# Why is tetrazole not practical as a diene in Diels–Alder reactions? An ab initio theoretical study

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## Abstract

An ab initio theoretical study of the reactivity of tetrazole tautomers, following the example of the ethylene cyclo-addition reactions, was undertaken. The geometries of the reactants, the transition structures, and the products for the three tetrazole tautomers were generated at RHF/3-21G*, RHF/6-31G*, and MP2/6-31G*. The energies were evaluated up to the MP4/6-31G*//MP2/6-31G* level. The relative stabilities of the tetrazole tautomers were studied, and their relative reactivities were predicted from their frontier molecular orbitals (FMO), the charge transfer between the reactants in the transition structures, the extent of the reaction calculated from the bond orders, and the electronic location of transition state calculated from the fraction of the overall charge transferred in the transition state. It was demonstrated that FMO and the charge transferred in transition states are not reliable methods for evaluation of relative reactivity of tetrazole tautomers. However the percentage of charge transferred, and the percentage of reaction advance can be useful when the energies of reactants and products are available. The calculated activation energies predict that the most reactive tetrazole tautomer is the non-aromatic **1T**, while the least reactive is aromatic **3T**. It was predicted that the cycloaddition reaction with tautomer **1T** is experimentally achievable but other side reactions with either tautomer **1T** or product **1TS** might prevent the accumulation of the primary cycloaddition product in the reaction mixture.

## 1. Introduction

Tetrazole attracted the attention of the wider scientific community more than 30 years ago when it was discovered that its derivatives have diverse pharmaceutical and biochemical properties [1]. Tetrazoles have mostly been used as substitutes for carboxylic acids because their $pK_a$ values are very similar. The increase in biological activity largely derives from the ability of tetrazole to bind more effectively (around 100 times) than the corresponding carboxylic acids. In addition, tetrazole is metabolically more stable than the acid derivatives.

Although tetrazoles are involved in many different organic reactions [2] that combine together their aromatic character, the acidity of the nitrogen proton, and, in highly polarized tetrazoles, the elimination of nitrogen, to the best of our knowledge there is no experimental evidence of tetrazole acting as dienes in Diels–Alder reactions. Here we present our theoretical study of the different tetrazole tautomers and their reactivity as dienes in Diels–Alder reactions.

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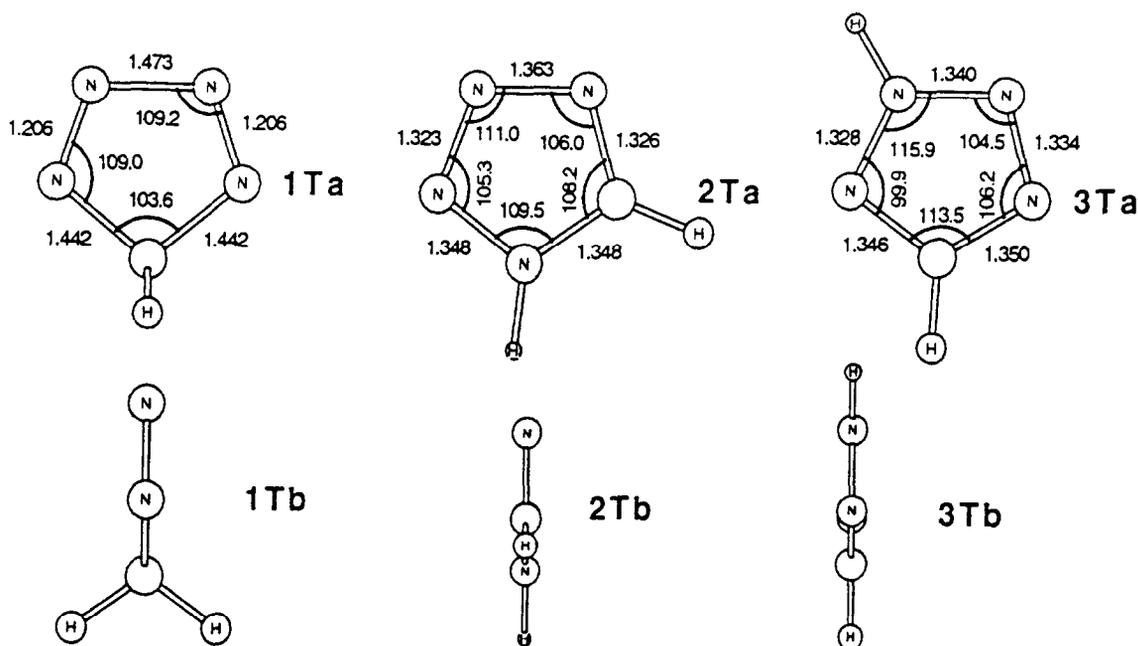
Fig. 1. The geometries of the three possible tetrazole tautomers calculated at the MP2/6-31G* level (a, front; b, side view).

