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# CASCSF Study on the Photochemical Transposition Reactions of Pyrazines

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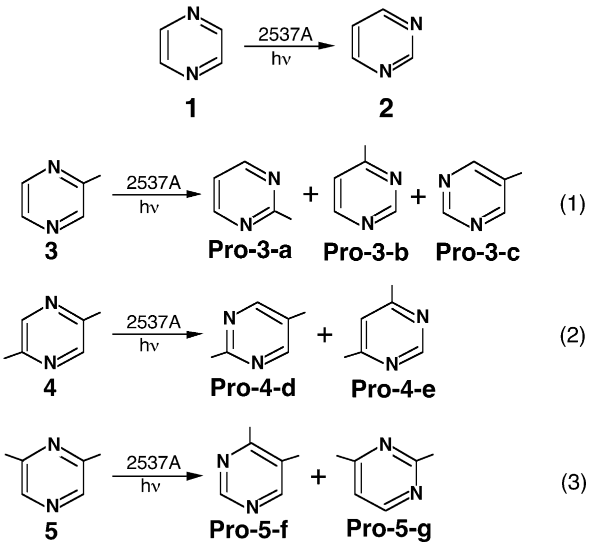
Several reaction pathways for the photochemical transformations of methyl-substituted pyrazine in its first excited state $^1(\pi \rightarrow \pi^*)$ have been determined using the CASSCF (six-orbital/six-electron active space) and MP2-CAS methods with the 6-311G(d) basis set. Our model investigations suggest that conical intersections play a crucial role in the photoisomerization of pyrazines. Moreover, the present theoretical findings indicate that all of the photoisomerizations of pyrazines adopt the same reaction path as follows: pyrazine → Franck−Condon region → conical intersection → pyrimidine. That is, although an excited-state pyrazine molecule can initiate a phototransposition process easily, this process can be completed on the ground-state potential energy surface after passage through a conical intersection where a fast, radiationless decay is possible. The existence of these nonadiabatic reaction pathways is consistent with the available experimental observations of the photochemistry and photophysics of pyrazine and its methyl derivatives. In the present work, we propose a simple *p*-$\pi$ orbital topology model, which can be used as a diagnostic tool to predict the location of the conical intersections, as well as the geometries of the phototransposition products of various heterocycles.

## I. Introduction

The organic photochemistry of heterocyclic organic systems has been a topic of considerable interest over the past four decades, from both a synthetic as well as a mechanistic perspective.[1] An important characteristic of the photoreactions of many heterocyclic aromatic systems is that products are formed by the permutation of ring atoms. Most products are related via isomerization reactions that result in an interchange of two neighboring atoms. For instance, about forty years ago it was reported that irradiation of pyrazine (**1**) at 2537 Å can produce pyrimidine (**2**), as a result of the interchange of adjacent ring atoms.[2,3] See Scheme 1. It was observed that irradiation of 2-methylpyrazine (**3**) in the vapor phase leads to a mixture of 2-, 4-, and 5-methylpyrimidines (i.e., eq 1). Similar photochemical valence isomerization can also be found in the dimethylpyrazine (**4**, **5**) system (i.e., eqs 2 and 3).

It is these fascinating experimental results that inspired this study. The calculations of reaction pathways for such diazine photoreactions and the location and identification of the structures of the crucial points are therefore of great academic interest. In fact, an understanding of the detailed mechanism of such transformations is essential to the rationalization of the mechanisms of intramolecular photochemical valence isomerizations that are useful in synthetic chemistry. Theoretical methods are the only techniques for determining the properties of the various excited-state potential energy surfaces. However, to the best of our knowledge, until now no theoretical work has been devoted to the study of the photochemistry of such azabenzenes. We have thus undertaken the investigation of the potential energy surfaces of aromatic diazine systems. It is surprising how little is known about the mechanisms of photoisomerizations of pyrazines, considering the importance of azabenzenes in synthetic chemistry and the extensive research activity on the corresponding benzene species.[4]

**SCHEME 1**



The objective of the present work is an understanding of the photochemical mechanism of the transformation of pyrazines to pyrimidines. As illustrated in Scheme 1, the reaction mechanisms of three different reactions were investigated by CASSCF and MP2-CAS calculations. 2-Methylpyrazine (**3**), 2,5-dimethylpyrazine (**4**), and 2,6-dimethylpyrazine (**5**) were used as model systems, respectively. It will be shown below that the conical intersection (CI)[5] plays a crucial role in the photoisomerization of these aromatic diazine systems.

## II. Methology

All geometries were fully optimized without imposing any symmetry constraints, although in some instances the resulting structures showed various elements of symmetry. The CASSCF

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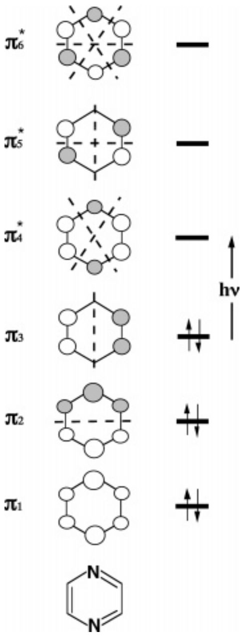
**SCHEME 2**



calculations were performed using the MCSCF program released in GAUSSIAN 03.[6]

The six electrons in the six *p*-$\pi$ orbital CASSCF method were used with the 6-311G(d) basis sets for geometry optimization (vide infra). The state-averaged CASSCF(6,6) method was used to determine geometry on the intersection space. The optimization of CIs was achieved in the ($f - 2$)-dimensional intersection space using the method of Bearpark et al.[7] implemented in the Gaussian 03 program. Every stationary point was characterized by its harmonic frequencies computed analytically at the CASSCF level. Localization of the minima and conical intersection minima have been performed in Cartesian coordinates; therefore, the results are independent of any specific choice of internal variables.

