

# The Photochemical Isomerization of Pyrazoles: An *Ab Initio* Study

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**Abstract:** The photochemical isomerization of pyrazoles was studied using *ab initio* methods. The singlet excited singlet state can evolve to give the Dewar isomer and the corresponding triplet state. The latter shows a lower energy and probably can be obtained with higher efficiency. The triplet state can evolve to give the corresponding 1,2-biradical and, then, the isomerization product. The same behavior was obtained by using 1,5-dimethylpyrazole. However, 1-methyl-5-phenylpyrazole gave a different behavior. The triplet state cannot evolve to give the corresponding biradical. The isomerization product can be obtained only from the Dewar isomer.

**Key Words:** photochemistry, pyrazoles, isomerization, heterocycles, *ab initio* calculations.

## INTRODUCTION

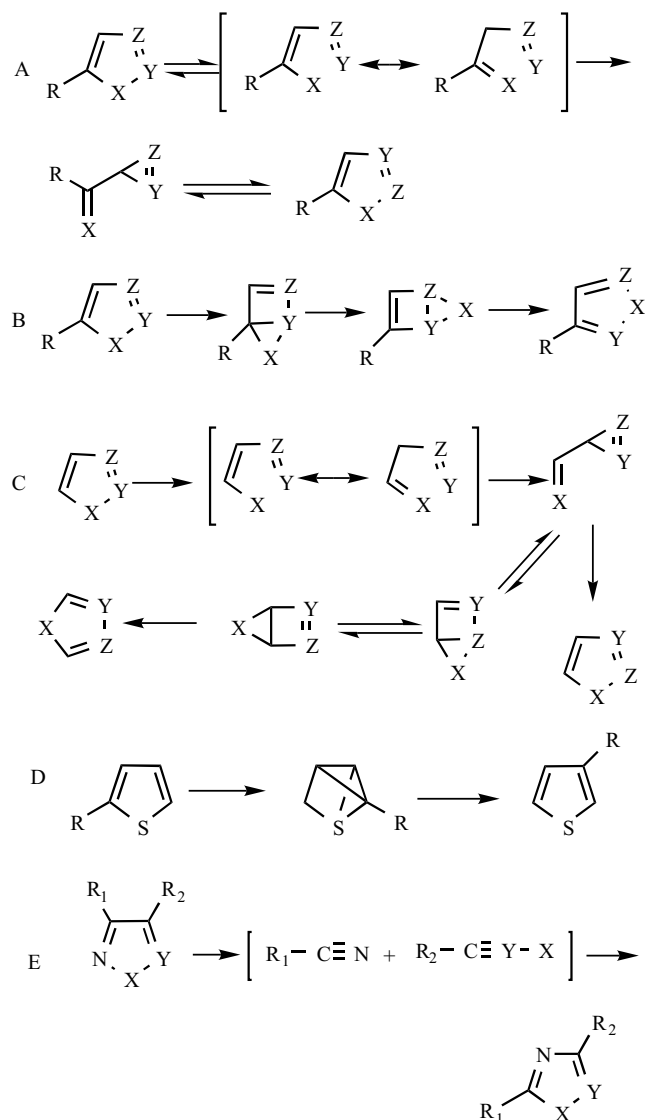
Five mechanisms can be invoked in order to justify the photochemical isomerization of pentaatomic aromatic heterocycles: 1. the ring contraction – ring expansion route (RCRE) (Scheme 1, A); 2. the internal cyclization – isomerization route (ICI) (Scheme 1, B); 3. the van Tamelen – Whitesides general mechanism (VTW) (Scheme 1, C); 4. the zwitterion – tricycle route (ZT) (Scheme 1, D); 5. the fragmentation – readdition route (FR) (Scheme 1, E). Recently we reported that the photochemical isomerization of pentaatomic aromatic heterocycles can be described using a unifying hypothesis [1-7]. In this hypothesis, if the first excited singlet state of a molecule is populated, the molecule can convert into the corresponding triplet state or into the corresponding Dewar isomer. The efficiency of these processes will depend on energetic factors. If the Dewar isomer is formed, the isomeric product is obtained. If the triplet state is formed, cleavage of the X-C $\alpha$  bond can occur to give ring opening products, decomposition products or ring contraction products. However, if the radical formed after the X-C $\alpha$  cleavage shows a higher energy than the triplet state, the triplet state will not be able to give the biradical with high efficiency, and then, it will be quenched in radiative and non radiative processes. In this case, the Dewar isomer could be responsible for the isomerization reaction, but the isomeric product will probably be produced in very low quantum yields. These results were obtained on the basis of both semiempirical calculations [2, 3] and *ab initio* results on the photochemical isomerization of furan, thiophenes, and thiazoles [4-7].

In this paper, we want to report our results on pyrazole derivatives using *ab initio* calculations in order to test the validity of the above-described hypothesis.