## 2. Methodology

The ab initio program Gaussian 92 [3] was employed to fully optimize the geometries without any symmetry constraints at the restricted Hartree–Fock (HF) [4] with the standard basis sets, 3-21G* and 6-31G*. Electron correlation was incorporated by applying second-order Møller–Plesset theory for geometry optimization, and for energy evaluation, third- and fourth-order Møller–Plesset theory (MP3 and MP4) keeping the core electrons frozen (FC) [5]. Analytic vibrational frequencies were obtained up to the HF/6-31G* level to determine the number of imaginary frequencies which characterize each stationary point (where minima have zero and transition structures have one imaginary frequency). The normal coordinates of the imaginary vectors of the transition structures were carefully examined and were visualized by a graphical program. The movements suggest the formation or breaking of the new bond corresponding to the forward and backward reaction, respectively. We have no reason to assume that at the MP2/6-31G* theory level there are other minima along the potential energy surface.

## 3. Results and discussion

Tetrazole can assume three different tautomer forms, as presented in Fig. 1. The tautomers of tetrazole have been the subject of a number of semiempirical and ab initio calculations. Earlier results show that tautomer 3T is 6.9 kcal mol$^{-1}$ more stable than 2T [6]. On the basis of MNDO calculations, Dewar and Gleicher suggested that the two tautomers 2T and 3T have very similar energy [7]. Low level ab initio calculations were used to calculate the dipole moment: for structure 2T it was 5.17 D, while for 3T it was 2.54 D [8]. Our results of the calculation of the dipole moment are presented in Table 1.

Our calculations are in good agreement with the experimental value and other evidence that indicates that tautomer 3T is dominant in the gas phase. This is not the case in solution. It has been determined that the dioxane solution of tetrazole has a dipole moment of 5.11 D [10] as was predicted by our calculations for tautomer 2T. This is consistent with other experimental evidence where products are generated from tautomer 2T in solution.

The relative energies of different tetrazole

Table 1
Calculated dipole moment (D) for the different tautomers of tetrazole

| Tautomer | HF/3-21G* | HF/6-31G* | MP2/6-31G* | Experimental [9] |
|----------|-----------|-----------|------------|------------------|
| 1T | 3.55 | 3.28 | 3.30 | |
| 2T | 5.84 | 5.64 | 5.75 | |
| 3T | 2.32 | 2.29 | 2.31 | 2.19 ± 0.05 |

tautomers are presented in Table 2. While the HF/3-21G* predicts that the most stable tautomer in the gas phase should be **2T**, the higher theoretical levels show that **3T** is more stable, as determined on the basis of the dipole moment discussed above. All tetrazole tautomers have the ring atoms in one plane. MP4/6-31G*//MP2/6-31G* shows that **1T** has too high an energy to be present in equilibrium with the other enantiomers, while the energy difference between **2T** and **3T** (2.66 kcal) shows they are in equilibrium. This is also the case with tetrazole in solution. This is not surprising because both structures represent aromatic heterocyclic compounds while **1T** is non-aromatic.

The products of the cycloaddition reaction with ethylene can be very useful compounds: all of them, after elimination of nitrogen or hydrogen cyanide, can produce a new heterocyclic compound. To determine the stability of the products we have generated their structures (Fig. 2) and evaluated their energies by ab initio methods. To the best of our knowledge there is no experimental data on the structural parameters for any of these compounds. As expected, **1TP** is symmetrical, with the N–C bond between the ethylene and tetrazole moiety being 1.508 Å. The N–N bond distance of the nitrogen moiety corresponding to the Diels–Alder reaction of nitrogen and diazole is 1.500 Å. The N–C bond distances in structures **3TP** and **2TP** are a little longer (1.512 Å and 1.526 Å, respec-

tively). The relative energies of the different products and the energies of the reaction are presented in Table 3.

