Isomerization of Free Base Porphyrin. Theoretical Study

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The photoinduced isomerization reaction of free base porphyrin molecule has been calculated using the DFT-B3LYP method combined with the 6-31G(d,p) basis set. To prove the accuracy of results, the 6-311G+(2p,2d) basis set was used. Two types of isomerization mechanisms were studied. It was found that the stepwise pathway of isomerization is the most appropriate. The geometric parameters of isomers and the transition structures of different multiplets are discussed. Zero-point energy and vibrational frequencies analysis are given.

INTRODUCTION

The waste products of the pharmaceutical industry give rise to utilization and water purification issues. In order to prevent an upcoming ecological disaster, first of all, one needs to know what processes are occurring in aqueous solution with the presence of a chemical cocktail.

Since tap water is mostly taken from open water sources, e.g., rivers and lakes, then one of the key factors that is responsible for induced reactions is solar light. It is known that many radical type reactions take place due to the absorption of light.[1] The impact of solar radiation is responsible for getting the number of aromatic conjugated compounds from the ground to the excited states in which they can be chemically reactive and therefore harmful to human beings.[2] The prominent example of photoinduced toxicity is singlet oxygen. Molecular oxygen in its ground state is absolutely safe, while the excited singlet state of the same molecule has extremely high oxidative properties.[3] Knowledge about mechanisms of photoisomerization processes is of great importance for monitoring tap water quality, because the photochemical rearrangements of organic molecules may often lead to the toxic groups of anthropogenic compounds for the environment.[4]

The focus of the present study is the photoisomerization of free base porphine molecule. Porphyrins and chlorins are essential systems in numerous important biological processes such as photosynthesis by means of which photonic energy is converted and accumulated as chemical energy; they are also involved in oxygen transport and storage in hemoglobin.[5−7] Moreover, porphyrin derivatives are also common constituents of numerous drugs that are proven to be anticancer agents.[8]

The free base porphine (H_2P) is structurally the simplest member of the porphyrin class of compounds. The fluorescence spectrum of H_2P in a *n*-octane single crystal shows a doublet structure which arises from a superposition of two almost identical spectra displaced by 65 cm^{-1}.[9,10] These two spectra result from the presence of two distinct H_2P molecules in *n*-octane. It was established that two sets of

the H_2P molecules which occupy equivalent positions in the host crystal related to different orientations of the N−H··· H−N axis.[11] While the porphine planes are parallel for the two sites, the N−H···H−N axes are at right angles. Solov'ev[12] succeeded in observing the change of the location of central protons from one set of opposite nitrogens to the other when tetrabenzoporphine (TBP) molecules were excited by light at 77 K. Meanwhile, in the dark the transformations of central protons have not been registered so far. This fact assumes that isomerization of the H_2P molecules takes place in the excited S_1 state or in the lowest T_1 state. Photoinduced double proton transfer in porphine was discovered 30 years ago.[11,12]

It is also well-known that many compounds apart from porphine exhibit this type of reaction (α-naphthol, methyl salicylate). Völker and van der Waals[11] proposed that the reaction of photoisomerization associated with the intersystem crossing from the S_1 state into the triplet manifold leads to a shift of the inner protons due to vibronic coupling between the two lower triplet states. Indeed, from the previous time-dependent density functional theory (DFT) calculations[13] the first excited singlet and triplet states in the H_2P molecule are separated only by 0.75 eV, whereas the two lowest triplet states lie even closer and the energy gap between them is just about 0.2 eV. However, until now the mechanism of the excited-state proton transfer in free base porphine is not clear. In particular, it is not clearly understood whether this occurs in a concerted way by a simultaneous two-proton shift or via a less stable cis tautomer, where two N−H groups are sitting on neighboring pyrrole rings. In this work the DFT calculations for investigations of these two possible pathways of isomerization were performed.

METHOD OF CALCULATIONS

The density functional calculations were carried out using the Becke's three-parameter hybrid functional (B3LYP) method[14] with the 6-31G(d,p) basis set[15] for different H_2P conformations. The structures of H_2P were optimized for the first triplet state using the GAUSSIAN 03 program[16] with implementation of the 6-311+G(2d,2p) basis set for refine-