## RESULTS AND DISCUSSION

The irradiation of 1-methylpyrazole (**1**) gave 1-methylimidazole (**2**) (Scheme 2) [8, 9]. Afterwards, a ring-

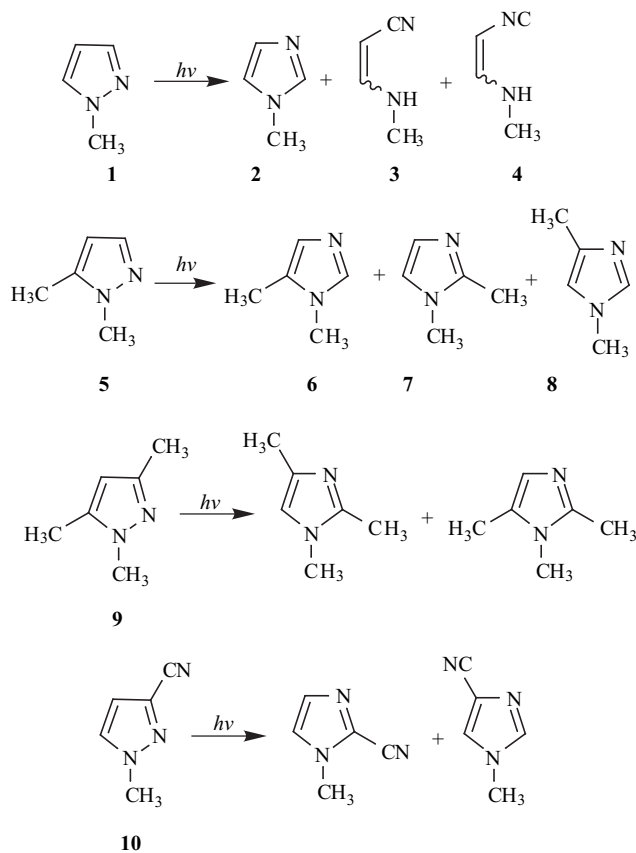
opening product (**3**) was observed in the reaction mixture [10], and finally was also (**4**) detected in the residue after the



Scheme 1.

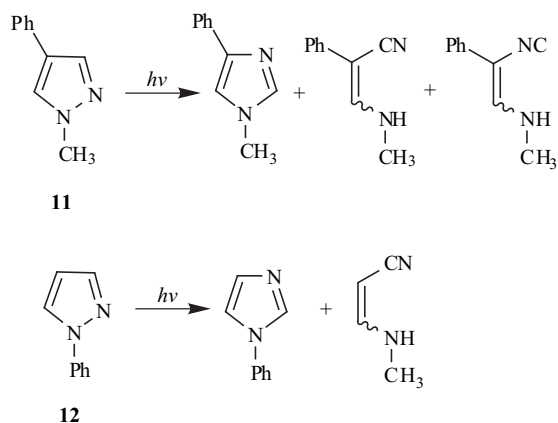
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reaction [11]. The irradiation of 1,5-dimethylpyrazole (**5**) gave a mixture of three products (**6-8**). While (**7**) and (**8**) can be obtained through both RCRE and ICI mechanisms, (**6**) can be obtained only with a ring contraction – ring expansion mechanism (Scheme 2) [10, 12]. The formation of (**8**) is temperature dependent: at 77 K it was not obtained [12]. Dewar pyrazole was invoked in the photoisomerization of 1,3,5-trimethylpyrazole (**9**), in the synthesis of (**7**) and (**8**) starting from (**6**), and in the isomerization of cyanopyrazole (**10**) (Scheme 2) [13-16]. A zwitterionic intermediate was also proposed [17].



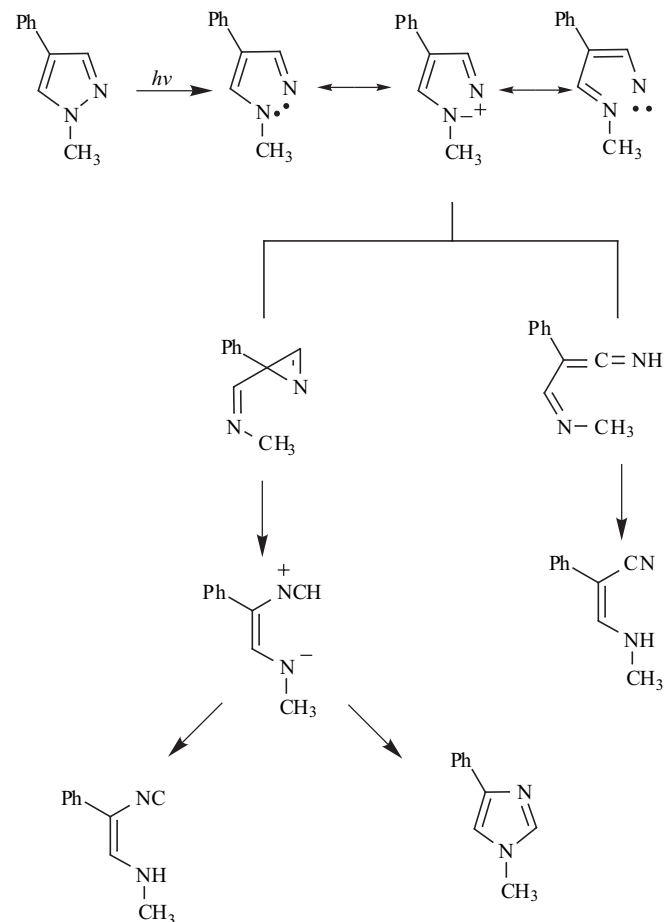
Scheme 2.

Ring opening products were observed in the photoisomerization of 1-methyl-4-phenylpyrazole (**11**) [11, 18] and in the reaction of 1-phenylpyrazole (**12**) (Scheme 3) [19].

