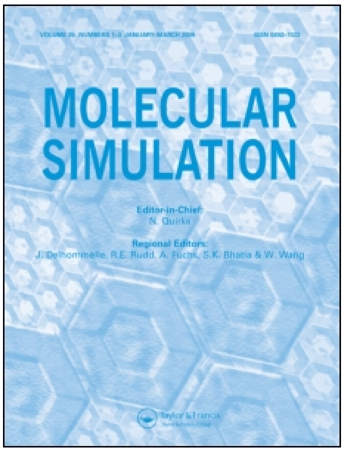

Molecular Simulation
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713644482

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To cite this Article Iyama, T. and Tachikawa, H.(2004) 'Potential Energy Curves for the Isomerization of Protonated Schiff Base of Retinal on the Triplet State Surface', Molecular Simulation, 30: 13, 917 — 921
To link to this Article: DOI: 10.1080/08927020412331298685
URL: http://dx.doi.org/10.1080/08927020412331298685

Molecular Simulation, Vol. 30 (13–15), 15 November–30 December 2004, pp. 917–921

Potential Energy Curves for the Isomerization of Protonated Schiff Base of Retinal on the Triplet State Surface

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(Received January 2004; In final form April 2004)

Potential energy curves (PECs) for the *trans–cis* isomerization of protonated Schiff base of retinal (PSBR) have been calculated by means of the time-dependent density functional theory (TD-DFT) method at the B3LYP/3-21G* level. The isomerization from all *trans* to 13-*cis* forms of PSBR in bacteriorhodopsin (bR) in the ground state (S_0) and low-lying triplet states (T_1–T_{10}) were considered in the present calculation. The excitation energies from S_0 to T_1 in all *trans* and 13-*cis* forms were calculated to be 1.16 and 1.17 eV, respectively. The shape of PEC for the ground state (S_0) showed that the activation barrier is located in $\theta_{13-14} = 90°$, where θ_{13-14} is twist angle around the $C_{13} = C_{14}$ double bond of PSBR. The shape of PEC for the triplet state (T_1) was very similar to that of S_0. In the first excited triplet state, PEC (T_2 state), two potential barriers are located at $\theta_{13-14} = 67°$ and 112°, while the energy minimum is located at $\theta_{13-14} = 91°$. The mechanism of the photo-isomerization on the low-lying triplet states is discussed on the basis of theoretical results.

Keywords: Potential energy curves; Time-dependent density functional theory; Bacteriorhodopsin; Protonated Schiff base of retinal

INTRODUCTION

Protonated Schiff base of retinal (PSBR) is the chromophore group of the protein rhodopsin, and is one of the visual pigments in humans and also the light-driven *trans*-membrane proton pump in bacteriorhodopsin (bR) [1–15]. The retinal chromophore bound covalently to the apoprotein by a protonated Schiff base linkage to a lysine residue on helix G. The photo-absorption of PSBR causes a *cis–trans* isomerization and induces a signaling state of the protein that is amplified biochemically through interaction with G protein transducin. Therefore, studying of the mechanism of initial step for the photo-absorption of PSBR is important theme in biochemistry and in biophysics.

Information on the potential energy surface (PES) for the ground and low-lying excited states is very important for elucidating the mechanism of the photo-isomerization process of PSBR. However, the information on PES is quite limited because PSBR is a large molecular system, such that the calculation of the electronic excited states has been significantly difficult. Only information on the excited states of small model molecules of PSBR can be obtained by theoretical calculations. In particular, the potential energy curves (PECs) of the triplet states are scarcely known from theoretical point of view.

Recently, pico-second time-resolves Raman spectroscopy has applied to the study of the photo-isomerization of 13-*cis* retinal in non-polar solvents [16]. It was found that 13-*cis* → all-*trans* isomerization takes place mainly on the excited singlet state (S_1). Although the singlet mechanism is one of the major pathways in the photo-isomerization of 13-*cis* retinal, it was also pointed out that the intersystem crossing to the triplet state takes place and the reaction proceeds partially on the T_1 state [16]. Therefore, studying of the triplet state gives important information on the photo-isomerization of 13-*cis* form.

