

## COMMUNICATION

# A possible attributions of excited-state process for PIP and PIP-c system in methanol solvent

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**Abstract:** In this work, based on the DFT/TDDFT methods, we theoretically studied isomerides (2-phenylimidazo[4,5-b]pyridine (PIP) and 2-(phenyl)imidazo[4,5-c]pyridine (PIP-c)) about their excited state behavior in methanol solvents. Via comparing potential energy barriers, we deem that the single emission for these two systems should be attributed to the normal fluorescence mentioned in previous experiments if ESIPT could not occur. While if the potential barriers are suitable for ESIPT, the non-radiative path should be great mechanism in the excited state. Intersection and intersystem crossing could successfully explain the single fluorescence phenomenon for PIP and PIP-c system.

**AMS subject classifications:** 65D18, 78M50, 74E40

**Keywords:** Hydrogen bond, ESIPT, potential energy barrier, MOs.

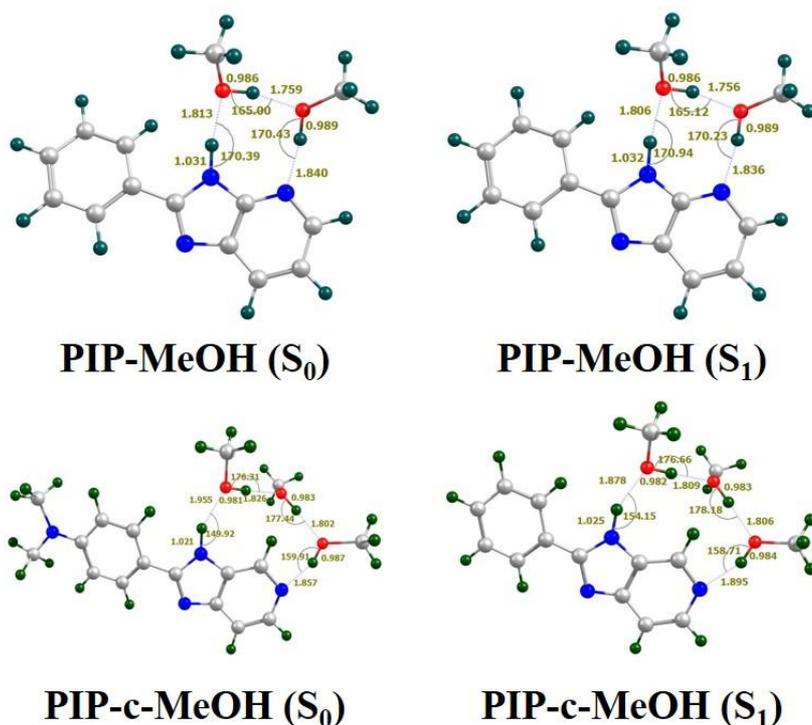
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Excited state intra- or inter- molecular proton transfer (ESIPT) reaction is the initial event of numerous photo-physical and photochemical processes existing in nature, and it crucial in chemistry [1-5]. In addition, because of the transient property of its ground state, molecules containing ESIPT has been used in several applications. The basic photophysical principle of ESIPT refers to a hydrogen transfer from proton donor to proton acceptor, which leads to a corresponding balance between enol and keto tautomers, stimulating a dual emission and large Stokes Shifts [6-8]. Based on excitation, electrons are facilitated to the single excited state of enol structure form enol\*. In turn, the ultrafast ESIPT happens forming keto\* configuration. In general, due to their structures, the keto\* emits a low energy than enol\* tautomer. Thus two fluorescence bands are observed and a broader range of the steady-state emission can be