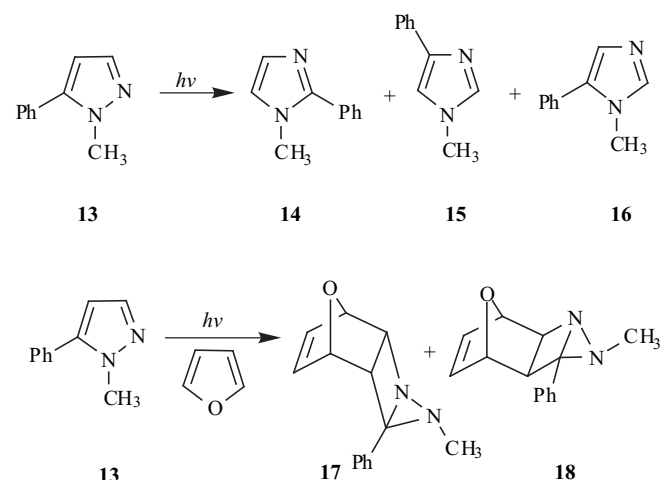


Scheme 3.

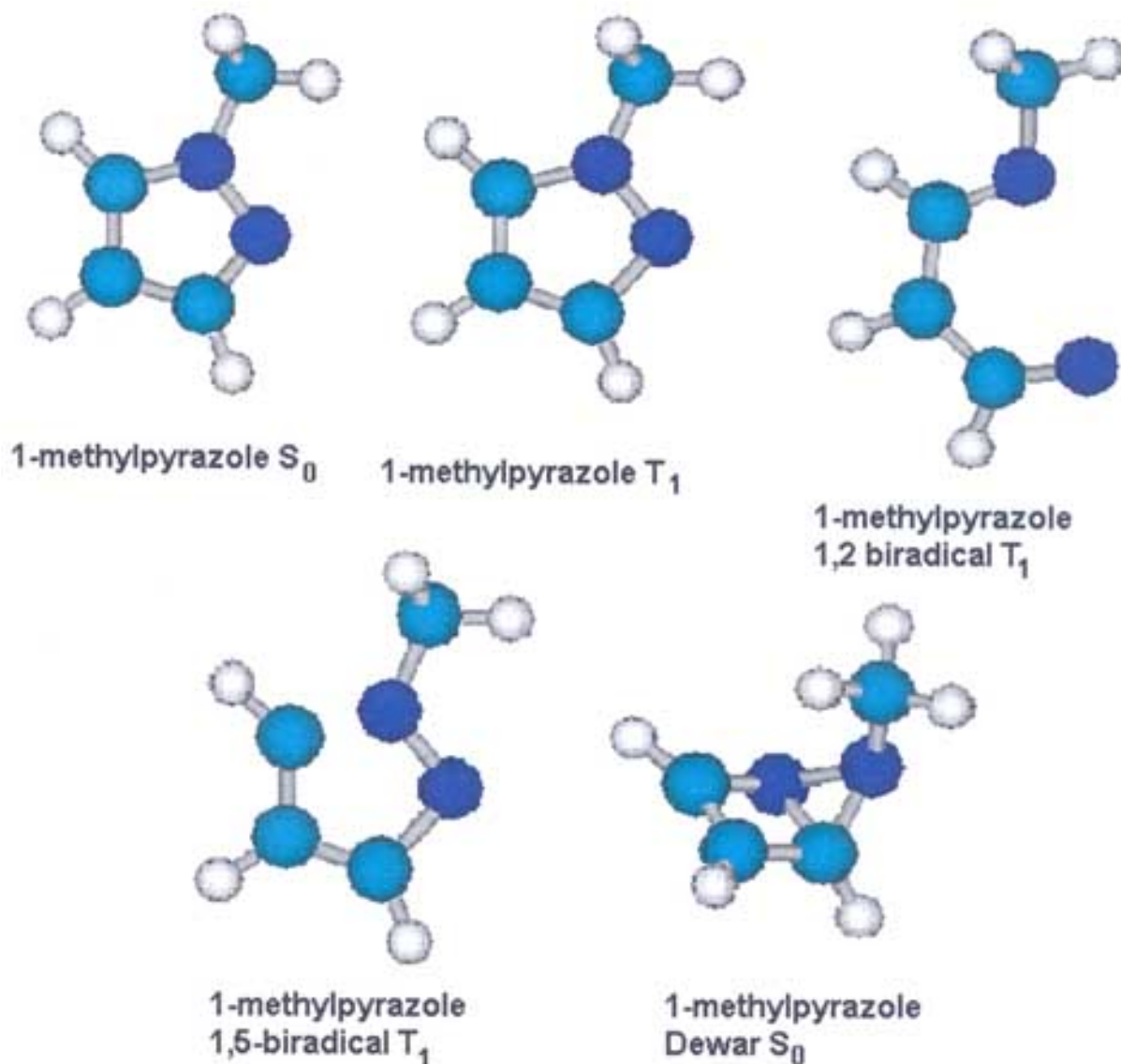
The mechanism depicted in the Scheme 4 accounts for the formation of the ring opening products [11]. It is a variation of the RCRE mechanism. By contrast, on irradiation 1-methyl-5-phenylpyrazole (**13**) gave (**14**), (**15**), and (**16**) (Scheme 5) [11]. Compounds (**14**) and (**15**) can be obtained via an ICI mechanism: in fact, the irradiation of (**13**) in the presence of furan gave the corresponding Diels-Alder adducts [(**17**) and (**18**)] between the Dewar pyrazole derivative and furan (Scheme 5) [11]. There are several data in agreement with a mechanism involving an excited singlet state [11, 19].



Scheme 4.



Scheme 5.