In a previous paper, we reported PECs for the isomerization of PSBR from all-*trans* to 13 *cis*-forms [17]. The PECs for the ground singlet and triplet states calculated by the density functional theory (DFT) calculation were the only PECs calculated. However, PECs for the S_0 and T_1 states were

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ISSN 0892-7022 print/ISSN 1029-0435 online © 2004 Taylor & Francis Ltd
DOI: 10.1080/08927020412331298685

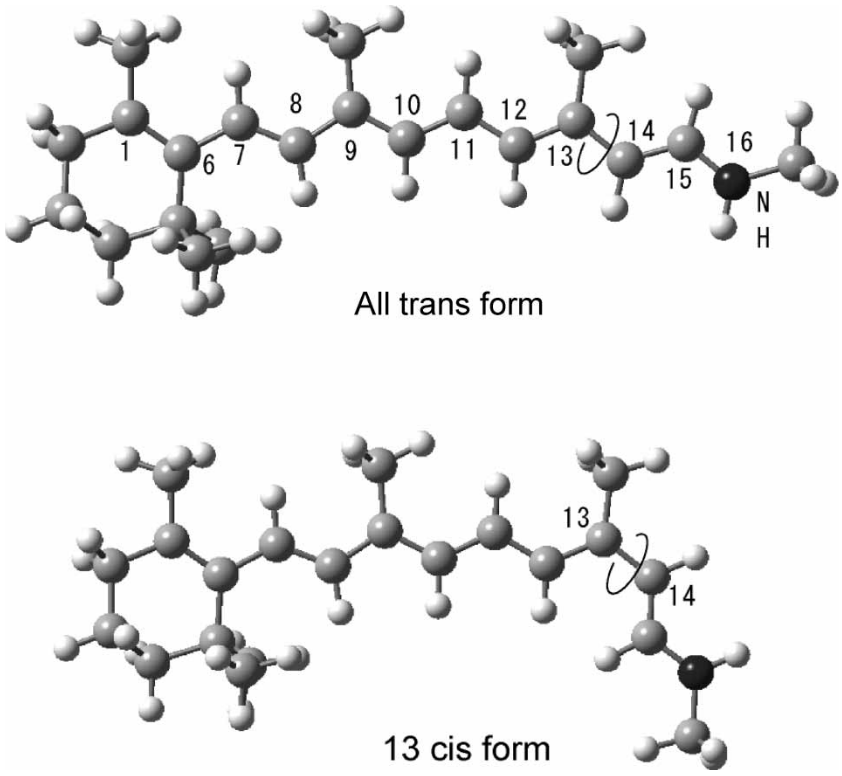

FIGURE 1 Optimized structures of all *trans* and 13-*cis* forms of protonated Schiff base of retinal (PSBR) calculated at the B3LYP/3-21G* level.

calculated in previously [17]. The higher triplet states are important in elucidating the isomerization of PSBR.

In the present study, we extend the previous work to the low-lying triplet excited states along the isomerization coordinate from all-*trans* form to 13-*cis* form of PSBR, and calculated the PECs means of time-dependent density functional theory (TD-DFT) in order to shed light on the mechanism of the photoisomerization of PSBR at the triplet states. The ground singlet (S_0) and low-lying excited triplet states (T_1–T_{10}) were also calculated.

METHOD OF THE CALCULATIONS

The structures of all *trans* and 13-*cis* forms of PSBR were fully optimized at the B3LYP/3-21G* level of theory [18,19]. Using the optimized geometry of all-*trans* form of PSBR, PECs were calculated as a function of reaction coordinate θ_{13-14}, where θ_{13-14} is twist rotation angle around $C_{13}-C_{14}$ bond of PSBR. If θ_{13-14} is equal to zero, PSBR has all *trans*-form, whereas 13-*cis* form has the angle $\theta_{13-14} = 180.0°$. The ground and low-lying triplet states (S_0 and T_1–T_{10}) were calculated by means of time-dependent (TD)-DFT method [20] at the B3LYP/3-21G* level. All calculations were carried out using Gaussian 98 program package [21].

RESULTS

Structures of all *Trans*- and 13-*cis* Forms of PSBR

The structures of all *trans*- and 13-*cis* forms of PSBR were fully optimized at B3LYP/3-21G* level, and the optimized structures are illustrated in Fig. 1. All vibrational frequencies obtained for both forms were positive, indicating that the structures are located in local minima on the ground state PES.

