672

Theoretical Studies of Solvation Effects on 2-(2-Hydroxyphenyl)benzimidazole

Ayaka Kuroki, Hiroshi Ushiyama,* and Koichi Yamashita

Department of Chemical System Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656

Stabilization energies at enol, keto, and transition state structures of 2-(2-hydroxyphenyl)benzimidazole in several types of solvents are systematically examined by quantum chemistry calculations. The solvent effects on the stability of keto are discussed and it has been shown that the keto form on the ground state does not have a local minimum in any type of solvents.

Proton transfer is one of the most fundamental processes which occurs in various chemical and biological systems. In 2-(2-hydroxyphenyl)benzimidazole (HPBI), intramolecular proton-transfer reaction takes place on the first excited state potential energy surface (PES).[1–7] In various kinds of isomers of HPBI, enol is the most stable on the ground state PES, on the other hand, keto form is the most stable in the first excited state (Figure 1). After photoexcitation of enol, proton transfer takes place on the first excited state and then keto form is generated. Because this feature and properties of the ground and excited state PESs are similar to the phototautomerization reaction of DNA base pairs, the proton-transfer reaction in HPBI systems has been vigorously examined.[1–7]

Although the keto form is the global minimum on the first excited state PES, it is not clear that the keto form on the ground state PES has a local minimum or not. When we consider HPBI as a model of DNA base pair, the stability of keto form is an important problem. Recently, Chipem et al. theoretically examined the stability of keto form and suggested that the existence of keto form on the ground state in gas phase. They also indicated that the keto form is stabilized in the solvents with larger polarity.[8]

In this letter, we systematically examine the effects of polarities of solvent on the stabilization energies of the HPBI enol and keto forms on the ground state and discuss the activation energies of proton transfer and the reverse reaction.

All the calculations in this letter were performed with Gaussian 09 package using B3LYP and 6-31+G(d,p) basis set.[9] Solvent stabilization effects were evaluated by using the polarizable continuum model (PCM).[10] All the computations were performed using the Research Center for Computational Science, Okazaki, Japan. We examined nine types of solvents with different dielectric constants listed in Table 1.
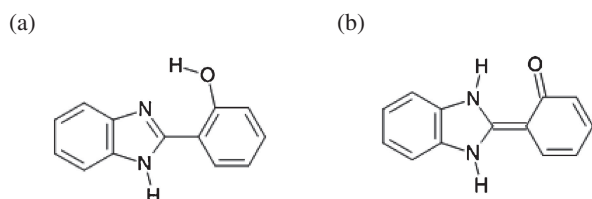
The geometries of enol and keto structures were optimized in these solvents. In our calculation, the local minimum corresponding to keto without solvent cannot be found in spite of the better basis set than that of the previous work.[8]

The energies of enol, keto, and transition state of HPBI on the ground state are shown in Figure 2a. All the energies are

Table 1. Examined solvents with dielectric constants

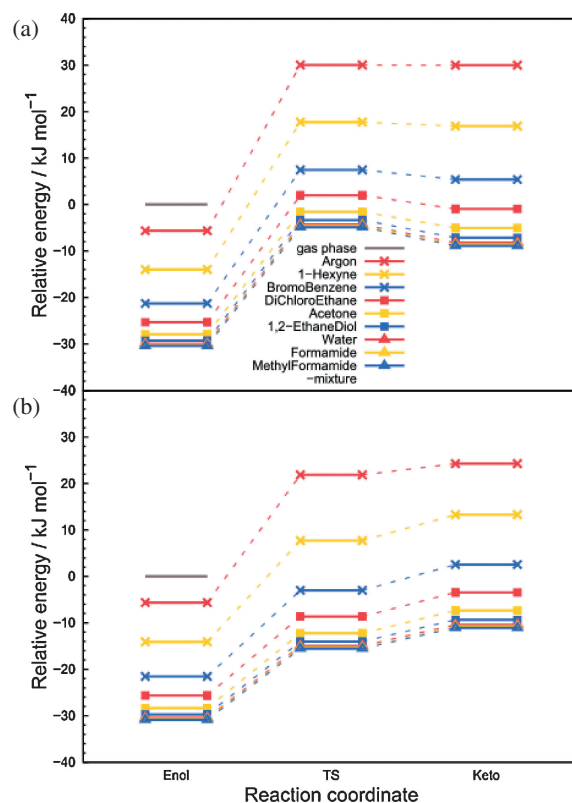| Solvent	Dielectric constant
Argon	1.43
1-Hexyne	2.61
Bromobenzene	5.39
Dichloroethane	10.12
Acetone	20.49
1,2-Ethanediol	40.24
Water	78.35
Formamide	108.94
Methylformamide mixture	181.56

Figure 2. Energy diagrams of enol, transition state, and keto on the ground state in several types of solvents, (a) without and (b) with zero-point energy corrections, respectively.
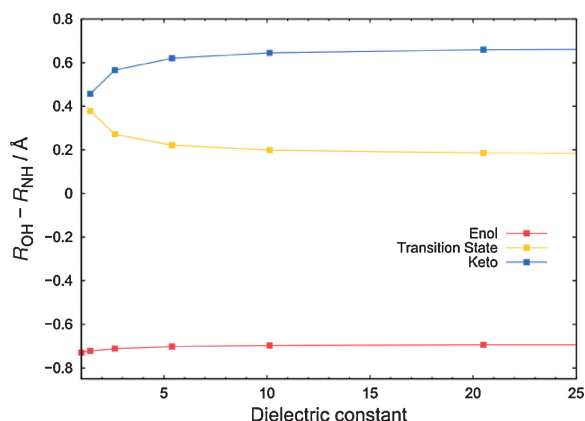

Figure 1. Isomeric forms of HPBI, (a) enol and (b) keto are shown.