**Fig. (1).** Structures of possible intermediates in the photochemical isomerization of 1-methylpyrazole.

We performed some *ab initio* calculations using 6-31G\*\* basis set on Gaussian 98, using UHF method. The calculations were usually done using Møller-Plesset perturbations (MP2). The Polak-Ribiere algorithm with gradient calculations was adopted for geometry optimizations. The open-shell states were treated at the same level of accuracy as the closed state states. We verified that the obtained structures were minima on the potential energy surfaces calculating the frequencies of the optimized structures.

We investigated the ground state and the lowest triplet state of 1-methylpyrazole, the triplet biradicals that result from the homolytic cleavage of the N(1)-X( $\alpha$ ) bond (these biradical intermediates are supposed to occur in the isomerization process leading to the formation of the cyclopropenyl derivatives), and Dewar 1-methylpyrazole in its singlet state. The structural properties of all these compounds and/or intermediates are shown in Fig. 1 and Table 1 and 2.

1-Methylpyrazole in the ground state has a clear dienic character; on the contrary, in the triplet state  $C_3$ - $C_4$  bond is shorter than in the ground state, while both  $N_2$ - $C_3$  and  $C_4$ - $C_5$  bonds are longer than in ground state. Both  $S_0$  and  $T_1$  states of 1-methylpyrazole are planar. Triplet excited 1-methylpyrazole is a  $\pi,\pi^*$  triplet with the LSOMO at  $-11.11$  eV and the HSOMO at  $-6.25$  eV. The 1,2 biradical intermediate is a  $\sigma,\pi^*$  triplet with the LSOMO at  $-11.25$  eV and the HSOMO at  $-10.50$  eV.

The relative energies for the five above-mentioned structures are shown in Fig. 2 and Table 1. The results are in agreement with the experimental results. In fact, the singlet excited singlet state can evolve to give the Dewar isomer and the corresponding triplet state. The latter shows a lower energy and probably can be obtained with higher efficiency. The triplet state can evolve to give the corresponding 1,2-biradical and, then, the isomerization product.

**Table 1. Structural Properties and Energy of Possible Intermediates in the Photochemical Isomerization of Pyrazole Derivatives**

Compound	Electronic state	Structural element						Relative energy [kcal/mol]
		N <sub>1</sub> -N <sub>2</sub> (Å)	N <sub>2</sub> -C <sub>3</sub> (Å)	C <sub>3</sub> -C <sub>4</sub> (Å)	C <sub>4</sub> -C <sub>5</sub> (Å)	C <sub>5</sub> -N <sub>1</sub> (Å)	C <sub>5</sub> -N <sub>2</sub> (Å)	
1-Methylpyrazole	S <sub>0</sub>	1.3308	1.3040	1.4090	1.3646	1.3408		0
1-Methylpyrazole	T <sub>1</sub>	1.3598	1.4875	1.3739	1.3986	1.4241		78
1-Methylpyrazole biradical 1,2	T <sub>1</sub>		1.3036	1.4247	1.4215	1.3053		21
1-Methylpyrazole biradical 1,5	T <sub>1</sub>	1.3597	1.4872	1.3740	1.3986			78
1-Methylpyrazole Dewar	S <sub>0</sub>	1.4593	1.4710	1.3170	1.5137	1.4097	1.4573	94
1,5-Dimethylpyrazole	S <sub>0</sub>	1.3364	1.3017	1.4068	1.3689	1.3457		0
1,5-Dimethylpyrazole	T <sub>1</sub>	1.3892	1.3587	1.3623	1.5193	1.4360		60
1,5-Dimethylpyrazole biradical 1,2	T <sub>1</sub>		1.3039	1.4243	1.4320	1.3075		22
1,5-Dimethylpyrazole biradical 1,5	T <sub>1</sub>	1.2894	1.3504	1.4229	1.3632			62
1,5-Dimethylpyrazole Dewar	S <sub>0</sub>	1.4805	1.4584	1.3194	1.5159	1.4305	1.4447	87
1-Methyl-5-phenylpyrazole	S <sub>0</sub>	1.3345	1.2997	1.4002	1.3757	1.3574		0
1-Methyl-5-phenylpyrazole	T <sub>1</sub>	1.3947	1.3572	1.3619	1.5075	1.4302		42
1-Methyl-5-phenylpyrazole biradical 1,2	T <sub>1</sub>		1.3573	1.3615	1.5075	1.4298		52
1-Methyl-5-phenylpyrazole biradical 1,5	T <sub>1</sub>	1.2856	1.3568	1.4121	1.3815			47
1-Methyl-5-phenylpyrazole Dewar	S <sub>0</sub>	1.4765	1.4606	1.3187	1.5176	1.4353	1.4405	76

**Table 2. Other Structural Properties of Possible Intermediates in the Photochemical Isomerization of Pyrazole Derivatives**

