

Hindered cis-trans isomerization in 9-cis retinal: a two-state model dynamics simulation

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Rhodopsin is the photosensitive chemical found on the outer segment of rod-like cells in the retina, the light-sensing structure of the eye. The 11-cis retinal chromophore in rhodopsin is changed to all-trans retinal upon exposure of rhodopsin to light. Isomerization of retinal to the all-trans form is essentially completed in 200 fs with a 0.67 quantum yield.¹ Isorhodopsin is an analogue of rhodopsin that contains a 9-cis retinal chromophore instead of 11-cis retinal embedded in the same opsin environment. Light-induced isomerization of the 9-cis retinal chromophore to the all-trans form is known to occur at a longer timescale (600 fs)² and at a reduced quantum yield (0.22)³ resulting in a weaker visual response.

The dynamics of the photoisomerization of a model protonated Schiff base of 9-cis retinal in isorhodopsin is investigated using nonadiabatic molecular dynamics simulation combined with ab initio quantum chemical calculations on-the-fly. The classical time-evolution of the trajectories employ the velocity Verlet algorithm while the quantum chemical part is treated at the complete-active space self-consistent field level for six electrons in six active π orbitals with the 6-31G basis set (CASSCF(6,6)/6-31G). Seventy-one trajectories were calculated in total with a 0.5 fs time step. The probabilities of nonadiabatic transitions between the S_1 ($^1\pi\pi^*$) and S_0 states are estimated in light of the Zhu-Nakamura theory.

Figure 1 shows the population of the 9-cis, all-trans and 11-cis photoproducts as well as the still-unreacted residual of the starting material. Thirteen percent of the trajectories yield the all-trans isomer in this simulation: the quantum yield of the all-trans photoproduct is 0.13. If the 9-trans (11-cis) products are counted as a trans product, the ratio is 0.18, which is in excellent agreement with the experimentally measured quantum yield of 0.22. This is significantly lower than the one obtained by Ishida et al. for 11-cis PSB retinal of 0.27 (or 0.49 if the 11-trans (9-cis) form are counted as a trans form).⁴ Experimentally, the all-trans quantum yield for rhodopsin is 0.67,¹ around three times more than that for isorhodopsin. The rhodopsin/isorhodopsin quantum yield ratio for the two simulations is 2.1 to 2.7, in good agreement with the experimental ratio.

On the average, it takes 441 fs to form the all-trans isomer from the 9-cis form; the time scale of isomerization is shorter than, but in reasonable agreement with the experimental reaction time of 600 fs.²

Formation of the all-trans product begins about 280 fs and peaks around 660 fs after photoexcitation in the case of the 9-cis model trajectory calculation. If the 11-cis (9-trans) form is counted as a trans photoproduct, formation of the said product starts around 200 fs in

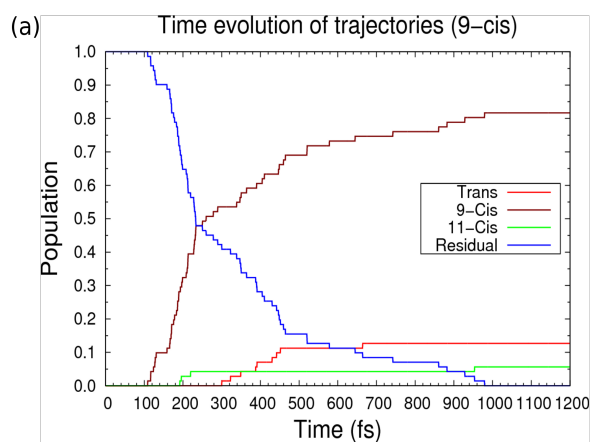


Figure 1. Population change calculated for all the trajectories in the isorhodopsin (9-cis) model system.

this simulation. This is consistent with Schoenlein et al.'s observation that “measurements on isorhodopsin show an initial photoproduct absorption by 200 fs, which continues to grow-in until 600 fs”² reinforcing the validity of our model simulation.