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Table 1. DFT Calculated Bond Lengths (Å) and Bond Angles (deg) for the Ground and Triplet Excited States of Free Base Porphyrin Molecule, for Which the Numbering Schemes Are Presented in Figures 1–3

	ground state			excited state		
	trans	cis	TS	trans	cis	TS
$C_{23}-C_{24}$	1.37	1.36	1.36	1.4	1.37	1.38
$C_{24}-C_{20}$	1.43	1.47	1.45	1.4	1.44	1.43
$C_{20}-C_{19}$	1.39	1.4	1.4	1.43	1.4	1.44
$C_{19}-C_{16}$	1.4	1.4	1.4	1.39	1.4	1.38
$C_{16}-C_{17}$	1.46	1.46	1.46	1.46	1.44	1.46
$C_{17}-C_{18}$	1.36	1.36	1.36	1.35	1.37	1.36
$C_{20}-N_{21}$	1.37	1.36	1.37	1.37	1.37	1.37
$C_{16}-N_{15}$	1.36	1.36	1.35	1.37	1.37	1.38
$C_{24}-H_{37}$	1.08	1.08	1.08	1.08	1.08	1.08
$C_{19}-H_{36}$	1.09	1.09	1.09	1.09	1.09	1.09
$C_{17}-H_{35}$	1.08	1.08	1.08	1.08	1.08	1.08
$N_{21}-H_1$	1.01	1.92	1.35	1.01	1.91	1.35
$\alpha(C_{23}-C_{24}-C_{20})$	108.00	106.60	107.80	107.56	106.85	107.60
$\alpha(C_{24}-C_{20}-N_{21})$	106.58	110.44	108.84	107.31	110.30	109.61
$\alpha(C_{20}-N_{21}-C_{22})$	110.81	106.03	106.75	110.25	105.73	106.27
$\alpha(N_{21}-C_{20}-C_{19})$	125.50	127.08	130.75	124.49	126.23	129.82
$\alpha(C_{20}-C_{19}-H_{36})$	115.92	114.74	113.59	115.08	113.58	112.34
$\alpha(C_{20}-C_{19}-C_{16})$	127.09	130.53	131.72	128.08	132.84	133.21
$\alpha(C_{19}-C_{16}-N_{15})$	125.53	127.08	126.07	125.23	126.23	125.65
$\alpha(C_{16}-N_{15}-C_{14})$	105.43	106.03	106.15	105.35	105.73	106.03
$\alpha(N_{15}-C_{16}-C_{17})$	111.12	110.44	110.63	110.85	110.3	110.01
$\alpha(C_{16}-C_{17}-C_{18})$	106.17	106.60	106.41	106.48	106.85	106.79
$\alpha(C_{16}-C_{17}-H_{35})$	125.37	125.24	125.37	125.21	125.29	125.16
$\alpha(H_1-N_{21}-C_{20})$	124.59			124.87		147.98
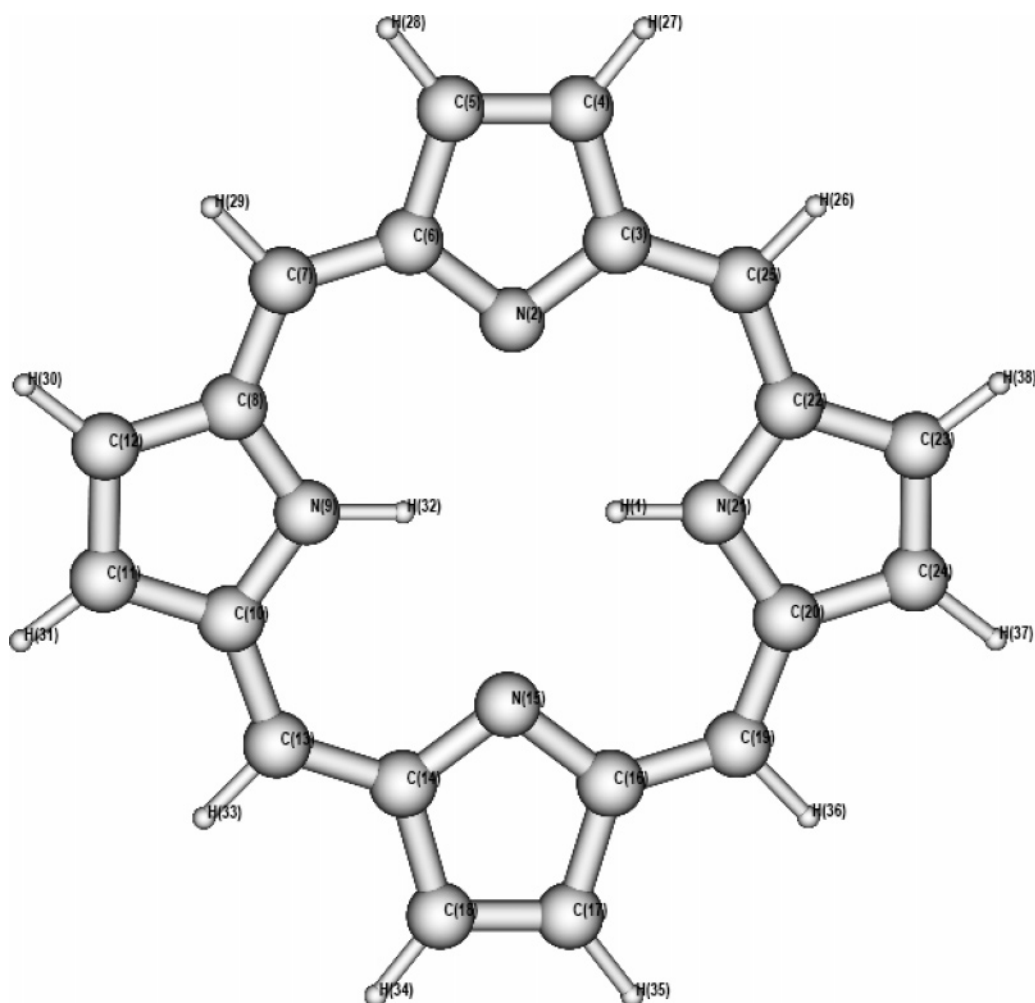
Figure 1. Trans isomer.