The calculations indicate that all *trans*-forms 3.6 kcal/mol are more stable than that of the 13-*cis* form of PSBR. The structures of 13-*cis* and all *trans*-forms are almost similar to each other. For example, the N–H bond lengths for 13-*cis* and all *trans*-forms were calculated to be 1.013 and 1.012 Å, respectively, and the $C_{11} = C_{12}$ bonds were 1.391 Å (13-*cis*) and 1.385 Å (*trans*).

PEC for the Isomerization

Using the optimized structure of all *trans* forms of PSBR, the PECs for the ground state (S_0) and low-lying triplet states (T_1–T_{10}) were calculated as a function of twist angle (θ_{13-14}). The calculated PECs are plotted in Fig. 2. Zero level of the energy is that of all *trans*-forms of PSBR at the S_0 state ($\theta_{13-14} = 0°$).

The ground state PEC (S_0) shows that the energy barrier is located at $\theta_{13-14} = 90°$ and the barrier height from all *trans*-forms was calculated to be

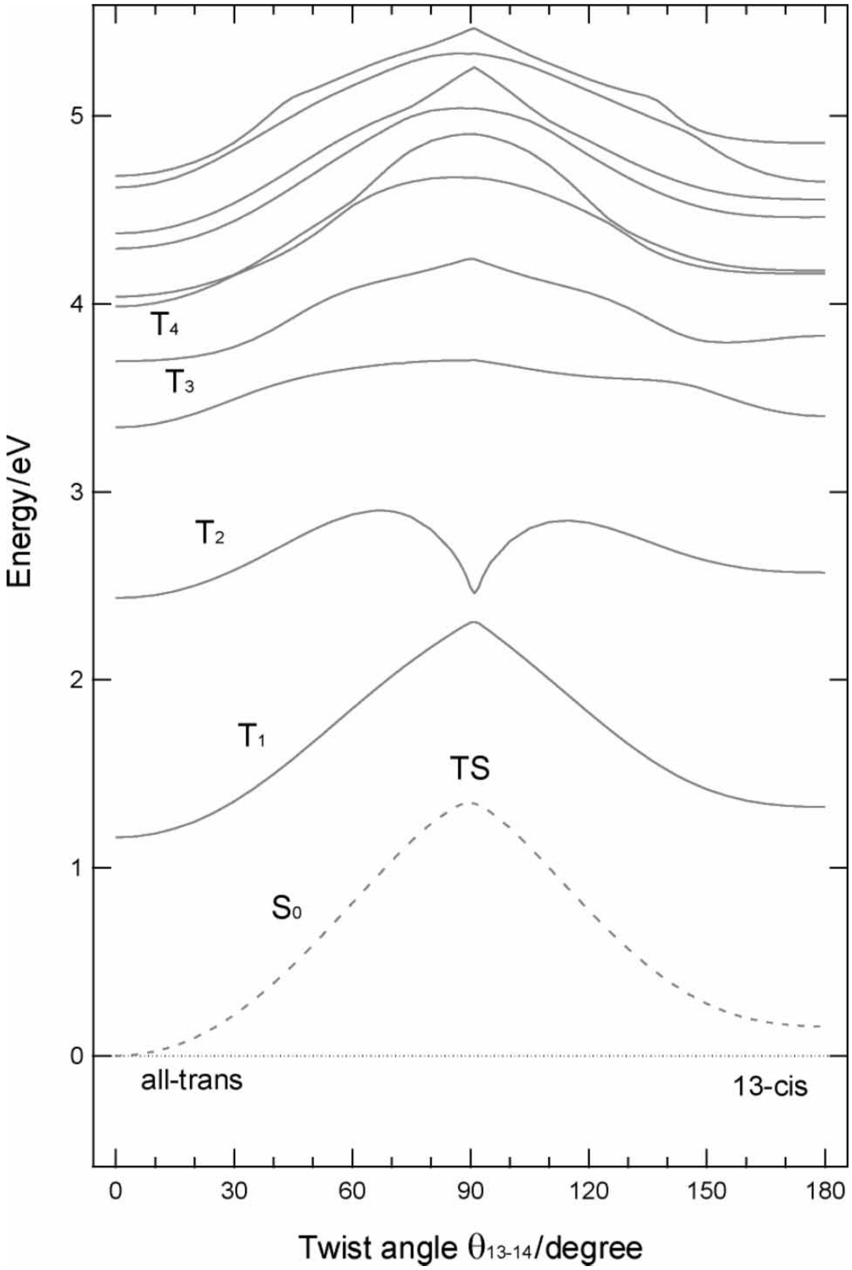

FIGURE 2 Potential energy curves for the isomerization from all *trans*- to 13 *cis* forms of PSBR. The ground (S_0) and low-lying triplet states (T_1–T_{10}) are shown.

1.34 eV. This point is a transition state in the isomerization at the ground state (S_0).

The shape of the PEC at the T_1 state is similar to that of S_0 state: the peak of the T_1 state is located at $\theta_{13-14} = 91°$ and the barrier height is calculated to be 1.16 eV which is 0.18 eV lower in energy than that of the S_0 state. The excitation energies from S_0 to T_1 states in all *trans*- and 13 *cis*-forms were calculated to be 1.16 and 1.17 eV, respectively.

The shape of the PEC for the T_2 state was much different from those of S_0 and T_1. Two peaks are located at $\theta_{13-14} = 67°$ (*trans* region) and $= 112°$ (*cis* region). The barrier heights for *trans* and 13-*cis* regions were calculated to be 0.47 and 0.30 eV, respectively. These barriers are formed by the avoided crossing between T_2 and T_3 states. The energy minimum was located at $\theta_{13-14} = 91°$. At this point, the difference of the energies between T_1 and T_2 states is only 0.075 eV. We calculated higher triplet states as shown in Fig. 2. Several avoided crossing points were found.

Electronic States of PSBR at the T_1 and T_2 States

In the present study, PECs for the triplet states are considered as the isomerization pathway. Let us show the molecular orbitals of PSBR for the low-lying triplet states. PSBR has 82 occupied MOs at the ground