Since tautomer **1T** is not aromatic, the reaction outcome should be exoenergetic, as predicted with all employed theory levels. The two other tautomers (**2T** and **3T**) have extra aromatic stability and as in the course of the reaction their aromaticity diminishes, this makes the reaction less exoenergetic. Furthermore, considering the results in Table 2, tautomer **3T** is the most stable and consequently its reaction with ethylene is expected to be the least exoenergetic. As indicated in Table 3, this is indeed the case, and the reaction is actually energy demanding. The values of the reaction energy vary strongly with the improved theory level. The case is similar when comparing the relative energies of the products. For example, with RHF/3-21G* they are all within a 6.00 kcal mol$^{-1}$ range, **2TP** being the most stable, and **3TP** the least stable. MP2/6-31G* predicts that **3TP** is the most stable, while **1TP** has the same energy as **2TP** and the energy range is 14.85 kcal mol$^{-1}$. Considering the energies of the reactions, it is quite reasonable that the products are not very stable, and the reaction might produce other heterocycles, or even, in the case of tautomer **3T**, the reaction might be reversible with an extremely low backward reaction barrier. This will be discussed later.

Table 2
Calculated relative energies (kcal mol$^{-1}$) of the different tetrazole tautomers

| TS | E1 | E2 | E3 | E4 | E5 | E6 | E7 |
|----|------|------|------|------|------|------|------|
| 1T | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2T | −28.75 | −30.63 | −24.84 | −26.19 | −33.95 | −26.81 | −28.66 |
| 3T | −27.76 | −29.71 | −26.69 | −28.41 | −37.78 | −29.44 | −31.32 |

Key: E1, HF/3-21G*; E2, HF/3-21G + ZPVE [11]; E3, HF/6-31G*; E4, HF/6-31G* + ZPEV [11]; E5, MP2/6-31G*; E6, MP3/6-31G*//MP2/6-31G*; E7, MP4/6-31G*//MP26-31G*.
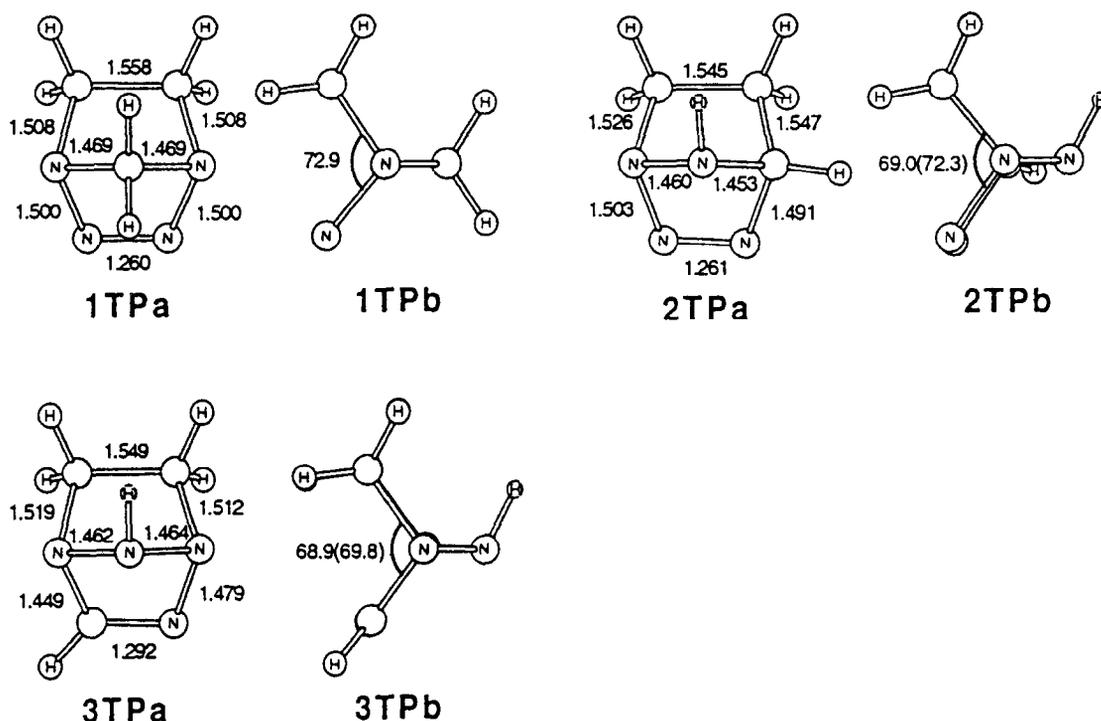
Fig. 2. Products of ethylene addition to tetrazoles generated by MP2/6-31G*: a, front; b, side views.