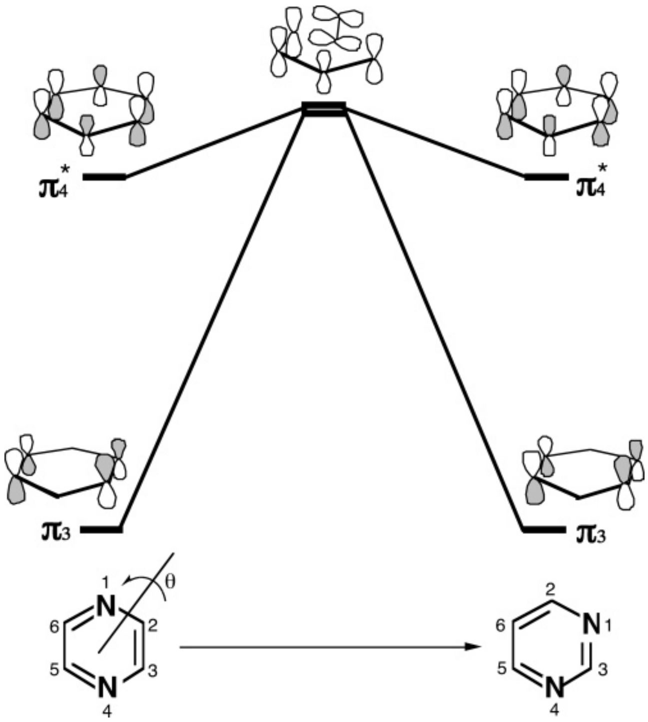
To correct the energetics for dynamic electron correlation, we have used the multireference Møller−Plesset (MP2-CAS) algorithm[8] as implemented in the program package GAUSSIAN 03. Unless otherwise noted, the relative energies given in the text are those determined at the MP2-CAS-(6,6)/6-311G(d) level using the CAS(6,6)/6-311G(d) (hereafter designed MP2-CAS and CASSCF, respectively) geometry.

## III. General Considerations

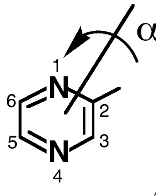
In this section, we will analyze the electronic structures of pyrazine, which form the basis for this study. It was reported experimentally that the excited state involved in the photoisomerization of pyrazine and its methyl derivatives is the $^1(\pi,\pi^*)$ state, whereas $^3(n,\pi^*)$ and $^3(\pi,\pi^*)$ states, which can be obtained from the $^1(n,\pi^*)$ state, do not apparently play any significant role.[2,9] For this reason, it seems likely that the photochemical transposition reactions of pyrazines proceed on singlet surfaces, and also only involve the $\pi \rightarrow \pi^*$ transition. We shall therefore focus on $^1(\pi,\pi^*)$ surfaces from now on. A general outline of the six *p*-$\pi$ orbitals in pyrazine has been given previously[10] and is shown explicitly in Scheme 2. As can be seen, the lowest singlet $\pi \rightarrow \pi^*$ excitation is the singlet $\pi_3 \rightarrow \pi_4^*$ transition (vide infra).

In the present work, we shall therefore use the *p*-$\pi$ orbital model to search for the CIs of the photoisomerization reaction of the pyrazine molecule, which is isoelectronic to benzene.

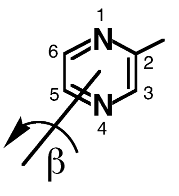
**SCHEME 3**



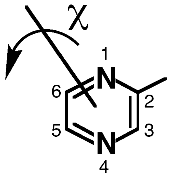
Scheme 3 shows the qualitative potential energy curves for the $S_0$ and $S_1$ states of pyrazine as a function of rotation about the $N_1{=}C_2$ double bond (i.e., the rotation angle $\theta$).[11] By twisting the $N_1{=}C_2$ $\pi$ bond in pyrazine, both $\pi_3$ and $\pi_4$* are raised in energy because of increased antibonding interactions. At last, these $\pi$ orbitals are degenerate in energy at a perpendicular geometry (90° of twisting). Accordingly, this excitation removes the barrier to rotation about the former N=C double bond and rotation toward a 90° orientation of the *p*-$\pi$ orbitals lowers the energy of the excited state. Besides this, the formation of a degenerate point as a result of the rotation of the N=C double bond strongly implies that a sloped $S_1/S_0$ surface crossing[12] should exist at a very similar geometry, and where decay to the ground state can be fully efficient.[4] It should be pointed out that the return to $S_0$ through a conical intersection at such a distorted quasi-tetrahedral geometry (vide infra) is basically similar to both the $H_4$[13(a)] and the pericyclic[13(b,c)] models proposed previously.



(path A)
**6**



(path B)
**7**



(path C)
**8**

With the above analysis in mind, we now use 2-methylpyrazine (**3**) as an example to examine the existence of a low-lying $S_1/S_0$ surface crossing. Consider the symmetry of molecule **3** itself. Three reaction pathways were suggested to exist on irradiation of **3**. In fact, experiments have shown that compound **3** gives rise to (1,2), (4,5), and (1,6) transpositions (eq 1).[2] Figure

