which cannot be taken into account for an isolated molecule. The largest difference was between the measured and calculated angles for H5C5N1 (115° and 125.74°) and H1N1N2 (131° and 120.63°, respectively); the minor difference for C5N4N3 (109.4° and 106.27°) [10]. Similar discrepancies between experimental and calculated values were reported by Wong et al. [11] for H5C5N1 (115 vs 124.88) and for C5N1H1 (120° vs 130.32°). The authors have stated that the calculated geometry of 1H tetrazole at the MP2 level differs signifi-

Table 2
Optimized structural parameters of 1H tautomeric form of tetrazole (angles are in degrees, and lengths in Å)

Structural parameters	RHF/6-31G ^a	B3LYP/6-31G	B3LYP/6-311++G**	Exptl ^b	Exptl ^c
N1C5	1.343	1.359	1.346	1.33	1.308
N2N1	1.353	1.390	1.351	1.33	1.332
N3N2	1.270	1.315	1.287	1.30	1.295
N4N3	1.372	1.409	1.363	1.33	1.346
C5N4	1.305	1.333	1.312	1.30	1.315
H5C5	1.061	1.075	1.077	0.98	0.88
H1N1	0.989	1.007	1.009	1.10	0.81
N3N2N1	106.64	105.75	106.05	107.6	106.0
N4N3N2	110.67	110.707	110.71	107.8	110.5
C5N4N3	106.27	105.74	105.74	109.4	105.5
N1C5N4	108.00	108.96	108.38	106.7	108.8
H5C5N1	125.74	125.23	124.99	115	127
H1N1N2	120.63	120.23	120.50	131	123
C5N1N2		108.85	107.82	108.5	109.2
C5N1H1		130.92	129.66	120	127
N4C5H5		125.82	128.94	138	124

^a Taken from Ref. [10].

^b Taken from Ref. [13].

^c Taken from Ref. [14].

cantly from the available solid state structural data. These two sets of calculated parameters [10,11] were compared with the experimental values of the first known polymorph [13]. A comparison between these above-mentioned calculated angles and those measured recently for the second polymorph [14] (columns 3 and 5) showed a far better agreement. Evidently, the calculated values match better the structural features of this new polymorphic structure.

2.2. Ionization potentials

The vertical and adiabatic IP of both tautomers were calculated individually for the σ radical cation, $^2A'$, and the π radical cation, $^2A''$. The significant difference between these hybrid DFT and previous HF results [10] is that HF produced IP according to the Koopmans' theorem (the negative of the highest occupied orbital energy) higher by 1–2.5 eV than those calculated as the difference between the energies of the ion and the corresponding neutral molecule, whereas B3LYP produced IP lower by ~ 2.5 eV: for 1H 8.37 and 8.91 eV, and for 2H – 8.55 and 8.84 (first value for σ and second value for π orbitals, respectively). The experimental value is equal to 11.3 eV [16]. Contrary to HF results, within Koopmans' approximation, the first ionization occurs from σ orbital and the ionization from a π orbital is higher.

When ionization energy was calculated as the difference between the energies of the ion and the corresponding neutral molecule, present calculations using the B3LYP/6-311++G** basis set were in agreement with the previous results on the following points:

- for 1H tetrazole, the σ radical cation has a lower energy than the π radical cation (vertical IP 11.12 and 11.14 eV, adiabatic 10.65 and 11.06 eV, respectively, for σ and π radical cations);
- σ radical cation of 1H tetrazole has a lower IP than 2H tetrazole (vertical IP 11.12 and 11.32 eV; adiabatic IP 10.65 and 10.90 eV, respectively, for 1H and 2H).

Koopmans' approximation predicts the right ionization order as compared with the above results.

Energies of the π radical cation of 2H tautomer could not be calculated because molecular orbitals

of the cation were swapped during SCF calculations producing σ radical cation $^2A'$ instead of $^2A''$.

The problem of identifying the photoelectron peaks by electron rejection from a single state was not continued in view of the results of Palmer and Beveridge [16]. They have reinterpreted UV photoelectron spectra of 2H-tetrazole in the light of *ab initio* multi-reference CI calculations. The states corresponding to the lowest photoelectron peaks were assigned as $1^2A'' + 1^2A'$ and $2^2A'' + 2^2A'$.