To evaluate the reactivity, we have generated the transition state structures for all three tautomers (Fig. 3). As expected, transition structure **1TS** is symmetrical because in the course of reaction there is a plane of symmetry bisecting both reactants. The symmetry is missing for the other tautomers and both **2TS** and **3TS** represent asynchronous concerted Diels–Alder cycloadditions of ethylene to tetrazole (Fig. 3). Although the bond distance for the determination of synchronicity of the reaction is reliable only when two bonds of the same type are being formed, it is not appropriate in other cases. In the latter case, more relevant information can be obtained by comparison of the bond orders of the new forming bonds in the transition structures [12]. The bond orders calculated for the MP2/6-31G* optimized structures are presented in Table 4.

The bond orders for **1TS** show that this is a symmetrical structure and the reaction is synchronous. From the other two, **2TS** is more asynchronous (Table 4) with Mulliken and Lowdin bond order differences of 0.175 and 0.152, respectively. This can be explained by the n–p repulsion interactions that are present in the N–C bond formation. In **2TS**, only one N–C bond is being formed,

Table 3
Thermodynamic and relative energy data of ethylene addition to the tetrazole tautomers

| | Total energy (a.u.) | | | DE (reaction) (kcal mol$^{-1}$) | | | DE (relative) (kcal mol$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | a | b | c | a | b | c | a | b | c |
| **1TP** | −332.85068 | −334.74901 | −335.79716 | −16.79 | −1.75 | −19.13 | 0.0 | 0.0 | 0.0 |
| **2TP** | −332.85702 | −334.75238 | −335.79710 | 7.99 | 20.97 | 14.86 | −3.98 | −2.11 | 0.04 |
| **3TP** | −332.84623 | −334.73073 | −335.77350 | 13.77 | 36.42 | 33.49 | 2.79 | 11.47 | 14.85 |

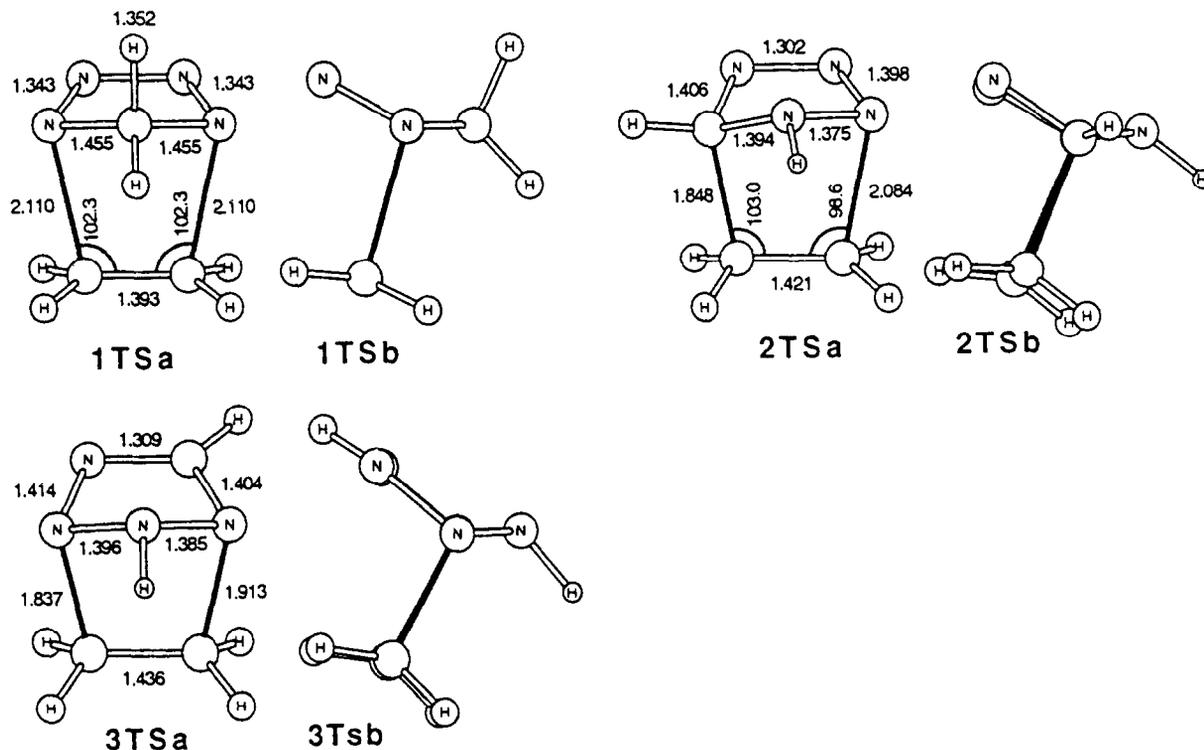Key: a, RHF/3-21G*; b, RHF/6-31G*; c, MP2/6-31G*.