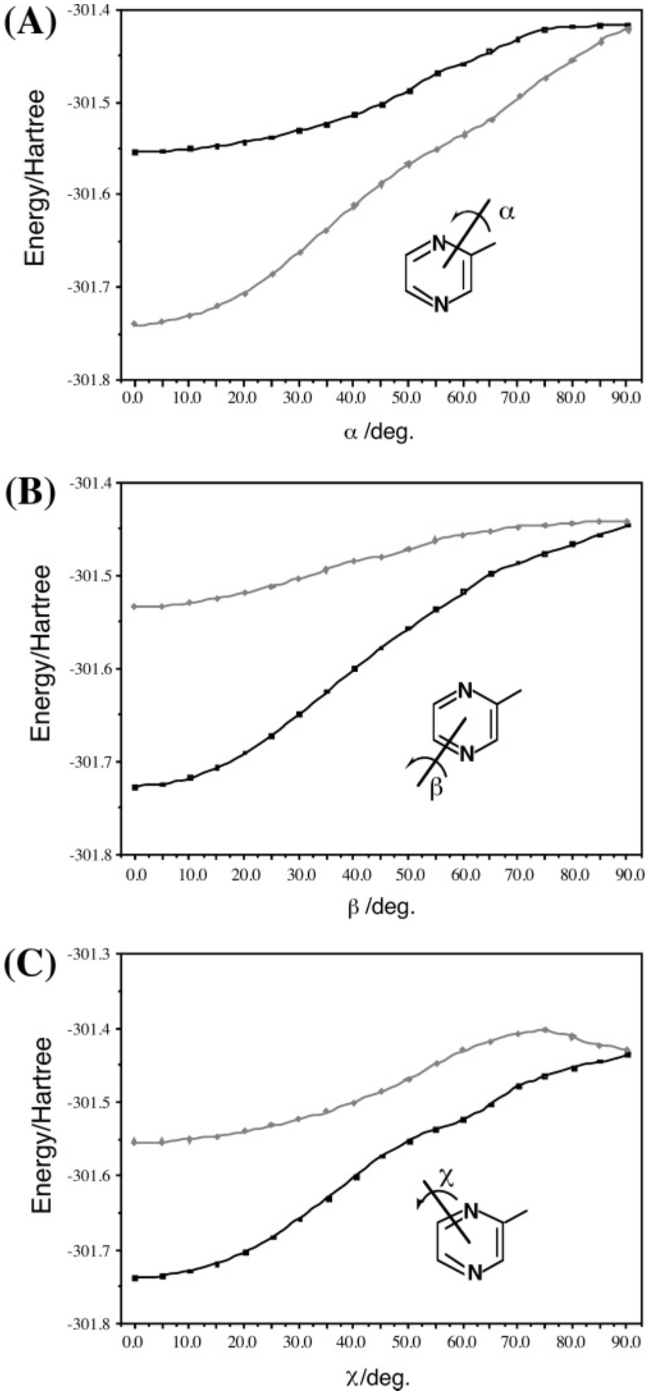


**Figure 1.** Minimum-energy pathway of 2-methylpyrazine (**3**) along the torsion angle coordinate optimized for the $S_1$ state at the CAS-(6,6)/6-311G(d) level of theory. Three reaction paths of the photoisomerizations of **3** are proposed: (A) path A; (1,2) transposition. (B) path B; (4,5) transposition. (C) path C; (1,6) transposition. Also see ref 13.

1 displays the potential energy profiles along the geometrical parameters α, $\beta$, and $\chi$, as given in **6**−**8**, respectively.[14] These profiles show the same general features as predicted previously: the reaction paths all terminate at a very close $S_1-S_0$ energy gap at around the 90° twisted geometry. The narrowness of these energy gaps provides further evidence for an enhanced intramolecular rotation in the six-membered ring geometry, and possibly the existence of a CI. We shall use these findings to explain the mechanisms for the photochemical transposition reactions of azabenzenes in a later section.

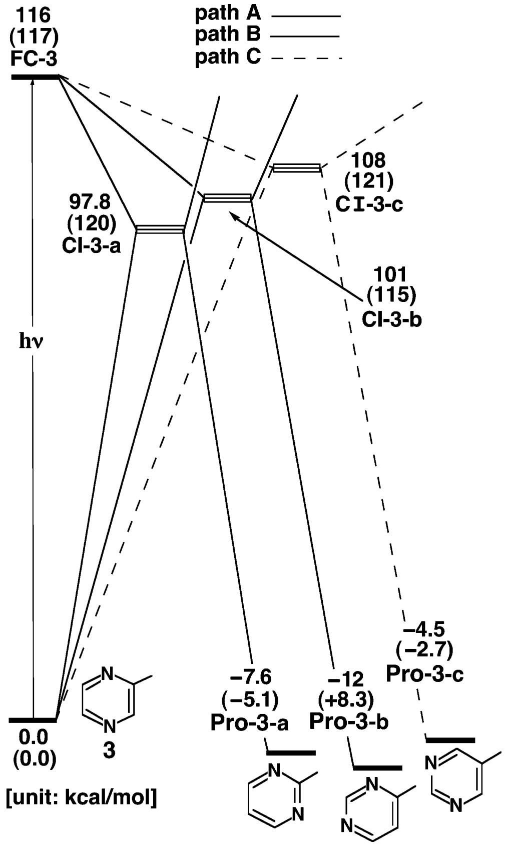


**Figure 2.** Energy profiles for the photoisomerization modes of 2-methylpyrazine (**3**). The abbreviations FC and CI stand for Franck−Condon and conical intersection, respectively. The relative energies were obtained at the MP2-CAS-(6,6)/6-311G(d)//CAS(6,6)/6-311G(d) and CAS(6,6)/6-311G(d) (in parentheses) levels of theory. All energies (in kcal/mol) are given with respect to the reactant (**3**). For the CASSCF optimized structures of the crucial points, see Figure 3. For more information, see the text.

## IV. Results and Discussion

**1. Monomethyl-Substituted Pyrazine.** Let us first consider the photoisomerization of monomethyl-substituted pyrazine (i.e., 2-methylpyrazine, **3**) as indicated in eq 1. As mentioned earlier, three minimum-energy pathways on the singlet excited potential energy surfaces of **3** were characterized by optimizing the geometries along the rotation angles α (**6**), $\beta$ (**7**), and $\chi$ (**8**), as shown in Figure 1, which can lead to products 2-dimethylpyrimidine (**Pro-3-a**), 4-dimethylpyrimidine (**Pro-3-b**), and 5-dimethylpyrimidine (**Pro-3-c**), respectively. For an understanding of the difference found between the three reaction paths, it is best to start the discussion with the reaction profiles as summarized in Figure 2, which also contains the relative energies of the various points with respect to the energy of the reactant, 2-methylpyrazine (**3**). The structures of the various critical points on the possible mechanistic pathways of Figure 2 are illustrated in Figure 3. Cartesian coordinates and energetics calculated for the various points at the CASSCF level are available as Supporting Information.