ment of our results obtained in the 6-31G(d,p) basis set. The triplet-state geometry of the trans conformation of the H_2P

molecule has been optimized with the D_{2h} symmetry restriction; cis conformation was optimized in C_{2v} symmetry, while
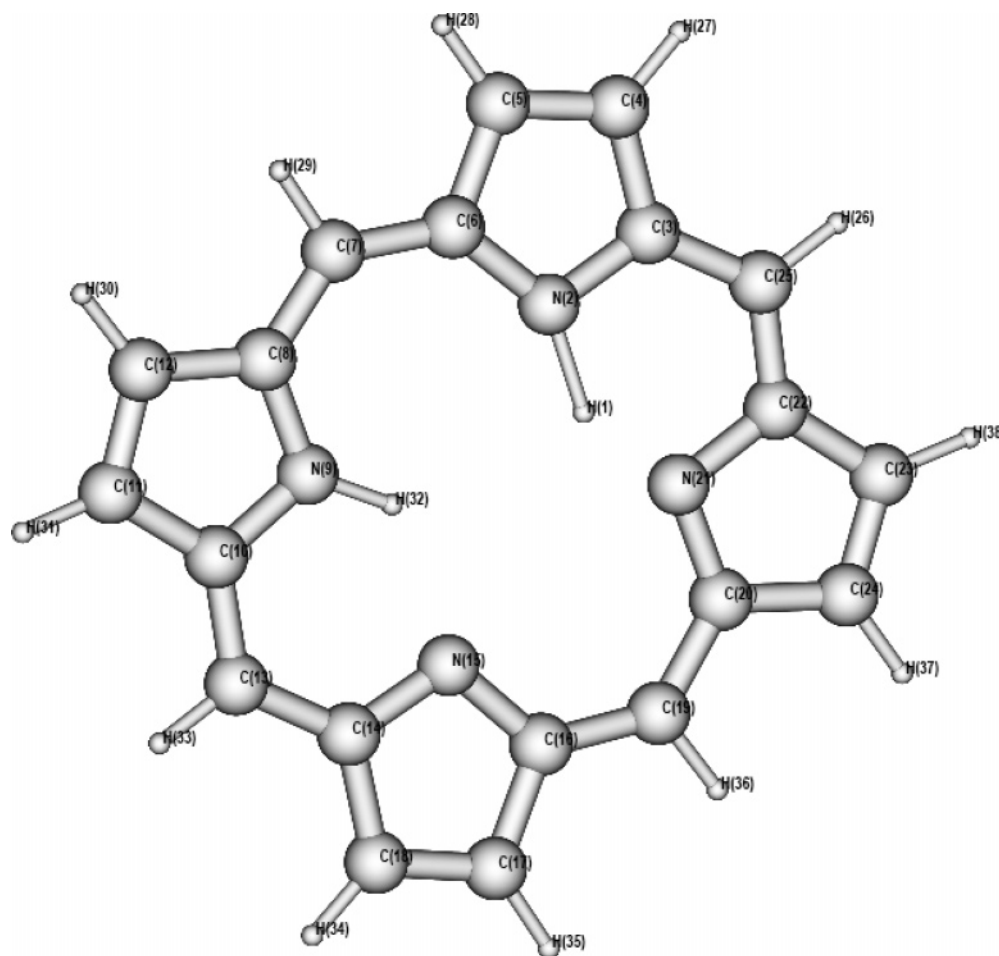
Figure 2. Transition state.

transition-state calculations were done without symmetry elements.