Fig. 3. Transition structures of ethylene addition to tetrazole generated with MP2/6-31G*: a, front; b, side views.

and the repulsion interactions push the atoms away making the transition state quite asynchronous. In **3TS**, two N–C bonds are being formed, and as a consequence of the n–p repulsion interactions, ethylene is almost symmetrically pushed away from the tetrazole moiety in the transition structure.

The reactivity can be judged on the basis of the bond orders in the transition state. As determined previously, the non-aromatic tautomer **1T** has around 30 kcal mol$^{-1}$ higher energy than the aromatic tautomers, **2TS** and **3TS**. Because the

aromaticity of the two tautomers **2T** and **3T** is destroyed in the product, these products must have a higher energy than the corresponding reactants, as was demonstrated in Table 4. Bearing in mind this information, the bond orders or degree of product formation should give a qualitative picture of the tautomer reactivity. From the sum of the Mulliken bond orders in the transition state, the reactants have advanced 34.6%, 60.8%, and 67.7% toward the products in **1TS**, **2TS**, and **3TS** estimated at the MP2/6-31G* level, assuming that the sum of these bond orders in the products

Table 4
Bond orders [13] of new forming bonds in ethylene addition to tetrazole

| TS | Mulliken bond order | | | | Lowdin bond order | | | |
|---|---|---|---|---|---|---|---|---|
| | a | b | a − b | a + b | a | b | a − b | a + b |
| **1TS** | 0.346 | 0.346 | 0.000 | 0.692 | 0.383 | 0.383 | 0.000 | 0.766 |
| **2TS** | 0.696 | 0.521 | 0.175 | 1.217 | 0.680 | 0.528 | 0.152 | 1.208 |
| **3TS** | 0.694 | 0.660 | 0.034 | 1.354 | 0.737 | 0.672 | 0.064 | 1.409 |

Key: TS, transition state structure; a, left-forming bond of TS (see Fig. 3); b, right-forming bond of TS (see Fig. 3).

Table 5
Energy (kcal mol$^{-1}$) gap between the HOMO of ethylene and the LUMO of tetrazole

| TS | $DE_{FMO}1$ | $DE_{FMO}2$ | $DE_{FMO}3$ |
|----|------|------|------|
| 1TS | 10.74 | 10.22 | 10.12 |
| 2TS | 11.88 | 12.13 | 11.60 |
| 3TS | 11.45 | 11.85 | 11.21 |

Key: $DE_{FMO}1$, HF/3-21G*; $DE_{FMO}2$, HF/6-31G*; $DE_{FMO}3$, HF/6-31G*//MP2/6-31G*.

is 2. Because the transition structure **1TS** is much closer to the reactants, it is expected that the activation barrier should be very low, lower than for any of the other two. Of the other two, **2TS** should have the lower energy, although transition state **3TS** is closer to the product because **2TP** is 14.81 kcal mol$^{-1}$ more stable than **3TP**, and **2T** is 3.83 kcal mol$^{-1}$ less stable than **3T** on the reaction coordinate estimated at MP2/6-31G* (Tables 3 and 2, respectively). Thus the reactivity order is predicted to be **1TS**, **2TS**, and **3TS**.