The quality of our methyl-substituted pyrazine model has been tested by computing the $S_1-S_0$ energy gap at the Franck−Condon (FC) structure. See **FC-3** in Figure 2. Remarkably, the computed vertical excitation energy (116 kcal/mol) to the lowest excited $\pi^*$ state of **3** is in good agreement with the experimental irradiation of 2537 Å (= 113 kcal/mol) light to **3**. As discussed in the previous section, the calculated 116 kcal/mol band for **3** is best described as the $\pi_3 \rightarrow \pi_4^*$ transition. Accordingly, our

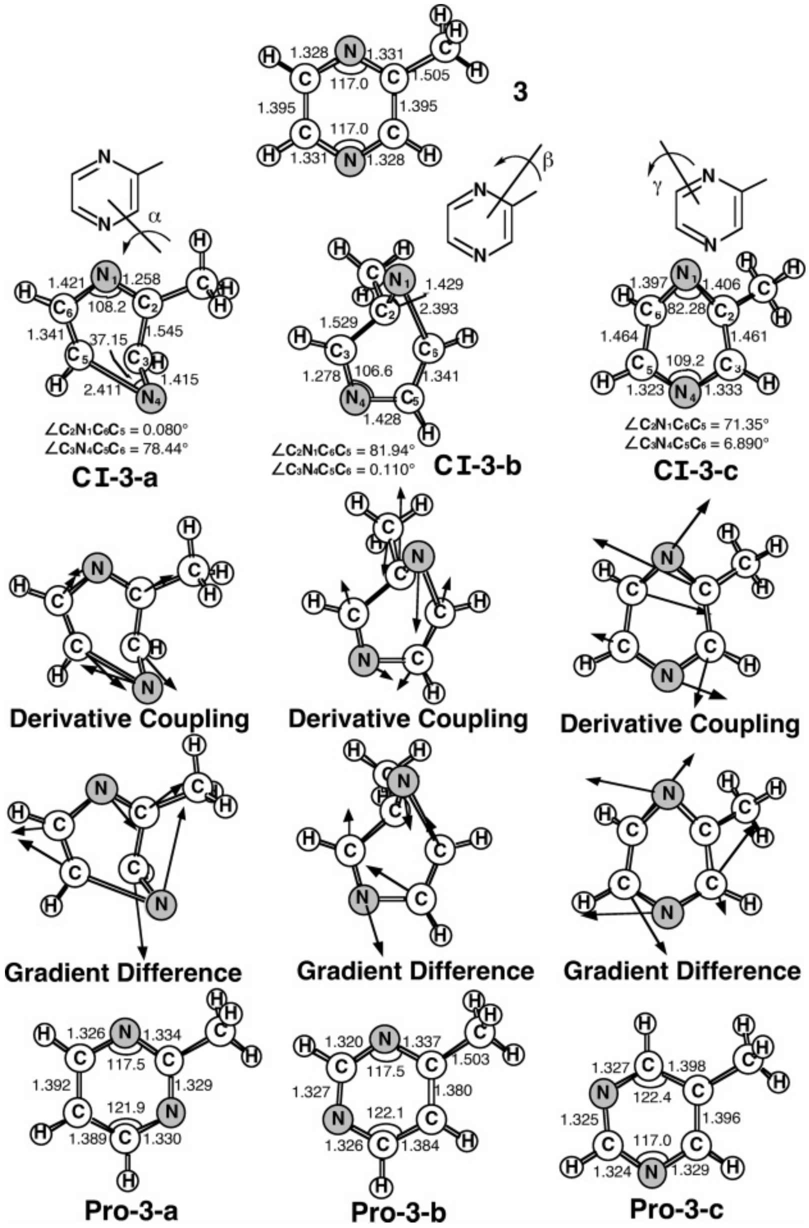


**Figure 3.** CAS(6,6)/6-311G(d) geometries (in Å and deg) for the 2-methylpyrazine (**3**), conical intersection (CI), and isomer products (**Pro-3-a**, **Pro-3-b**, and **Pro-3-c**). The derivative coupling and gradient difference vectors, those that lift the degeneracy, were computed with CASSCF at conical intersections **CI-3-a**, **CI-3-b**, and **CI-3-c**. The corresponding CASSCF vectors are shown in the inset. For more information, see the Supporting Information.

computational results confirm the experimental observations[2] that the only excited state involved in the photorearrangement of pyrazine and of its derivatives is the singlet ($\pi$, $\pi^*$).

We next investigate the subsequent process, relaxation on an excited-state potential surface. On the basis of the earlier prediction, we search for a conical crossing point between $S_0$ and $S_1$ surfaces for three reaction pathways as given in eq 1. As Figure 1 shows, because the formation of a narrow energy gap between the $S_0$ and $S_1$ states found by twisting about one N═C double bond strongly implies the existence of a CI in a nearby geometry, geometry optimization on the $S_1$ ($\pi_3 \rightarrow \pi_4^*$) excited state is thus performed by twisting structure **3**. The photochemically active relaxation path starting from the $S_1$ ($\pi_3 \rightarrow \pi_4^*$) excited state of the $C_1$ structure of **3** leads to the $S_1/S_0$ CI where the photoexcited system decays nonradiatively to $S_0$. As a result, the lowest energy point of the intersection seam of the $S_0$ and $S_1$ states was located for each reaction path, which were identified as **CI-3-a**, **CI-3-b**, and **CI-3-c**, respectively, as presented in Figures 2 and 3. Also, the orientation of two vectors (i.e., the nonadiabatic coupling and gradient difference vectors) is shown in Figure 3. As one can see, the most characteristic feature in the geometries of these CIs is that one C−N bond lies out of the molecular plane as predicted earlier. Namely, in forming the conical intersection structures, planarity is lost and one N atom moves out of plane by 78° (**CI-3-a**), 82° (**CI-3-b**), and 71° (**CI-3-c**), respectively. Accordingly, from the structures at these $S_1/S_0$ CI points, the nature of the relaxation path on the $S_1$ potential surface can be regarded as C−C and N−C bond cleavage leading to the exchange of two neighboring atoms. These calculations thus reveal that the geometry of the CI, from which it undergoes intramolecular rotation, is approaching the geometry of planar pyrimidine.[15]