Figure 3. Relative coordinates $R_{OH} - R_{NH}$ for enol, transition state, and keto are shown.

Figure 4. A schematic picture of PESs for enol and keto. The solid and dashed lines show PESs in solvents with small and large dielectric constants, respectively.

measured from the energy of the most stable structure (enol) in the gas phase. The stationary points of keto exist in the presence of any solvent. In addition, as the dielectric constants of the solvent increase, the energies of enol, keto, and transition state become lower. The dipole moments of enol and keto forms are 3.9 and 6.0 D, respectively. Because of the larger dipole moment of keto, the stabilization energy of keto is larger than that of enol and transition state. Therefore, the larger dielectric constants of the solvents make the activation energy of tautomerization reaction from enol to keto decrease and that of the reverse reaction increase.

The structures of enol, keto, and transition state are also affected by the dielectric constants of solvents. To examine the proton position, we examine the difference of distances between the transferring proton and phenolic oxygen, R_{OH}, and between the proton and imidazole nitrogen, R_{NH}. In Figure 3, $R_{OH} - R_{NH}$ for enol, keto, and transition state structures are shown as a function of the dielectric constants of solvents. For enol and keto, $R_{OH} - R_{NH}$ becomes larger as the dielectric constants increase. It means that the proton position moves from phenolic oxygen to imidazole nitrogen. On the other hand, $R_{OH} - R_{NH}$ for transition state becomes shorter. It shows that the proton between phenolic oxygen and imidazole nitrogen comes close to oxygen. These phenomena can be also understood by considering the larger dipole moment of keto on the ground state. The schematic pictures of PES are shown in Figure 4. Here we assume that potential profiles (curvatures) around enol and keto do not change and only their energies shift due to solvent effects. The solid lines show PESs for enol and keto in solvent with small dielectric constant. The dashed lines are PESs for enol and keto in solvent of large dielectric constant. Both enol and keto become stable and PESs for enol and keto shift to the lower right as yellow arrows show. As we mentioned above, the stabilization energies of keto are larger than that of enol, the intersection between PESs for enol and keto (it corresponds to transition state) shifts to the lower left as a red arrow shows in Figure 4.

However, by considering the zero-point vibrational energies (ZPE), potential profiles change drastically. Energies of enol, transition state, and keto forms with ZPE correction are shown in Figure 2b. When ZPE is considered, the barriers for proton transfer disappear because the ZPE of keto is larger than that of transition state in any solvent. Although unharmonic effects on
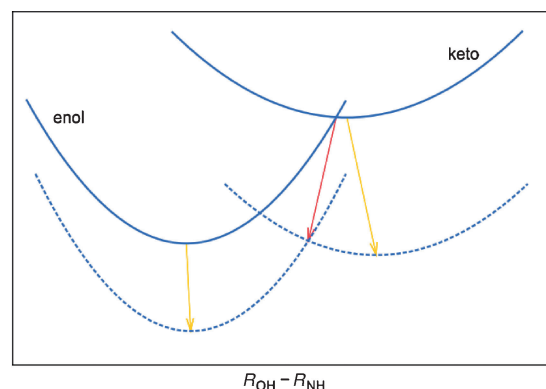
ZPE correction may be important, this result suggests that keto does not have a local minimum.

Although keto in the gas phase has no local minimum in our calculations, we show that the ground state PES has local minimum at keto form with the higher level of calculation in all solvents. This is consistent with the previous calculations of Chipem et al.[8] However, when ZPE are considered, these local minima disappear in all solvents. Therefore, based on our calculations, we conclude that keto form is not stable on the ground state PES.

Reference
1 H.-H. G. Tsai, H.-L. S. Sun, C.-J. Tan, *J. Phys. Chem. A* **2010**, *114*, 4065.
2 M. Forés, M. Duran, M. Solà, M. Orozco, F. J. Luque, *J. Phys. Chem. A* **1999**, *103*, 4525.
3 J. E. Kwon, S. Y. Park, *Adv. Mater.* **2011**, *23*, 3615.
4 A. K. Ogawa, O. K. Abou-Zied, V. Tsui, R. Jimenez, D. A. Case, F. E. Romesberg, *J. Am. Chem. Soc.* **2000**, *122*, 9917.
5 F.-Y. Dupradeau, D. A. Case, C. Yu, R. Jimenez, F. E. Romesberg, *J. Am. Chem. Soc.* **2005**, *127*, 15612.
6 C. E. Fellows, U. Täuber, C. C. Rodegheri, C. E. M. Carvalho, D. F. Acevedo, S. G. Bertolotti, C. Barbero, *Opt. Mater.* **2004**, *27*, 499.
7 F. A. S. Chipem, G. Krishnamoorthy, *J. Phys. Chem. A* **2009**, *113*, 12063.
8 F. A. S. Chipem, N. Dash, G. Krishnamoorthy, *J. Chem. Phys.* **2011**, *134*, 104308.
9 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, D. J. Fox, *Gaussian 09 (Revision A.02)*, Gaussian, Inc., Wallingford, CT, **2009**.
10 G. Scalmani, M. J. Frisch, *J. Chem. Phys.* **2010**, *132*, 114110.