An evaluation of the tetrazole tautomer reactivity in Diels–Alder reactions can also be obtained on the basis of the frontier orbitals energies [14].

Ethylene addition to tetrazole is an inverse electron-demand Diels–Alder reaction, and consequently it is HOMO dienophile controlled. For example, the energy difference between the HOMO of tetrazole **T3** and ethylene is 2.01 kcal mol$^{-1}$ higher than the other combination calculated at the HF/6-31G*//MP2/6-31G* level. All calculations of the frontier orbitals for the optimized structures at different theory levels predict that the non-aromatic tetrazole tautomer **1T** is the most reactive (Table 5). Of the two aromatic tautomers, **3T** has a 0.3–0.4 kcal mol$^{-1}$ lower FMO energy gap than **2T** (Table 5).

The reactivity predicted on the basis of the

Table 6
Transfer of negative Mulliken charge from ethylene to tetrazole

| TS | $Dq1$ | $Dq2$ | $Dq3$ |
|----|------|------|------|
| 1TS | 0.185 | 0.256 | 0.222 |
| 2TS | 0.083 | 0.124 | 0.168 |
| 3TS | 0.097 | 0.165 | 0.261 |

Key: $Dq1$, HF/3-21G*; $Dq2$, HF/6-31G*; $Dq2$, MP2/6-31G*.

Table 7
Fraction of the overall charge transferred in the transition structures

| TS | $q_f1$ | $q_f2$ | $q_f3$ |
|----|------|------|------|
| 1TS | 40.3% | 59.1% | 50.5% |
| 2TS | 25.6% | 45.5% | 60.2% |
| 3TS | 22.9% | 41.5% | 64.3% |

Key: $q_f1$, RHF/3-21G*; $q_f2$, RHF/6-31G*; $q_f2$, MP2/6-31G*.

frontier orbitals is not very reliable for reactants that bear lone pairs which can cause considerable repulsions in the transition states. These repulsions are not accounted for in FMO theory because the reactants are considered separately. In that regard the charge transfer from the donor to the acceptor in the transition state might give better insight into the reactivity of the different tetrazole tautomers. If the amount of charge transferred in the transition state is in direct correlation with its position along the reaction coordinate, it can give a qualitative order of reactivity. According to this approach the least reactive is actually not the most stable tetrazole tautomer **3T** but rather tautomer **2T**, while at the MP2/6-31G* level **3T** is the most reactive rather than **1T** (Table 6). This clearly demonstrates that the amount of charge transferred is not enough to describe the reactivity of the involved reactants. However, the fraction of the charge transferred in the transition structure in relation to the overall charge transferred in the products should give a better picture of the reactivity. The results of these calculations are presented in Table 7.

HF and MP2 predict diametrically different reactivities based on the fraction of charge transferred in the transition structures. Taking a similar approach as when considering the bond orders for estimation of the geometry transformation along the reaction coordinate, the fraction of the charge transferred gives a measure of the electronic transformation. Calculated at MP2/6-31G* level, **3TP** has the highest transfer of charge and the transition structure is electronically closest to the products. Since the reactants are the lowest point on the reaction coordinate, the transition state must have a higher energy than any of the other two transition states. By similar comparison it is

Table 8
Total energies (a.u.) of reactants and transition structures for ethylene addition to tetrazole

| Species | E1 | E2 | E3 | E4 | E5 |
|---|---|---|---|---|---|
| Ethylene | −77.60099 | −78.03172 | −78.28503 | −78.30596 | −78.31983 |
| 1T | −255.22294 | −256.71450 | −257.48165 | −257.48849 | −257.53858 |
| 2T | −255.26876 | −256.75408 | −257.53575 | −257.53121 | −257.58426 |
| 3T | −255.26718 | −256.75704 | −257.54186 | −257.53541 | −257.58849 |
| 1TS | −332.75299 | −334.65978 | −335.74338 | −335.74233 | −335.82535 |
| 2TS | −332.79313 | −334.68986 | −335.76718 | −335.77154 | −335.84764 |
| 3TS | −332.78611 | −334.67300 | −335.75028 | −335.75887 | −335.83215 |

Key: E1, HF/3-21G*; E2, HF/6-31G*; E3, MP2/6-31G*; E4, MP3/6-31G*//MP2/6-31G*; E5, MP4/6-31G*//MP2/6-31G*.

concluded that the reactivity order is the same as that obtained by the extent of bond formation, which is 1T, 2T, and 3T. Using a similar comparison of the percentage of charge transferred calculated at RHF/6-31G*, the same reactivity order is obtained by considering the energies of the tetrazole tautomers.