In addition, as shown in Figure 2, our computational results indicate that the three CI points (i.e., **CI-3-a**, **CI-3-b**, and **CI-3-c**) are 18, 15, and 8.0 kcal/mol lower in energy than **FC-3**, respectively. Similarly, the energies of their corresponding

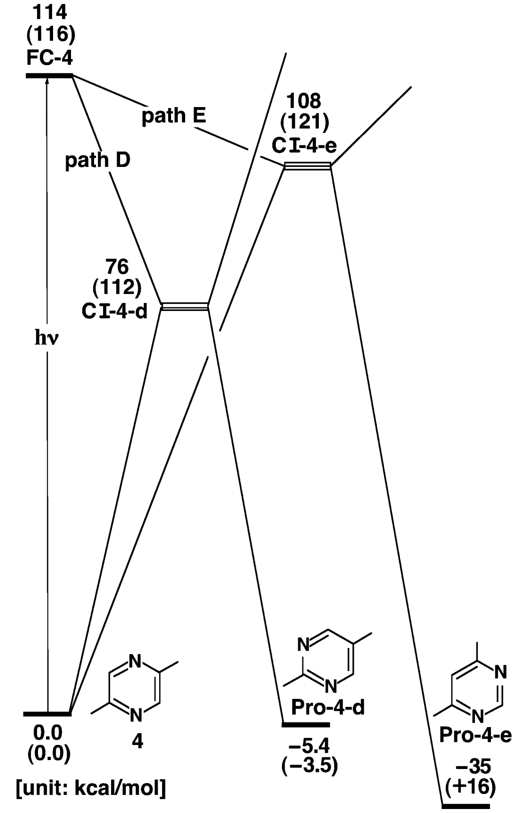
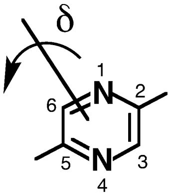


**Figure 4.** Energy profiles for the photoisomerization modes of 2,5-dimethylpyrazine (**4**). The abbreviations FC and CI stand for Franck−Condon and conical intersection, respectively. The relative energies were obtained at the MP2-CAS-(6,6)/6-311G(d)//CAS(6,6)/6-311G(d) and CAS(6,6)/6-311G(d) (in parentheses) levels of theory. All energies (in kcal/mol) are given with respect to the reactant (**4**). For the CASSCF optimized structures of the crucial points, see Figure 5. For more information, see the text.

photoproducts (i.e., **Pro-3-a**, **Pro-3-b**, and **Pro-3-c**) were calculated to be below that of the starting material (**3**) by 7.6, 12, and 4.5 kcal/mol, respectively. Consequently, our model calculations provide a qualitative explanation of the phototransposition of **3** to methylpyrimidines via the CIs. That is, an efficient photoisomerization occurs when photoexcited reactant **3*** evolves along a barrierless excited-state path, decays at a CI point,[5] and finally relaxes to the ground state between 2-methylpyrazine (**3**) and photoproducts (i.e., **Pro-3-a**, **Pro-3-b**, and **Pro-3-c**) to a point on the ground-state surface that lies below reactant **3**.[2]

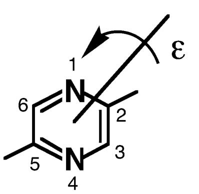
**2. Dimethyl-Substituted Pyrazine.** Next we consider the photoisomerization of 2,5-dimethylpyrazine (**4**) as depicted in eq 2. Like the case of 2-methylpyrazine (**3**), the photochemical reactions of **4** studied in this work are presumed to follow the same reaction paths as those shown earlier. That is, Rea (**4**) → FC → CI → Pro (pyrimidine). The potential energy profiles for photoisomerization of **4** to produce various pyrimidines at the MP2-CAS and CASSCF levels are given in Figure 4. Their selected geometrical parameters are collected in Figure 5, together with the nonadiabatic coupling and gradient difference vectors of the CI points. The Cartesian coordinates and energies calculated for the crucial points at the CASSCF level are available as Supporting Information.

As can be seen in Figure 4, the MP2-CAS vertical excitation energy of **4** (114 kcal/mol; **FC-4**) is surprisingly close to the experimental absorption band (2537 Å = 113 kcal/mol).[2] Thus, our theoretical investigations strongly suggest that the six *p*-$\pi$ orbitals of **4** play a decisive role in the photochemical transposition reactions. Because it is well-known that irradiation of dimethyl-substituted pyrazine causes the interchange of positions of adjacent ring atoms,[2] it will be shown below that these photoisomerizations can be interpreted easily using the reaction course involving CIs. Owing to the $D_{2h}$ symmetry of compound **4**, the lowest $^1(\pi \rightarrow \pi^*)$ state of **4** brings about two types of transpositions, that is, the (1,6) transposition and the (1,2) transposition. As a result, the photochemical transposition reactions of **4** can take place in two ways: either by twisting the N=C$_6$ bond (see **9**; path D) or by twisting the N=C$_2$ bond (see **10**; path E). These lead to the photoproducts 2,5-dimethylpyrimidine (**Pro-4-d**) and 4,6-dimethylpyrimidine (**Pro-4-e**), respectively. Indeed, it was reported experimentally that only two photoproducts (**Pro-4-d** and **Pro-4-e**) are observed on irradiation of **4**,[2] as stated in eq 2.