To find the proper initial guess structure for the transition state, a potential energy surface scan has been performed by variation of redundant coordinates of inner proton. Optimized structures were found together with the force constant matrices (Hessians) to provide harmonic vibrational frequencies and zero-point-energy (ZPE) corrections. The graphical representations of molecular structures were achieved using the Molden program package.[17]

RESULTS AND DISCUSSION

The proton tunneling of free base porphines has been studied by ^{1}H and ^{13}C NMR in liquid solution.[18,19] In its stable trans conformation of H_2P two protons attached to opposite nitrogens. During photoreaction they may switch from one pair of nitrogens to the other.

Table 1 lists the B3LYP/6-31G** geometric parameters for optimized structures of H_2P. It can be seen from Table 1 that triplet-state structures seem to be more relaxed in comparison with the singlet ones. The computed bond length of bridged carbons in the triplet state is 1.43 Å, while the same bond length for singlet ground state is 1.40 Å. One can observe the same trends also for cis and TS structures. Going from trans to cis conformation within one chosen multiplicity, it is easy to observe the tendency of porphyrin ring distortion. Thus the C(20)−C(19)−C(16) angle in the trans isomer is 128° whereas in the cis isomer this angle

has the value of 133°, while the C(22)−C(25)−C(3) angle decreases from 128° (in trans) to 124° (in cis). It should be noted that the spin density on inner H_1 hydrogen has small negative value and increases in the order trans (−0.039)− TS (−0.0048)−cis (−0.0051); meanwhile, the spin density of carbon (C$_7$) connecting the pyrrole rings decreases dramatically from $\rho = 0.4$ in trans to $\rho = 0.28$ and $\rho = 0.17$ in TS and cis conformations, respectively. Such behavior is very typical of proton transfer. This transformation may occur in a stepwise fashion through the "cis" isomer or by simultaneous shift of two central protons. Let us consider first the former type of isomerization.

Starting from the optimized triplet structure of the trans isomer, the reaction pathway was simulated by elongating one of the N−H bonds with the initial step 0.1 Å. During the trans → cis rearrangement the N−H bond cleaves and a new bond forms with the next adjacent nitrogen. The transition state (TS) was localized on the top of the potential energy surface by the Berny optimization algorithm. The trans → cis interconversion in a triplet state requires overcoming the barrier of 17.62 kcal/mol, while the activation energy of the reverse cis → trans tautomerization is only about 5.065 kcal/mol. The obtained results were refined with the extended 6-311+G(2d,2p) basis set. It was found that the calculated energies, geometric structures, and vibrational frequencies of all species have only little discrepancies using the two kinds of basis sets. For instance, the deviation in energy is no more then 0.8 kcal/mol. Therefore, the com-
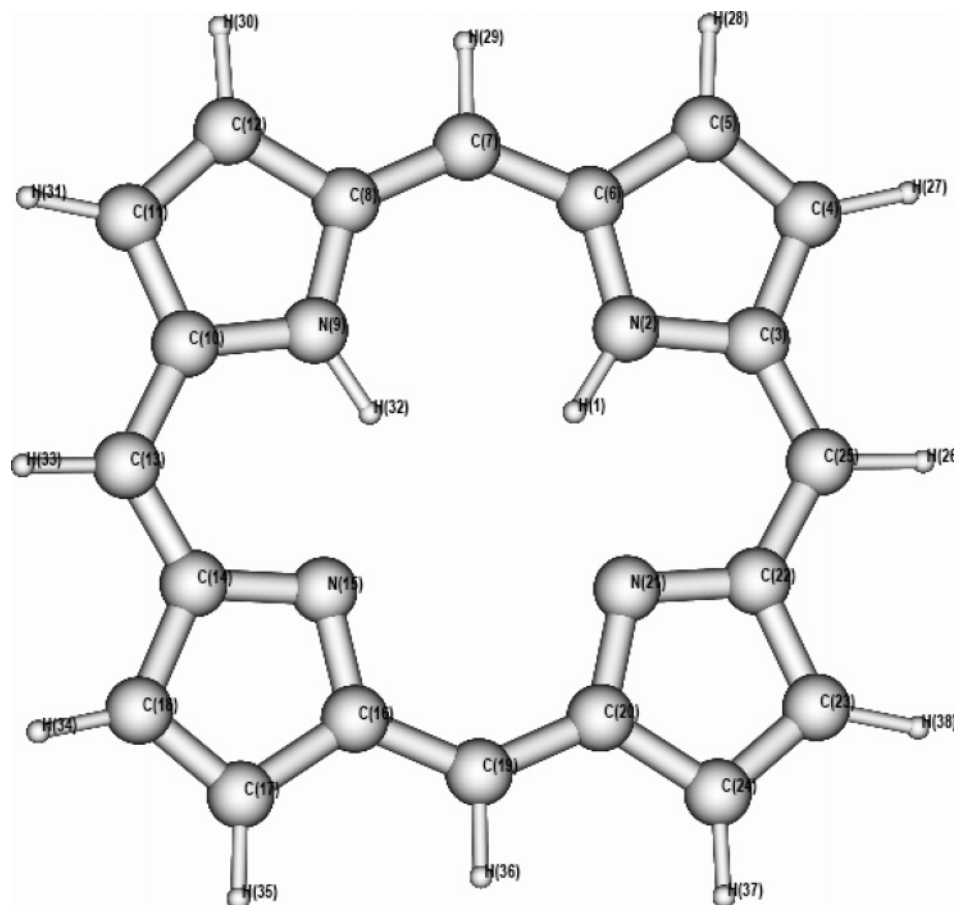
Figure 3. Cis isomer.