To determine quantitatively the reactivity of the tetrazole tautomers in the cycloaddition reactions with ethylene, the activation barrier of the reaction must be evaluated for the transition states [15] of the reaction. The total energies of the reactants and the transition structures, and the activation energies are presented in Tables 8 and 9, respectively.

Although the different theoretical models predict different activation energies, all of them show that the most reactive tetrazole tautomer is 1T, while the least reactive is 3T. This is the same conclusion as was qualitatively determined on the basis of both the bond orders and the fraction of charge transferred in the transition structures. For example, the activation barrier varies for tautomer 1T with ethylene from 14.62 kcal mol$^{-1}$ at the MP2/6-31G*

Table 9
Calculated activation energies (kcal mol$^{-1}$) for ethylene addition to the different tetrazole tautomers

| TS | $E_a1$ | $E_a2$ | $E_a3$ | $E_a4$ | $E_a5$ | $E_a6$ | $E_a7$ |
|---|---|---|---|---|---|---|---|
| 1TS | 44.51 | 47.68 | 54.23 | 57.44 | 14.62 | 32.71 | 20.75 |
| 2TS | 48.08 | 50.31 | 60.20 | 62.72 | 33.63 | 41.18 | 35.42 |
| 3TS | 51.49 | 53.94 | 72.63 | 75.15 | 48.07 | 51.76 | 47.80 |

Key: $E_a1$, HF/3-21G*; $E_a2$, HF/3-21G + ZPVE [15]; $E_a3$, HF/6-31G*; $E_a4$, HF/6-31G* + ZPEV [15]; $E_a5$, MP2/6-31G*; $E_a6$, MP3/6-31G*//MP2/6-31G*; $E_a7$, MP4/6-31G*//MP26-31G*.

to 57.44 kcal mol$^{-1}$ at the RHF/6-31G* + ZPEV level. The activation energies calculated at the MP4/6-31G*//MP2/6-31G* should be reasonably close to the real values [16]. Ethylene addition to 1T with an activation energy of 20.75 kcal mol$^{-1}$ should be feasible, considering that the activation energy for the ethylene addition to butadiene, for example, has been determined to be 25 kcal mol$^{-1}$.

We have not studied the stability of derivatives of product 1TP toward other possible thermal reactions, for example elimination of nitrogen and rearrangement of the derivatives of tetrazole tautomer 1T into derivatives of 2T. Consequently, at this stage we cannot state firmly that the derivatives of product 1TP will be accumulating in the reaction mixture of the cycloaddition reaction of tautomer 1T derivatives with electron-rich dienophiles, but rather that this reaction will have a relatively low activation energy [17].

## 4. Conclusions

From the ab initio calculations presented in this work, it can be concluded that, in the gas phase, of the three isomers of tetrazole, the 2-hydrogen tautomer (3T) is the most stable while the least stable is the 5-hydrogen tautomer (1T). The two aromatic tautomers 2T and 3T are extremely unreactive and it is predicted that they have higher than 35 kcal mol$^{-1}$ activation energy which is not achievable under normal reaction conditions. Only the non-aromatic tautomer is predicted to have a low enough activation energy and a high activation energy for the retro pathway, to make

this reaction feasible. However, the energy of the non-aromatic tautomer is around 30 kcal mol$^{-1}$ higher in relation to the two aromatic tetrazole tautomers **2T** and **3T**, and its presence in the mixture is negligible. In order to force this reaction in the desired direction, a hydrogen must be substituted with groups that will make the activation energy for the rearrangement into **2T** considerably higher than for the cycloaddition reaction.