(path D)

**9**



(path E)

**10**

Using the algorithm implemented in the Gaussian 03 program with a state-averaged CASSCF(6,6)/6-311G(d), the lowest energy point of the intersection seam of the S$_0$ and S$_1$ states was located for each of the reaction routes (i.e., **CI-4-d** and **CI-4-e**). Our MP2-CAS results shown in Figure 4 indicate that **CI-4-d** is 38 kcal/mol lower in energy than **FC-4**, whereas **CI-4-e** lies only 6.0 kcal/mol below **FC-4**. Competition between these reaction paths is presumably governed by the relative energies of the CIs involved.[15] As a result, path D would be more favorable than path E from the energetic viewpoint, suggesting that the quantum yield of 2,5-dimethylpyrimidine (**Pro-4-d**) should be larger than that of 4,6-dimethylpyrimidine (**Pro-4-e**).[14] These theoretical findings are in accordance with the experimental observation of the formation of **Pro-4-d** and **Pro-4-e**, the former being the major phototransposition product.[2]

In short, our model investigations demonstrate that upon absorption of a photon of light, 2,5-dimethylpyrazine (**4**) is excited vertically to S$_1$ followed by a rapid relaxation, via a conical intersection, to its ground-state product where it undergoes radiationless transition from **4** to dimethylpyrimidines (i.e., **Pro-4-d** and **Pro-4-e**).

The photorearrangement of another isomer of dimethyl substituted pyrazine, 2,6-dimethylpyrazine (**5**), as described in eq 3 is also examined. The reaction profiles computed for eq 3 of model compound **5** (Figure 6) resemble that of isomer **4**. Figure 6 is thus arranged in the same fashion as Figure 4. Selected optimized geometrical parameters for the crucial points can be taken from Figure 7. The Cartesian coordinates and total electronic energies calculated for these points at the CASSCF level are included in the Supporting Information.

As Figure 6 shows, the computed vertical excitation energy of model compound **5** (S$_0$ → S$_1$(S$_0$ geom); **FC-5**) is 114 kcal/mol, which is the same as that of isomer **4**. This computational result is in excellent agreement with the experimental value (2537 Å = 113 kcal/mol)[2] and is also consistent with the $\pi$−$\pi^*$ nature of the transition. Again, this theoretical finding strongly

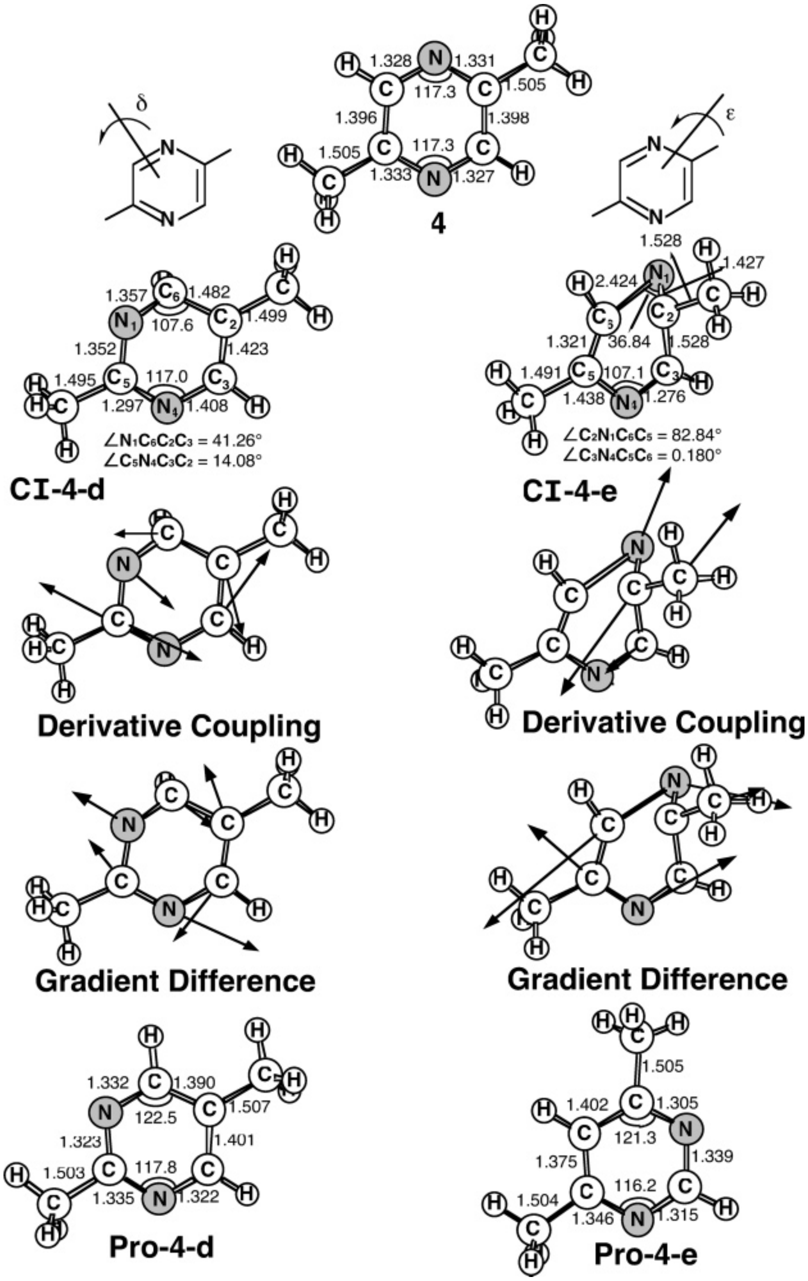
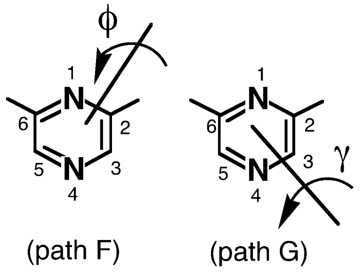


**Figure 5.** CAS(6,6)/6-311G(d) geometries (in Å and deg) for the 2,5-dimethylpyrazine (**4**), conical intersection (CI), and isomer products (**Pro-4-d** and **Pro-4-e**). The derivative coupling and gradient difference vectors, those that lift the degeneracy, were computed with CASSCF at conical intersections **CI-4-d** and **CI-4-e**. The corresponding CASSCF vectors are shown in the inset. For more information, see the Supporting Information.

suggests that the *p*-$\pi$ orbitals of **5** play a key role in its photorearrangements.