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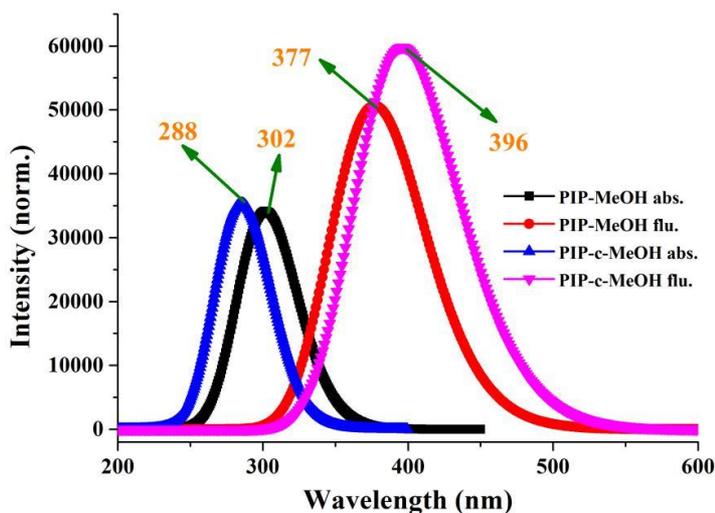
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covered, making these ESPT molecules suitable for optical chemosensors, white emitting OLEDs, material chemistry and UV filters, among other applications [9-15]. Microenvironment is a key factor for maintaining normal cell metabolism, which abnormal changes might lead to cytopathy [16-18]. As a kind of biologically active system, 2-phenylimidazo[4,5-b]pyridine (**PIP**) and 2-(phenyl)imidazo[4,5-c]pyridine (**PIP-c**) have been tested to be the inhibitor for Aurora-A, Aurora-B and Aurora-C kinases [19-21], which have been also certified to be good probes for microenvironment [18]. Krishnamoorthy and co-workers investigated these two system experimentally and found that only single emission in polar protic methanol solvent, which is different from 2-(4'-N,N-Dimethylaminophenyl)imidazo[4,5-b]pyridine and 2-(4'-N,N-dimethylaminophenyl)imidazo[4,5-c]pyridine containing two emissions [19, 20]. Recently, Zhao *et al.* have proved that the rotation reaction do not exist in the  $S_1$  state [22], that is to say, **PIP** and **PIP-c** should have familiar properties with 2-(4'-N,N-Dimethylaminophenyl)imidazo[4,5-b]pyridine and 2-(4'-N,N-dimethylaminophenyl)imidazo[4,5-c]pyridine. Thus why **PIP** and **PIP-c** only own single fluorescence is our focus in this present work.



**Figure 1:** The forms for **PIP** and **PIP-c** systems in methanol (MeOH) solvents. Herein, two MeOH molecules connecting with **PIP** (**PIP-MeOH**) and three MeOH molecules connecting with **PIP-c** (**PIP-c-MeOH**) should be the most stable configurations, respectively.

Based on density functional theory (DFT) and time-dependent DFT (TDDFT) methods, the methanol wire models of **PIP** and **PIP-c** forms have been optimized shown in **Figure 1**. Herein, two methanol and three methanol molecules connecting with **PIP** and **PIP-c** are according to the most stable conditions mentioned by Zhao *et al.* [22], respectively. All our calculations about electronic structures were carried out via Gaussian 09 program suit [23]. After testing some common basis sets for calculating excited state hydrogen bonds, we selected the Becke's three-parameter hybrid exchange function with Lee-Yang-Parr gradient-corrected correlation functional (B3LYP) and triple- $\zeta$  valence quality with one set of polarization functions (TZVP) basis set [24, 25] in all of our calculations. Solvent effect (methanol) was used based on Polarizable Continuum Model (PCM) using integral equation formalism variant (IEFPCM) [26, 27] to be consistent with previous experimental statement [19, 20].