Compound	Angle (°)									
	1-2-3	2-3-4	3-4-5	4-5-1	5-1-2	2-1-6	5-2-3	4-5-2	2-5-1	1-2-5
1-Methylpyrazole S <sub>0</sub>	105.61	111.51	103.69	107.29	111.89					
1-Methylpyrazole T <sub>1</sub>	102.55	110.95	106.85	107.38	112.27					
1-Methylpyrazole biradical 1,2 T <sub>1</sub>		126.94	126.99	122.54	83.68					
1-Methylpyrazole biradical 1,5 T <sub>1</sub>	102.56	110.95	106.85	107.38						
1-Methylpyrazole Dewar S <sub>0</sub>	108.60	96.86	88.52	114.51	61.03	121.42	85.12	89.30	61.17	61.17
1,5-Dimethylpyrazole S <sub>0</sub>	105.46	111.51	104.37	106.41	112.25					
1,5-Dimethylpyrazole T <sub>1</sub>	107.31	112.96	106.00	102.68	110.47					
1,5-Dimethylpyrazole biradical 1,2 T <sub>1</sub>	79.25	127.76	127.25	118.21	87.52					
1,5-Dimethylpyrazole biradical 1,5 T <sub>1</sub>	115.67	129.64	128.30	75.48	90.91					
1,5-Dimethylpyrazole Dewar S <sub>0</sub>	102.29	96.57	88.32	106.45	59.48	111.08	86.02	88.99	61.98	58.54
1-Methyl-5-phenylpyrazole S <sub>0</sub>	106.09	111.21	105.12	105.54	112.04					
1-Methyl-5-phenylpyrazole T <sub>1</sub>	108.04	113.10	105.1	104.63	108.92					
1-Methyl-5-phenylpyrazole biradical 1,2 T <sub>1</sub>	108.02	113.12	105.1	104.65	108.92					
1-Methyl-5-phenylpyrazole biradical 1,5 T <sub>1</sub>	115.73	129.69	127.44	75.93	91.22					
1-Methyl-5-phenylpyrazole Dewar S <sub>0</sub>	102.41	96.48	88.25	106.61	59.28	111.02	86.07	89.07	61.78	58.94

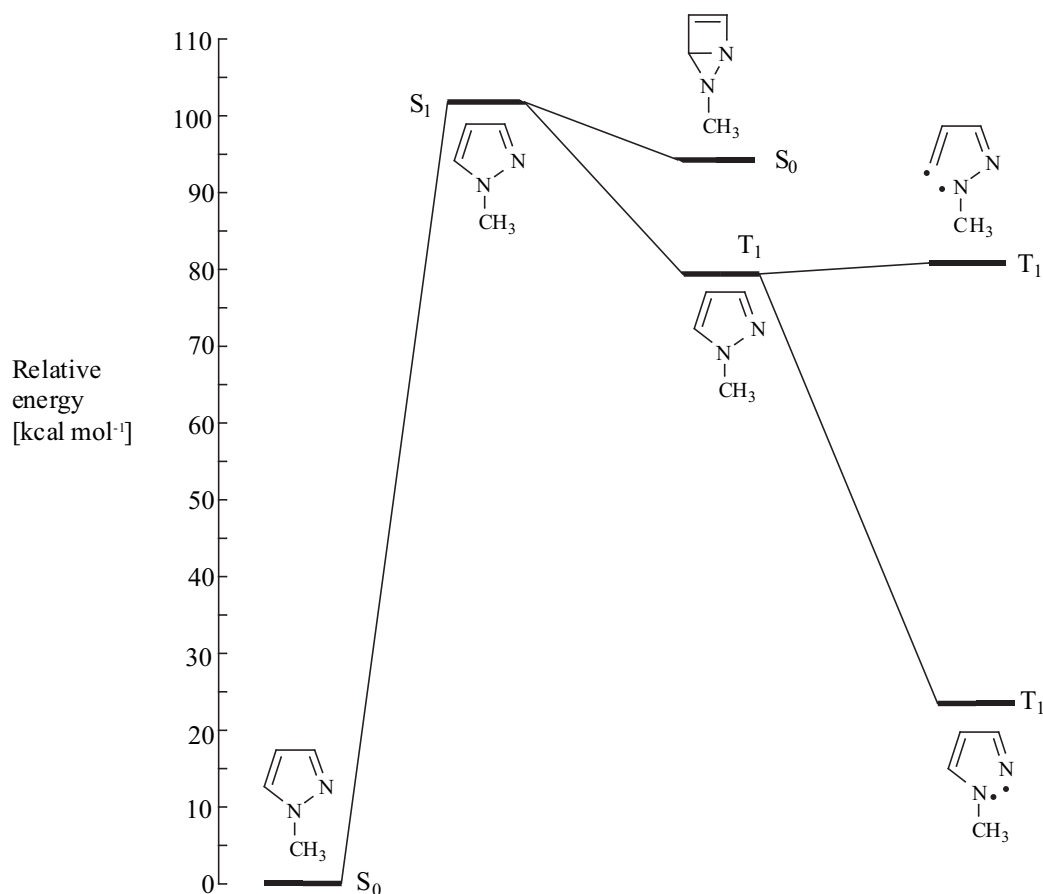


Fig. (2). Relative energy of the species involved in the photoisomerization of 1-methylpyrazole.