Table 2. Relative Energies of H_2P Isomers and Transition State (TS) in kcal/mol

conformation	triplet state		ground state
	6-31G(d, p)	6-311+G(2d, 2p)	6-31G(d,p)
trans	0.00	0.00	0.00
cis	12.55	12.44	8.19
TS	17.62	18.32	15.24

putationally inexpensive 6-31G(d,p) basis set was chosen as optimal for all calculations. Zero-point vibrational corrections to the energy of optimized structures were also estimated. Since the relative changes in zero-point energy are small (on the order of 0.9 kcal/mol), one can neglect them. The relative energies for optimized structures of H_2P calculated at the B3LYP/6-31G(d,p) level are listed in Table 2. The frequency calculation for the transition state (TS) gives a single imaginary frequency (-1514.4989 cm^{-1}), which indicates a large-amplitude in-plane motion of inner proton.

It should be noticed that, since the energy difference between the cis and TS structures is significantly smaller than the energy difference corresponding to the transition from the trans structure to the TS structure, the latter will be the rate-determining step of proton tunneling. This step may be enhanced by temperature. It was observed from experiment[20] that, as the temperature increases, transitions between different minima become possible due to the interactions with the thermal bath and the reaction yield increases considerably. At low temperatures tautomerization is also possible; however, direct transition from the trans to the cis form is complicated because of the high-energy barrier. It is possible to assume that at low-temperature

conditions the molecule is able to reach the cis minima of the triplet state via intersystem crossing since it is higher than the normal trans minima. The same isomer structures of H_2P were optimized in the ground singlet state. Surprisingly, the energy barrier was found to be 2.5 kcal/mol lower than the same barrier for the first triplet state. The existence of cis tautomer in the ground state was proved by the NMR technique.[21] Detection of this isomer in the excited triplet state is a rather hard task since such a species is expected to have a quite short lifetime and might be obscured in absorption by other higher populations of the triplet state of the trans isomer. At the same time the phosphorescence of the cis form also might be very small. From NMR experiment[19] it is known that the barrier in the ground-state potential lies 10 kcal/mol above the energy of the trans conformation. This is a qualitative agreement with the present calculations. It is known from Fourier transform fluorescence and phosphorescence of porphine in Ar and Xe matrixes[20] that the rate of the dark ground-state reaction is totally negligible. The question of why the reaction of photoisomerization takes place not on a potential energy surface of a ground singlet state which is energetically more favorable in comparison with the excited triplet state is still open. This will be a challenge for the future investigations.

The alternative pathway of photoisomerization was studied also. In this pathway two protons were fixed symmetrically between two neighboring N atoms while the rest of the atoms were optimized. Optimization of such a transition state converged to the structure that is identical to the transition state of the stepwise case isomerization. This fact supports

the idea that the stepwise pathway of isomerization of H_2P via the cis tautomer is the most appropriate.

The solvent effect on this molecule has been studied in the previous paper.[13] There, the PCM model was used for simulating toluene and water solvents. No significant effect was found for either polar or nonpolar solvents, though the first excited triplet state of H_2P seems to be more stabilized with the presence of solvent.

CONCLUDING REMARKS

The ground- and triplet-state geometries of H_2P were studied by density functional theory calculations. The proton tunneling effect has been simulated in two different models. The concerted mechanism of proton shift was found improbable. The transition states and intermediate conformations as well as the energy barriers have been calculated. The calculations indicate that the isomerization proceeds via the cis isomer by a stepwise mechanism.

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