**11** **12**

Furthermore, as in the case of model compound **4** shown previously, the photoisomerizations of **5** can occur in two ways: by twisting the N═C$_2$ bond (see **11**) or by twisting the N═C$_3$ bond (see **12**).[15] These two transpositions give rise to two final photoproducts, 4,5-dimethylpyrimidine (**Pro-5-f**) and 2,4-dimethylpyrimidine (**Pro-5-g**), respectively. Indeed, as stated in eq 3, only these two valence isomers have been detected experimentally.[2] Consequently, two minimum-energy pathways on the singlet excited potential energy surface of **5** were characterized by optimizing the geometries along the twisting N═C$_2$ (path F) and N═C$_3$ bonds (path G). The minimum conical intersection point at the CASSCF level has been obtained for each reaction path, **CI-5-f** and **CI-5-g**, respectively. As can be seen in Figure 6, the nitrogen returns to the plane of the molecule after being 106° and 49° above the plane in **CI-5-f** and **CI-5-g**, respectively. In addition, the MP2-CAS results indicate that **CI-5-f** is lower than **FC-5** by 13 kcal/mol in energy, whereas the competing **CI-5-g** is lower than **FC-5** only by 2.0 kcal/mol in energy. Thus, the energy difference between these two CIs is

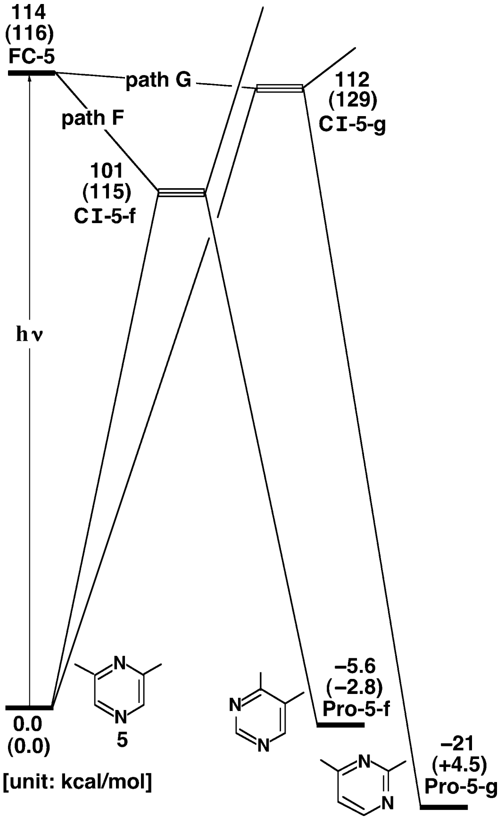


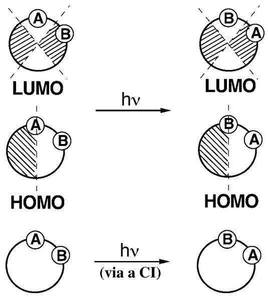
**Figure 6.** Energy profiles for the photoisomerization modes of 2,6-dimethylpyrazine (**5**). The abbreviations FC and CI stand for Franck−Condon and conical intersection, respectively. The relative energies were obtained at the MP2-CAS-(6,6)/6-311G(d)//CAS(6,6)/6-311G(d) and CAS(6,6)/6-311G(d,p) (in parentheses) levels of theory. All energies (in kcal/mol) are given with respect to the reactant (**5**). For the CASSCF optimized structures of the crucial points, see Figure 7. For more information, see the text.

substantially lower for path F and makes the (1,2) transposition (**11**) easy to proceed. This, in turn, would increase the quantum yield of **CI-5-f** larger than that of **CI-5-g**. The energetic arguments are in qualitative agreement with the experimentally observed relative product distributions of **Pro-5-f** and **Pro-5-g**.[2]

In brief, our theoretical investigations suggest that the initial excitation of **5** is a $\pi-\pi^*$ excitation to **FC-5**. Then, **5** in the $S_1$ state proceeds to rotate one N═C bond via a conical intersection and, subsequently, return to the ground state nonradiatively to give **Pro-5-f** and **Pro-5-g** without any intermediates.

## V. Extensions

The molecules that we have studied in the previous sections all have planar ring geometries with two electronegative atoms. The analysis of photochemical transpositions can easily be extended to other similar heterocyclic molecules. If a heterocyclic molecule absorbs a photon to go to an excited state, then the photoexcitation reaction is consistent with the $^1(\pi \rightarrow \pi^*)$ nature of the transition. In general, suppose this heterocyclic molecule bears at least one electronegative atom, the *p*-$\pi$ frontier orbital structure of the heterocyclic ring may also be described in terms of nodal planes as shown in **13**.[17] The HOMO of the heterocyclic molecule is an occupied antibonding $\pi$ orbital with the most electronegative atom (i.e., A) lying along the nodal plane. However, the LUMO (unoccupied $\pi^*$ state) of the reactant bears two nodal planes, which bisect A and B heteroatoms as shown schematically in **13**.