2.3. Tautomeric equilibria in solutions

The fact that the 2H isomer having a dipole moment 2.4 times lower than 1H is promoted in the gas phase is consistent with the observation of Wong et al. [17] that, in the gas phase, conformations with no dipole moment are usually preferred over those leading to dipoles. Using DFT/B3LYP, it was found that the 2H isomer is of a lower energy not only in a medium with $\epsilon = 2$ (e.g., cyclohexane) but also in media with $\epsilon = 3$ and 4 (methylene chloride and butanol). A reversal of energy took place near $\epsilon = 7$ (aniline). Plots of energies of both isomers vs dielectric constant are given in Fig. 2, whereas the plot of their energy difference (2H–1H) is given in Fig. 3.

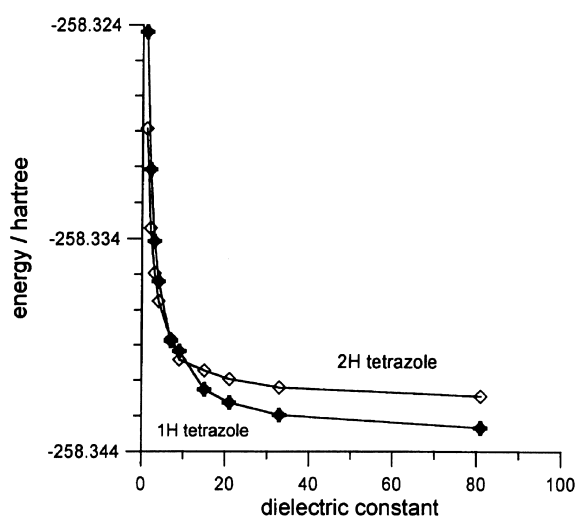


Fig. 2. Dielectric constant dependence of tetrazole energy.

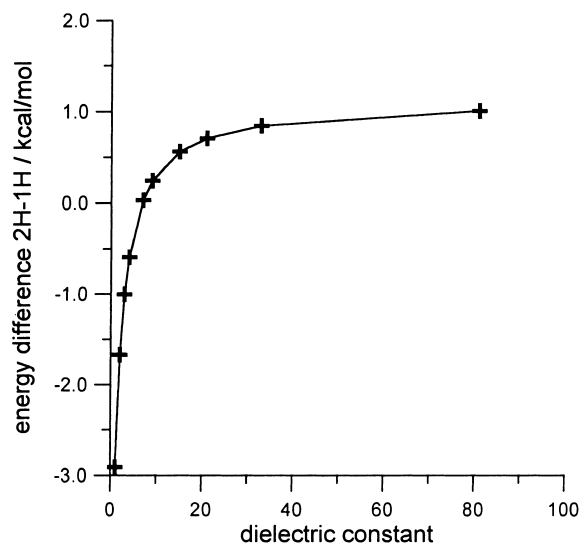


Fig. 3. Dielectric constant dependence of the energy difference between both tetrazole tautomers.

The solvent represented by a polarizable continuum is found to affect significantly dipole moments of the individual solute conformers. The induced dipole moments, calculated as the difference between the moments of molecules immersed in a solvent and those in the gas phase, are plotted in Fig. 4. The curves in Figs. 2–4 show an asymptotic behavior.

The charge distributions of dipolar compounds are often altered significantly in the presence of a solvent reaction field [18]. We have examined the charge distribution of tautomers in both the gas phase and in water by using Mulliken charges (Table 3) and charges calculated according to Bader's theory of atoms in molecules (AIM) [19]. The AIM results are given in Table 4. According to both methods, the charge distribution in water is less uniform than in the gas phase, which agree with the increased Mulliken dipole moments in polar solvents. These two distributions and their changes on passing from the gas phase to water do not differ significantly, except for the charge on carbon atom, which is negative when calculated by the first method, and positive, when calculated by the second method. Both tautomers show a large amount of charge relocation from protons to

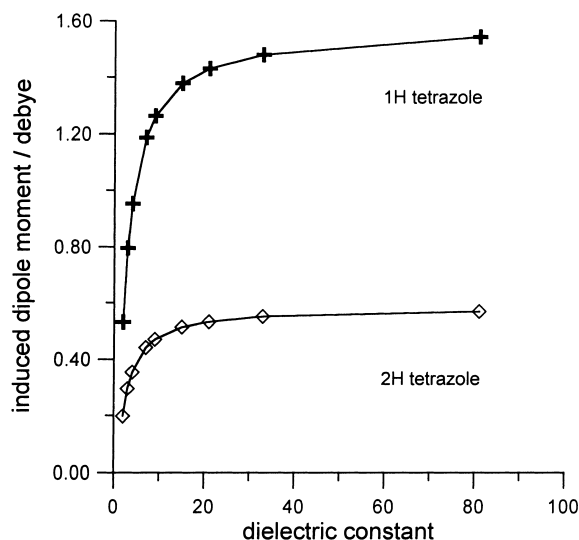


Fig. 4. Dielectric constant dependence of the induced dipole moment of both the tetrazole tautomers.

nitrogens (according to AIM, also from carbon to nitrogens).