It was demonstrated that the reaction is a Diels–Alder reaction with an inverse electron demand (HOMO diene controlled). Frontier orbital theory and the amount of charge transferred in the transition structure were of limited use for the prediction of the relative reactivity. The predictions based on the bond orders and the fraction of the overall charge transferred in the transition structure, however, can be very useful in this respect.

# References

[1] For a review of the medical applications of tetrazoles see: H. Sigh, A.S. Chawla, V.K. Kapoor, D. Paul and R.K. Malhotra, in G.P. Ellis and G.B. West (Eds.), Progress in Medical Chemistry, Vol. 17, Elsevier/North-Holland, Biochemical Press, 1980, p. 151.

[2] R.N. Burler, Tetrazole in A.R. Katritzky and C.W. Rees (Eds.), Comprehensive Heterocyclic Chemistry, Vol. 5, Pergamon Press, New York, 1984, p. 791.

[3] M.J. Frisch, G.W. Trucks, H.B. Schlegel, P.M.W. Gill, B.G. Johnson, M.W. Wong, J.B. Foresman, M.A. Robb, M. Head-Gordon, E.S. Replogle, R. Gomperts, J.L. Andres, K. Raghavachari, J.S. Binkley, C. Gonzalez, R.L. Martin, D.J. Fox, D.J. Defrees, J. Baker, J.J.P. Stewart and J.A. Pople, GAUSSIAN 92/DFT, Revision G.2, Gaussian, Inc., Pittsburgh PA, 1993.

[4] W.J. Here, L. Radom, J.A. Pople and P.v.R. Schleyer, Ab Inito Molecular Orbital Theory, Wiley, New York, 1986.

[5] C. Møller and M.S. Plesset, Phys. Rev., 46 (1934) 618.
J.S. Binkley and J.A. Pople, Int. J. Quantum Chem., 9 (1975) 229.
J.A. Pople, J.S. Binkley, R. Seeger, Int. J. Quantum Chem., 9 (1975) 229; Int. J. Quantum. Chem., S10 (1976) 1.

[6] L. Pujol and M. Roche, Bull. Soc. Chim. Fr., 4 (1969) 1097.

[7] M.J.S.Dewar and G.J. Gleicher, J. Chem. Phys., 44 (1966) 759.

[8] M.H. Palmer, R.H. Findlay and A.J. Gaskell, J. Chem. Soc. Perkin Trans. 2 (1974) 420.

[9] W.D. Krugh and P.L. Gold, J. Mol. Spectrosc., 49 (1974) 423.

[10] K.A. Jansen and A. Friediger, Kgl. Dan. Videnskab. Selskab. Mat.-Fys. Medd., 20 (1943) 1.

[11] (a) Scaled by 0.89: J.A. Pople, R. Krishnan, H.B. Schlegel and J.S. Binkley, Int. J. Quantum Chem. Symp., 13 (1979) 225.
(b) Scaled by 0.9135: J.A. Pople, A.P. Scott, M.W. Wong, L. Radom, Isr. J. Chem., 33 (1993) 345.

[12] J.A. Medrano, R.C. Bochicchio, J. Mol. Struct. (Theochem), 200 (1989) 463.
J.A. Medrano, R.C. Bochicchio and G.S. Das, J. Phys. B, 26 (1993) 827.

[13] Bond orders were calculated by the routine available in Spartan v 3.1, Wavefunction, Inc., 18401 Von Karman Ave., #370, Irvine, CA 92715.

[14] K. Fukui and H. Fujimoto, Bull. Chem. Soc. Jpn., 40 (1967) 2018; Bull. Chem. Soc. Jpn., 42 (1969) 2018.
K. Fukui, Angew. Chem., Int. Ed. Engl., 21 (1982) 801.

[15] For transition state theory see: T.H. Lowry, K.S. Richardson, Mechanism and Theory in Organic Chemistry, Harper & Row, New York, 3rd edn., 1987, p. 203, and references therein.
A.J. Kirby, Adv. Phys. Org. Chem., 29 (1994) 87, and references therein.

[16] On how well this theory level does in reproducing known experimental values, see W.J. Jorgensen, D. Lim and J.F. Blake, J. Am. Chem. Soc., 115 (1993) 2936.

[17] The study of these reactions is underway and the results will be published elsewhere.