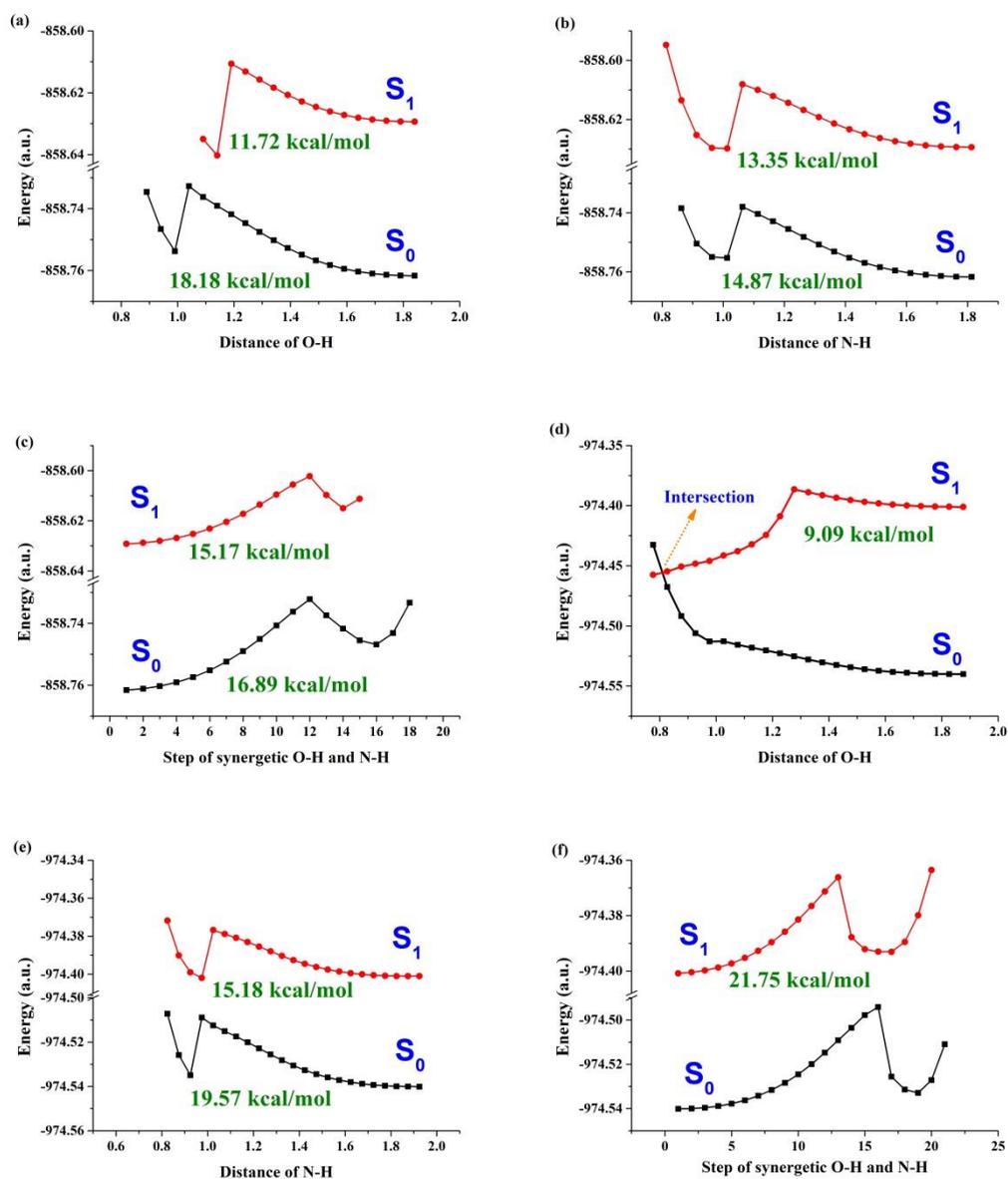
**Figure 2:** The calculated absorption and emission peaks for both PIP-MeOH and PIP-c-MeOH complex in MeOH solvent based TDDFT/B3LYP/TZVP theoretical level.

As shown in **Figure 1**, we labeled the primary bond lengths and bond angles of hydrogen bonds for **PIP** and **PIP-c**. In fact, we have also checked the different MeOH number for both **PIP** and **PIP-c** (i.e., one MeOH for **PIP** and two MeOH for **PIP-c**), and we have confirmed that two MeOH for **PIP** and three MeOH for **PIP-c** should be the most stable condition. Particularly, based on the calculated hydrogen bonding binding energy via the basis set superposition error (BSSE) [28], we found that the binding energy (23.61 kcal/mol) for two MeOH of **PIP** is more stable than one MeOH of **PIP** (10.58 kcal/mol). In the same way, three

MeOH of **PIP-c** is also more stable than two MeOH of **PIP-c** complex, which is in agreement with previous experimental work [20]. In addition, it can be found that all these intermolecular hydrogen bonds are strengthened in the  $S_1$  state [29-40], which provides the possibility for ESIPT reactions. To show the rationality of our theoretical level, we calculated the absorption and emission spectra for **PIP-MeOH** and **PIP-c-MeOH** complex seen in **Figure 2**. It should be noted that the calculated absorption of **PIP-MeOH** is 302 nm, which is close to previous experimental 320 nm [19]. Also the emission peak of **PIP-MeOH** is in good agreement with experimental 378 nm [19]. In the similar way, the theoretical results of **PIP-c-MeOH** are consistent with previous experiment [20]. Till now, we have confirmed the TDDFT/B3LYP/TZVP is suitable for these two systems. Following, we begin to explain the reason why only one fluorescence could be detected in previous experiments [19, 20].