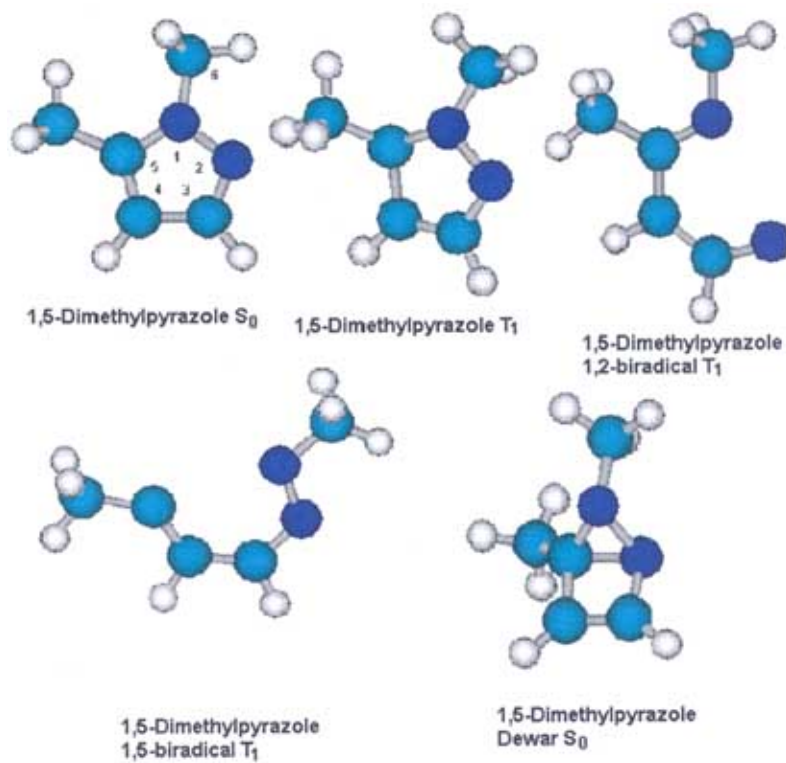


Fig. (3). Structures of possible intermediates in the photochemical isomerization of 1,5-dimethylpyrazole.

We investigated also the same type of structures in the photoisomerization. The structural properties of all these compounds and/or intermediates are shown in Fig. 3 and Table 1 and 2.

1,5-Dimethylpyrazole in the ground state has a clear dienic character; on the contrary, in the triplet state C<sub>3</sub>-C<sub>4</sub> bond is shorter than in the ground state, while both N<sub>2</sub>-C<sub>3</sub> and C<sub>4</sub>-C<sub>5</sub> bonds are longer than in ground state. Both S<sub>0</sub> and T<sub>1</sub> states of 1,5-dimethylpyrazole are planar. Triplet excited 1,5-dimethylpyrazole is a  $\pi,\pi^*$  triplet with the LSOMO at -11.01 eV and the HSOMO at -7.08 eV. The 1,2 biradical intermediate is a  $\sigma,\pi^*$  triplet with the LSOMO at -10.91 eV and the HSOMO at -10.34 eV.

The relative energies for the five above-mentioned structures are shown in Fig. 4 and Table 1. The results are in agreement with the experimental results. In fact, the singlet excited singlet state can evolve to give the Dewar isomer and the corresponding triplet state. The latter shows a lower energy and probably can be obtained with higher efficiency. The triplet state can evolve to give the corresponding 1,2-biradical and, then, the isomerization product.

Finally, we studied the structural properties of the possible photoisomerization intermediates in the reaction of 1-methyl-5-phenylpyrazole. In this case we have evidence for

the formation of the Dewar isomer. The structural properties of all these compounds and/or intermediates are shown in Fig. 5 and Table 1 and 2.

Also in this case, 1-methyl-5-phenylpyrazole in the ground state has a clear dienic character; on the contrary, in the triplet state C<sub>3</sub>-C<sub>4</sub> bond is shorter than in the ground state, while both N<sub>2</sub>-C<sub>3</sub> and C<sub>4</sub>-C<sub>5</sub> bonds are longer than in ground state. However, the T<sub>1</sub> state of 1-methyl-5-phenylpyrazole is not planar, and the methyl group is out of plane. Triplet excited 1-methyl-5-phenylpyrazole is a  $\pi,\pi^*$  triplet with the LSOMO at -9.74 eV and the HSOMO at -6.61 eV. The 1,2 biradical intermediate is a  $\sigma,\pi^*$  triplet with the LSOMO at -9.75 eV and the HSOMO at -6.60 eV. The 1,5 biradical intermediate is a  $\sigma,\pi^*$  triplet with the LSOMO at -9.77 eV and the HSOMO at -8.66 eV.

The relative energies for the five above-mentioned structures are shown in Fig. 6 and Table 1. The results are in agreement with the experimental results. In fact, the singlet excited singlet state can evolve to give the Dewar isomer and the corresponding triplet state. The latter shows a lower energy and probably can be obtained with higher efficiency. However, the triplet state can not evolve to give the corresponding biradical; in fact, they are at higher energy than the triplet state. Then, the isomerization product can be obtained only from the Dewar isomer.