In polar media, the degree of charge transfer is even more pronounced. Both methods demonstrate the flow of electron density from protons and atoms to which they are attached to most negatively charged nitrogens. The data in Table 4 show the outflow of negative charge in tautomer 1H from H1, N1, H5 and C5 to N2, N3, and N4, in 2H from H2, N2, H5, and C5 to N1, N3, N4; the data in Table 3 are very similar, except for N1 atom in 1H tetrazole, where the charge is virtually the same in the two media. The results are consistent with a similar investigation on solvent effects on charge distributions in tetrazole in the gas phase and in a polar medium ($\epsilon = 40$) by using the Onsager reaction field [11].

Bond orders and ellipticities calculated for 1H and 2H tetrazole using the AIM method do not differ much in both the media. However, bond orders within the rings differ significantly; in the 1H isomer in the gas phase, bond order is the largest for the N1–N2 bond (1.98) consistent with the formulation of a formal double bond between these atoms and with their shortest bond distance (Table 2, Exptl^c). For the second double bond,

Table 3
Calculated Mulliken electron population (SCF)^a

Atom	1H-tetrazole			2H-tetrazole		
	$\epsilon = 1.0$	$\epsilon = 78$	Δ_{charge}	$\epsilon = 1.0$	$\epsilon = 78$	Δ_{charge}
N1	7.158	7.159	−0.001	7.136	7.183	−0.047
N2	7.039	7.073	−0.034	7.075	7.045	0.030
N3	7.036	7.081	−0.045	6.982	7.024	−0.042
N4	7.176	7.238	−0.062	7.184	7.233	−0.049
C5	6.096	6.073	+0.023	6.151	6.141	+0.010
H1/H2	0.665	0.600	+0.065	0.649	0.592	+0.057
H5	0.830	0.776	+0.054	0.822	0.781	0.041

^a DFT B3LYP/6-311++G** wavefunction.

Table 4
Calculated electron population according to theory of AIM^a

Atom	1H-tetrazole			2H-tetrazole		
	$\epsilon = 1.0$	$\epsilon = 78$	Δ_{charge}	$\epsilon = 1.0$	$\epsilon = 78$	Δ_{charge}
N1	7.769	7.756	+0.013	7.604	7.618	−0.014
N2	7.070	7.091	−0.021	7.286	7.279	+0.007
N3	7.056	7.110	−0.054	7.054	7.079	−0.025
N4	7.613	7.670	−0.057	7.526	7.567	−0.041
C5	5.047	5.021	+0.026	5.079	5.077	+0.002
H1/H2	0.554	0.504	+0.050	0.546	0.505	+0.041
H5	0.891	0.846	+0.045	0.905	0.877	+0.028

^a DFT B3LYP/6-311++G** wavefunction.

N4C5, which is longer than the former, bond order is equal to 1.49.

In 2H, the N3–N4 bond which also is a double bond, has the largest bond order (1.82). The bond order of the second formal double bond, N1–C5, is lower, similarly as in 1H, and equal to 1.46. Interestingly, bond order of N2–N3 bond, formally single, is equal to 1.59 and lies between those of two double bonds.

3. Conclusions

1. Calculations by DFT/B3LYP are in agreement with those previously made by using HF in that the 2H tautomer is preferred in the gas phase (independently of the basis set used). In non-polar solvents, tautomeric preference is the same as in the gas phase. On the other hand, only the 1H tautomer has been found in the crystal state [13,14]. This fact is consistent with a continuous increase in the relative 1H stability as the dielectric constant is raised. The crystal field probably can be represented as a

medium with a larger dielectric constant than the range spanned by the known solvents.

2. Contrary to HF results [10], Koopmans' approximation predicts the right ionization order.
3. These geometrical features of the 1H tautomer in the gas phase which differed significantly from those found in the crystal state [13] agree much better with the parameters of the second, triclinic polymorph of that compound, which was reported much later [14].
4. Mulliken and AIM charge distributions are similar, both in the gas phase and in water.
5. On passing from the gas phase to a polar solvent, hydrogens become more positive and nitrogens more negative. In other words, a more polar character is developed in the presence of the solvent reaction field.

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