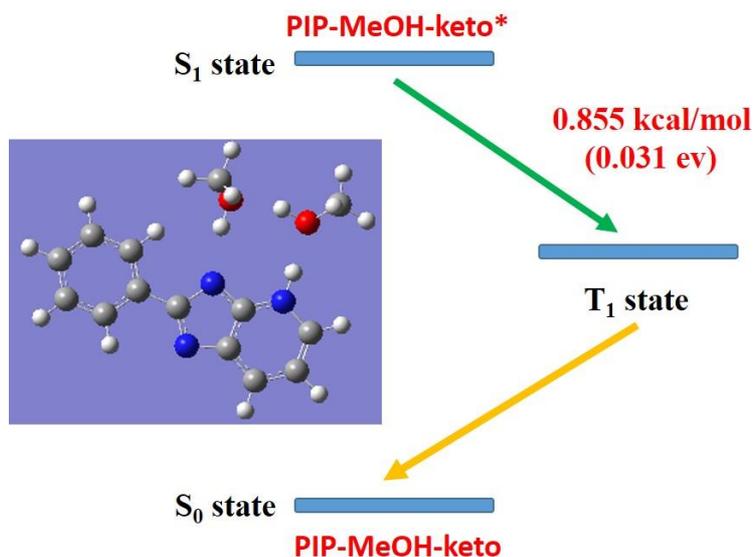
It is well known that potential energy curves should be a kind of conventional manner to solve the problem about excited state behavior; therefore, we theoretically constructed the potential energy curves to further study in-detail excited state mechanism for both **PIP** and **PIP-c** systems in MeOH solvent (shown in **Figure 3**). In this part, we consider three kinds of possible ESIPT conditions for **PIP** and **PIP-c** complex, respectively (i.e., closing the distance of O and H along with N-H...O; closing the distance of N and H along with O-H...N; synchronous closing O and H as well as N and H along with N-H...O and O-H...N for **PIP-MeOH** and **PIP-c-MeOH**, respectively). Clearly, the closing the distance of O and H along with N-H...O for **PIP-MeOH** and **PIP-c-MeOH** should be the easiest way due to the potential barriers. While, in fact, it is hard to say the ESIPT process could occur based on the potential energy barriers of 11.72 kcal/mol for **PIP-MeOH** and 9.09 kcal/mol for **PIP-c-MeOH**, since these barriers are little high more or less in the  $S_1$  state. That is to say, whether ESIPT existing in the  $S_1$  state is also an open question, while it is not important. If there is not ESIPT reaction for **PIP-MeOH** and **PIP-c-MeOH**, the single emission mentioned in previous experiment should be ascribed to the enol \*form (i.e.  $S_1$ -state **PIP-MeOH** and **PIP-c-MeOH**). Whereas if the barriers (11.72 kcal/mol and 9.09 kcal/mol) are suitable for ESIPT, how to explain the single fluorescence for **PIP-MeOH** and **PIP-c-MeOH**? For **PIP-c-MeOH** complex, it should be noticed in **Figure 3(d)** that there is an intersection between  $S_0$  and  $S_1$  state potential energy curves, which confirmed that there is a non-radiative process after relay transferring protons in the  $S_1$  state. For **PIP-MeOH** complex, if ESIPT occurs, this process is likely to happen firstly along with N-H...O with the lower barrier 11.72 kcal/mol, and then the relay ESPT reactions finished forming proton-transferred **PIP-MeOH** structure. Herein, for convenience, we named this form as **PIP-MeOH-keto\*** with -858.63014221 Hartree. In effect, it owns fluorescence in the  $S_1$  state, while after we calculated the triple state ( $T_1$ ) of this structure; we find that it located to be -858.63150605 Hartree. That is to say, the gap between  $S_1$  and  $T_1$  states is just 0.031 eV (0.855 kcal/mol). This kind of low energy gap might lead to the intersystem crossing process from  $S_1$  to  $T_1$ , then the no-detected phosphorescence with 0.0016

oscillator strength in previous experiment should be emitted back from  $T_1$  back to  $S_0$  state (shown in **Figure 4**).



**Figure 3:** View of three kinds of potential energy curves for both **PIP-MeOH** and **PIP-c-MeOH** systems in both  $S_0$  and  $S_1$  states. (a) and (d): Closing the distance of O and H along with N-H...O for **PIP-MeOH** and **PIP-c-MeOH**, respectively; (b) and (e): Closing the distance of N and H along with O-H...N for **PIP-MeOH** and **PIP-c-MeOH**, respectively; (c) Synchronous closing O and H as well as N and H along with N-H...O and O-H...N for **PIP-MeOH** and **PIP-c-MeOH**, respectively;

In summary, in this work, we theoretically investigated the excited state dynamical process for **PIP-MeOH** and **PIP-c-MeOH** complex in MeOH solvent via TDDFT methods. For these two complex, if the potential barriers are too high to occur ESIPT reaction, the single fluorescence reported in experiment should be ascribed to the normal enol\* emission. However, if the barriers are suitable for finishing ESIPT, these two systems have different excited state mechanism. For **PIP-MeOH**, the intersystem crossing from  $S_1$  state to  $T_1$  state should be a reasonable non-radiative mechanism, while for **PIP-c-MeOH**, the intersection is the main channel for non-radiative.



**Figure 4:** The probable excited state non-radiative mechanism for **PIP-MeOH** system.

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