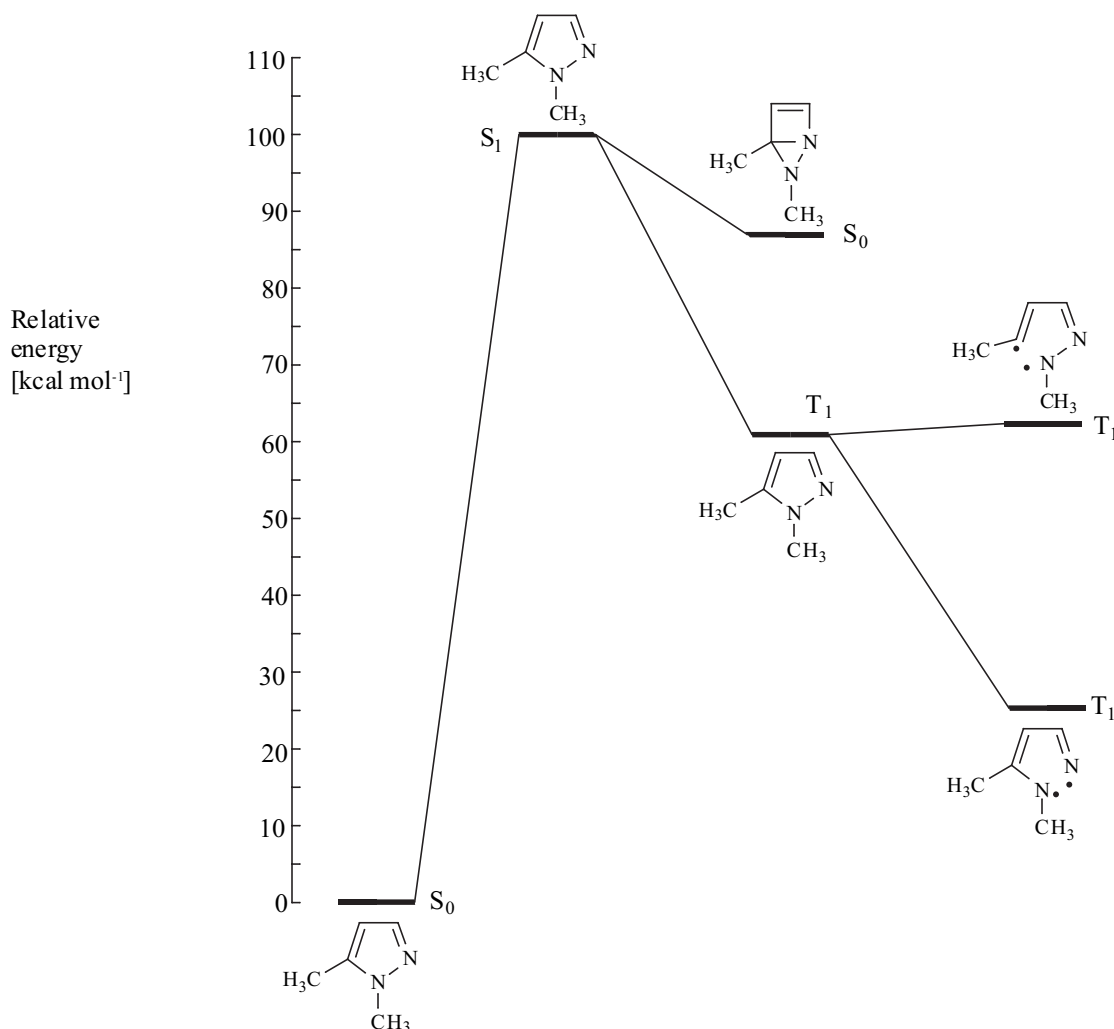


Fig. (4). Relative energy of the species involved in the photoisomerization of 1,5-dimethylpyrazole.

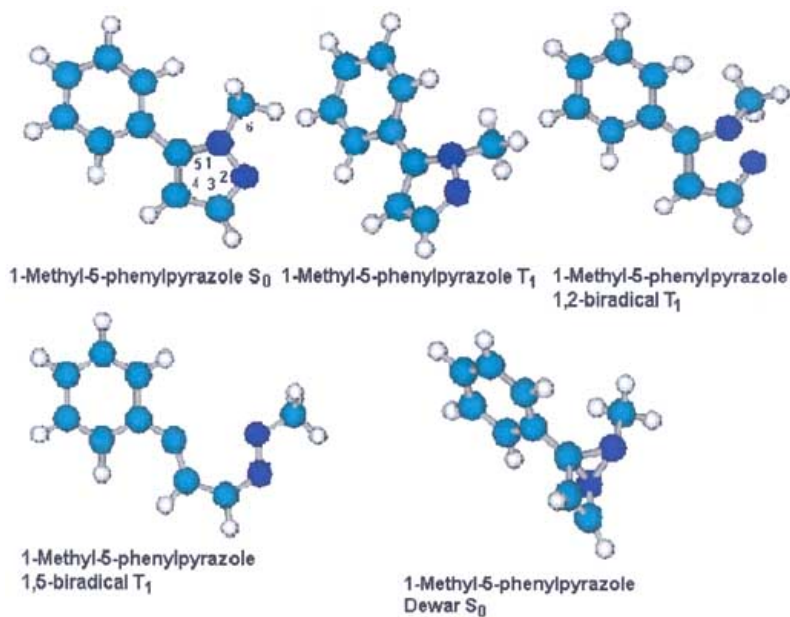


Fig. (5). Structures of possible intermediates in the photochemical isomerization of 1-methyl-5-phenylpyrazole.