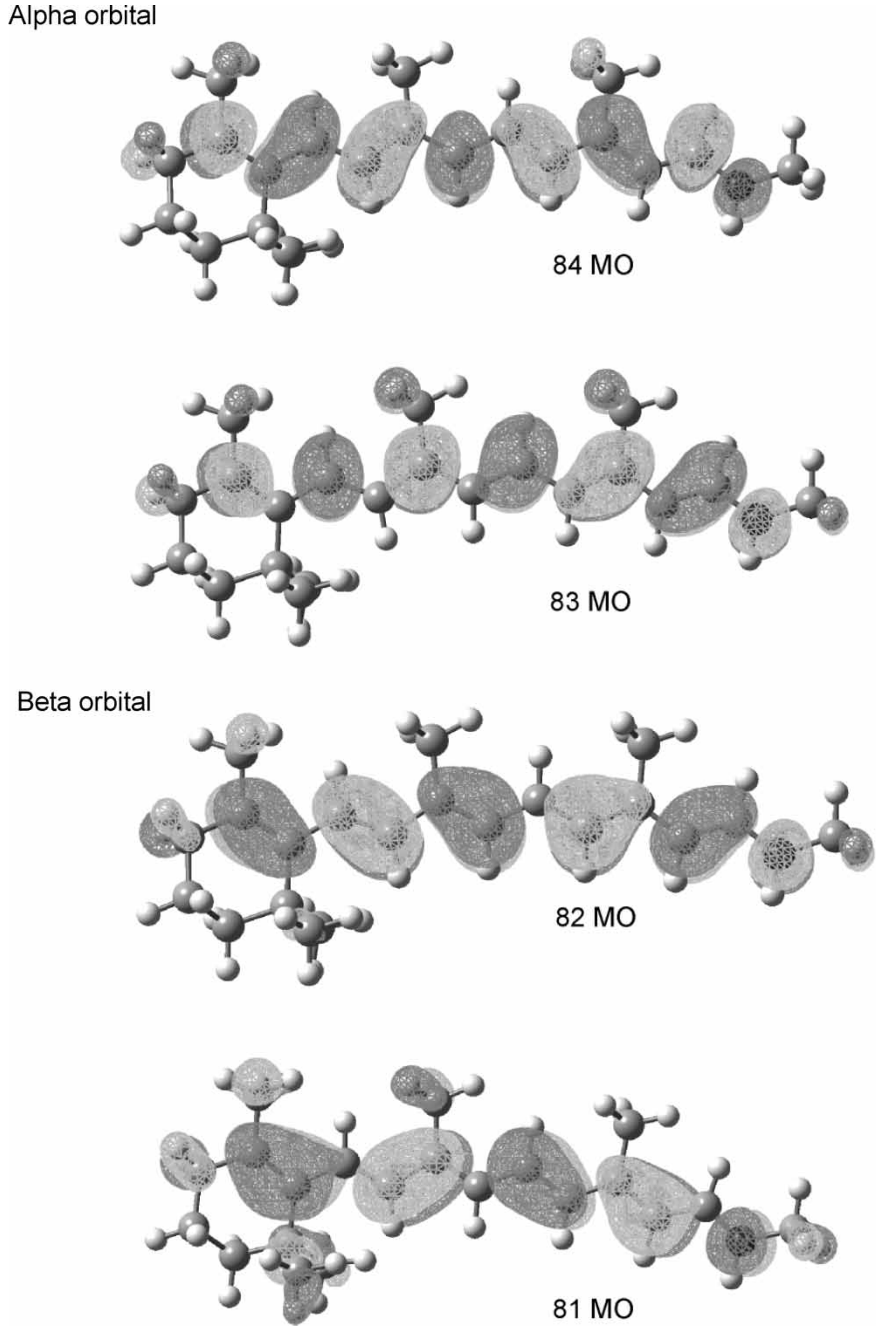

FIGURE 3 Molecular orbitals of PSBR at the T_1 state calculated at the B3LYP/3-21G* level. Positive and negative phases of MO are indicated by thin- and deep-black colour, respectively.

state and 83 alpha- and 81 beta-orbitals at the triplet T_1 state. The MOs for the T_1 state of all *trans* form of PSBR are illustrated in Fig. 3. Positive and negative phases of MO are indicated by thin- and deep-black colours, respectively. Two unpaired electrons in alpha orbital occupy 83 and 84 MO, while an unpaired electron in beta orbital occupies 81 MO at the T_1 state. These orbitals are mainly composed of π-orbital of polyene part of PSBR. This configuration is the reference function for the excited states.

TD-DFT calculation shows that the coefficients of the reference function at the T_2 state are 0.854 for $81 \rightarrow 82$ beta-MO and -0.670 for $83 \rightarrow 84$ alpha-MO, where $N \rightarrow M$ means the electronic configuration for the excitation from N to M. This indicates that the T_2 state is composed of π–π^* excited state in the polyene part of PSBR. The largest coefficient of the T_3 state is calculated to be -0.712 for $80 \rightarrow 82$ beta-MO, which is also the π–π^* excited state in the polyene part of PSBR.

CONCLUSION

In the present study, we calculated PECs for the isomerization from all *trans* to 13-*cis* forms of PSBR using the TD-DFT method. The reaction coordinate for the isomerization is the twist angle around the $C_{13}=C_{14}$ double bond of PSBR (θ_{13-14}). In this paper, low-lying triplet states were reported. The triplet T_1 and T_2 states take place the avoided crossing at $\theta_{13-14}=91°$. It is found that the reaction barrier, formed by crossing between T_2 and T_3 states, is located in $\theta_{13-14}=67°$ at T_2 state.

The photo-isomerization of PSBR has been an important theme in biochemistry and biophysics. However, its mechanism is still unclear because there is no data for the PEC which is possible to compare directly with the experiments. In the present study, for the first time, we show the PECs for the ground (S_0) and low-lying triplet states (T_1–T_{10}). It was found that the activation barrier exists on the T_2 surface for the isomerization.

Acknowledgements

The authors are indebted to the Computer Center at the Institute for Molecular Science (IMS) for the use of the computing facilities. One of the authors (H.T) also acknowledges a partial support from a Grant-in-Aid for Scientific Research (C) from the Japan Society for the Promotion of Science (JSPS).

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