**13**

It is the topology of the *p*-$\pi$ orbitals shown in **13** that promotes the interchange of A and B atoms. Thus, the central novel results for the photochemistry of such heterocyclic molecules are the existence of the conical intersections. That is to say, by irradiation of such heterocycles the photochemically active relaxation from the $S_1$ excited state leads to an $S_1/S_0$ conical intersection where the photoexcited system decays nonradiatively to $S_0$, yielding phototransposition products. Accordingly, from the above analysis, one may easily predict that a heterocyclic compound bearing at least one electronegative atom should undergo both a rapid and radiationless phototransposition through a conical intersection to return to the ground state. In fact, the photochemical formation of unstable isomers leading to a shift of ring atoms seems to be a general process in the photochemistry of heterocyclic compounds.[1] For instance, as mentioned already, many five- and six-membered heterocycles with at least one electronegative atom can undergo isomerization reactions in which two ring atoms interchange their positions under the influence of UV−visible light.[1,16] A more detailed account of the photochemical mechanisms of these various heterocyclic reactions obtained from calculations using the conical intersection model will be given elsewhere.[18]

## VI. Conclusions

We have studied the reaction mechanisms of photoreactions of 2-methylpyrazine (eq 1), 2,5-dimethylpyrazine (eq 2), and 2,6-dimethylpyrazine (eq 3), with respect to permutation of the ring atoms. From the present results, we can elaborate on the standard model of the photochemistry of pyrazine and of its methyl-substituted derivatives. Pyrazine is vertically excited to the $S_1$ state. Then, radiationless decay from $S_1$ to $S_0$ of pyrazine occurs via a conical intersection, which results in a rapid N═C bond rotation. Starting from this conical intersection, the products of the phototranspositions as well as the initial reactant can be reached on a barrierless ground-state relaxation path. As a result, these findings, based on the conical intersection viewpoint, have helped us to better understand the photochemical reactions, and to support the observations.[2]

Besides this, we propose a simple *p*-$\pi$ orbital topology model, which can be used as a guide to predict the location of the conical intersections as well as the geometries of the phototransposition products of various heterocyclic compounds. The results presented here, together with our work on the photochemistry of other five- and six-membered heterocycles,[18] appear to give convincing evidence that conical intersections are a common feature in such photoisomerizations and that they are directly involved in heterocycle photochemistry and photophysics.

It is hoped that the present work can stimulate further research on this subject.

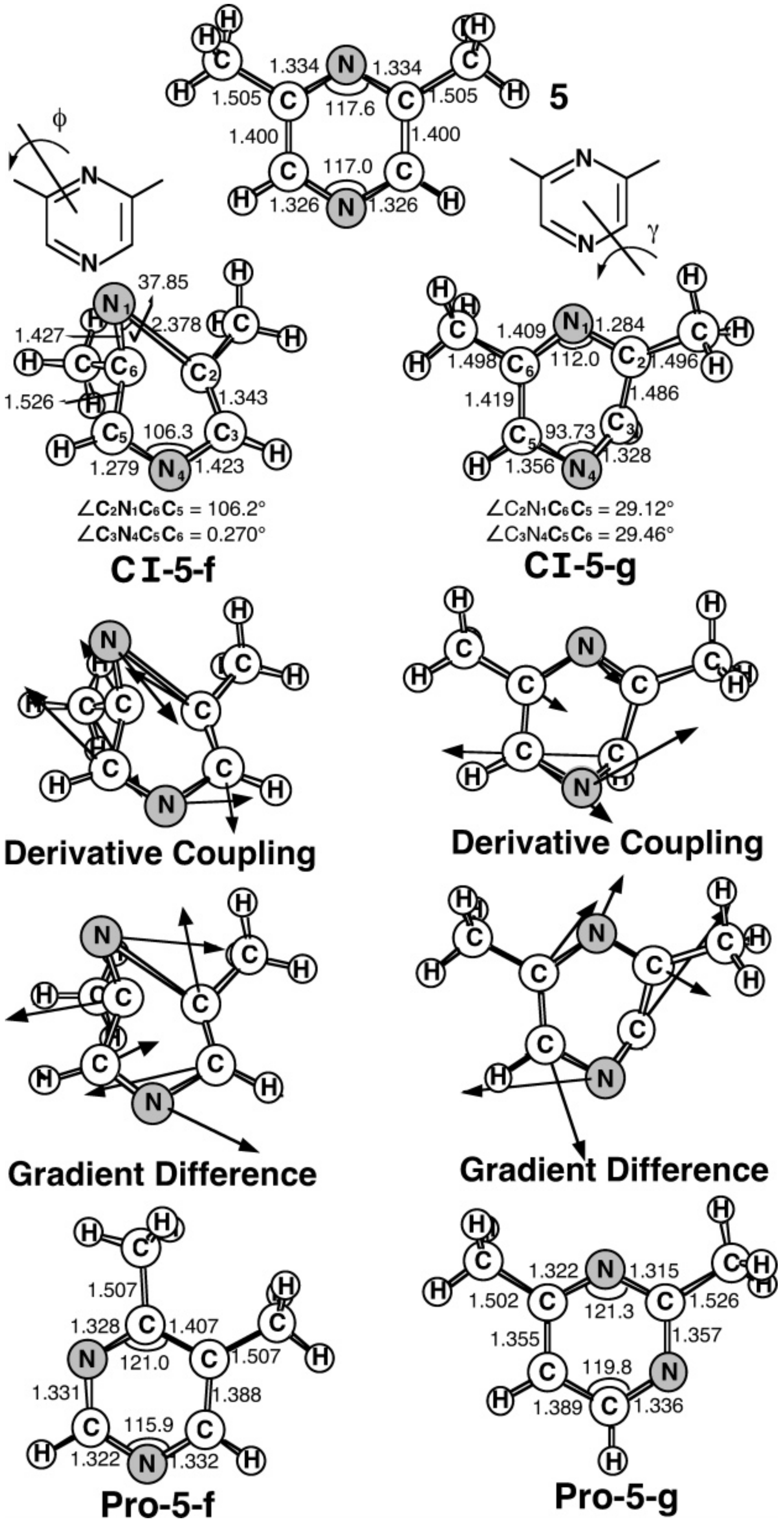


**Figure 7.** CAS(6,6)/6-311G(d) geometries (in Å and deg) for the 2,6-dimethylpyrazine (**5**), conical intersection (CI), and isomer products (**Pro-5-f** and **Pro-5-g**). The derivative coupling and gradient difference vectors, those that lift the degeneracy, were computed with CASSCF at conical intersections **CI-5-f** and **CI-5-g**. The corresponding CASSCF vectors are shown in the inset. For more information, see the Supporting Information.

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**Supporting Information Available:** CASSCF optimized geometries and MP2-CAS and CASSCF energies. This material is available free of charge via the Internet at http://pubs.acs.org.

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