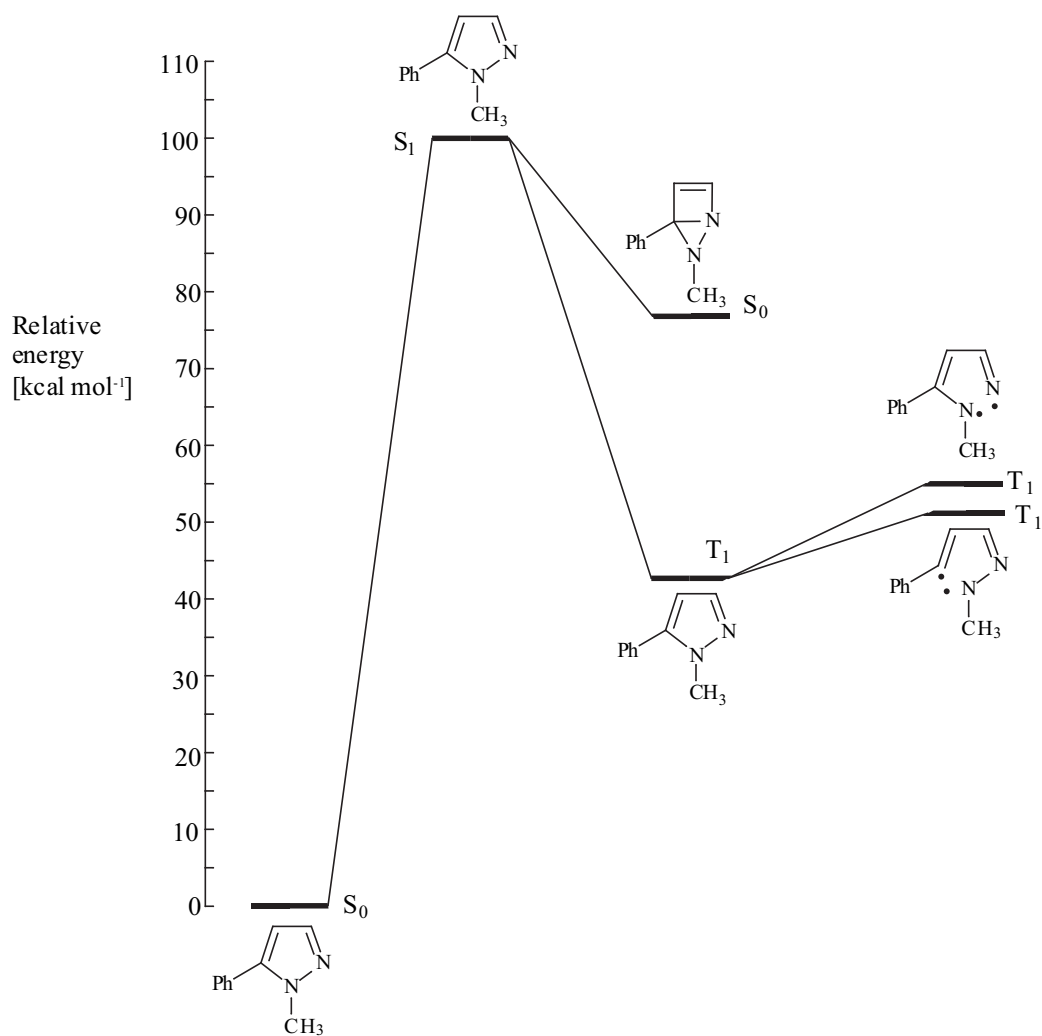


Fig. (6). Relative energy of the species involved in the photoisomerization of 1-methyl-5-phenylpyrazole.

In conclusion, we have shown that the isomerization of pyrazole can be rationalized by using the scheme proposed in Ref. 5. If the formation of the triplet state is allowed, it can evolve to give the corresponding biradicals if they show energy lower than the triplet state. On the contrary, internal conversion can quench the triplet state with high efficiency: in this case the photoisomerization can be performed through the Dewar isomer.

## REFERENCES

- [1] D'Auria, M. *Internet J. Sci.* **1997**, *4*, 15.  
[2] D'Auria, M. In *Targets in Heterocyclic Systems, Chemistry and Properties*, Attanasi, O.A.; Spinelli, D., Eds; Italian Society of Chemistry, **1999**; Vol. 2, pp 233-279.  
[3] D'Auria, M. *Heterocycles* **1999**, *50*, 1115.  
[4] D'Auria, M. *J. Org. Chem.* **2000**, *65*, 2494.  
[5] D'Auria, M. *Adv. Heterocyclic Chem.* **2001**, *79*, 41.  
[6] D'Auria, M. *J. Photochem. Photobiol., A: Chem.* **2002**, *149*, 31.  
[7] D'Auria, M. *Tetrahedron* **2002**, *58*, 8037.  
[8] Tiefenthaler, H.; Dörsheln, W.; Göth, H.; Schmid, H. *Helv. Chim. Acta* **1967**, *50*, 2244.  
[9] Pavlik, J.W. *The Spectrum* **2002**, *15*, 15.  
[10] Pavlik, J.W.; Kurzweil, E.M. *J. Org. Chem.* **1991**, *56*, 6313.  
[11] Pavlik, J.W.; Kebede, N. *J. Org. Chem.* **1997**, *62*, 8325.  
[12] Connors, R.E.; Burns, D.S.; Kurzweil, E.M.; Pavlik, J.W. *J. Org. Chem.* **1992**, *57*, 1937.  
[13] Beak, P.; Miesel, J.L.; Messer, W.R. *Tetrahedron Lett.* **1967**, 5315.  
[14] Beak, P.; Messer, W. *Tetrahedron* **1969**, *25*, 3287.  
[15] Barltrop, J.A.; Day, A.C.; Mack, A.G.; Shahrisa, A.; Wakamatsu, S. *J. Chem. Soc., Chem. Commun.* **1981**, 604.  
[16] Connors, R.E.; Pavlik, J.W.; Burns, D.S.; Kurzweil, E.M. *J. Org. Chem.* **1991**, *56*, 6321.  
[17] Labhart, H.; Heinzelmann, W.; Dubois, J.P. *Pure Appl. Chem.* **1970**, *24*, 495.  
[18] Pavlik, J.W.; Kebede, N.; Bird, N.P.; Day, A.C.; Barltrop, J.A. *J. Org. Chem.* **1995**, *60*, 8138.  
[19] Pavlik, J.W.; Connors, R.E.; Burns, D.S.; Kurzweil, E.M. *J. Am. Chem. Soc.* **1993**, *115*, 7645.