Our simulation confirms the experimental observation that the photoisomerization to the all-trans chromophore is slower than that of rhodopsin and at a lower quantum yield. We point out the existence of an energetic barrier to the C₉–C₁₀ twist coordinate in the excited state as the main reason for the delay and reduction in the generation of the all-trans isomer from isorhodopsin. Since these features are captured in a gas-phase simulation, it appears that these are intrinsic properties of the chromophore that may be altered, but not necessarily triggered by the surrounding environment of the retinal chromophore in the process of vision.

The energetics shown in Figure 2 suggests that once the barrier in the excited state is surmounted, the molecule has access to the conical intersection region that presumably controls the branching ratio between the 9-cis and all-trans photoproducts. At the conical intersection, the reactive ϕ_9 torsion coordinate is twisted further to $\sim 90^\circ$ from $\sim 0^\circ$ at the S_1 minimum and $\sim 26^\circ$ at the S_1 saddle point.

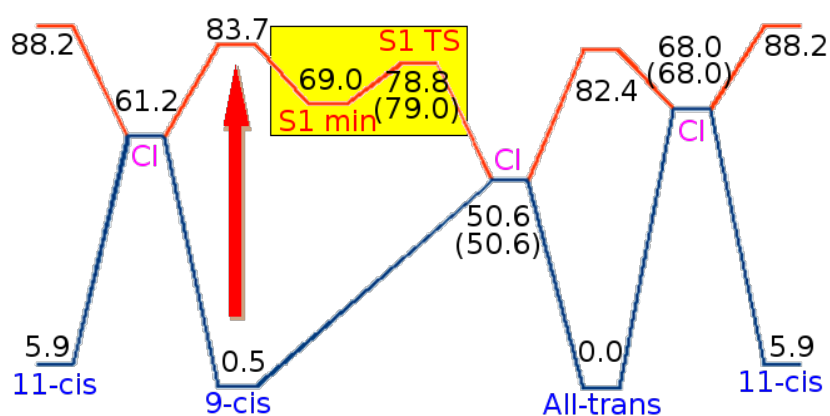


Figure 2. Energy diagram for the cis-trans isomerization of retinal. Energy is in kcal mol⁻¹.

The processes that occur from photoexcitation to ground-state relaxation of the PSB of isorhodopsin in the gas phase are summarized as follows:

1. The C₉=C₁₀ bond R₉ is stretched to a single bond and the torsion coordinate ϕ_9 is twisted to as far as $\pm 30^\circ$ after photoexcitation.
2. The bond oscillates between single- and double-bond character while ϕ_9 also oscillates within $\pm 30^\circ$ while being trapped in the S_1 well.
3. The barrier is surmounted and crank shaft motion of the two angles of ϕ_9 and ϕ_{11} occurs toward the transition point to the ground state. The R₉ bond is predominantly single bond in character during transition. When $|\phi_9|$ is greater than about 70° at the transition point, an all-trans photoproduct is likely to result.
4. The molecule relaxes in the ground state as R₉ shrinks back to a double bond and $|\phi_9|$ approaches 0° and 180° depending on the resulting photoproduct.

References

- [1] Schoenlein, R. W.; Peteanu, L. A.; Mathies, R. A.; Shank, C. V. *Science* **1991**, *254*, 412-415.
- [2] Schoenlein, R. W.; Peteanu, L. A.; Wang, Q.; Mathies, R. A.; Shank, C. V. *Journal of Physical Chemistry* **1993**, *97*, 12087-12092.
- [3] Hurley, J. B.; Ebrey, T. G.; Honig, B.; Ottolenghi, M. *Nature* **1977**, *270*, 540-542.
- [4] Ishida, T.; Nanbu, S.; Nakamura, H. *Journal of Physical Chemistry A* **2009**, *113*, 4356-4366.
- [5] Strambi, A.; Coto, P. B.; Frutos, L. M.; Ferre, N.; Olivucci, M. *Journal of the American Chemical Society* **2008**, *130*, 3382-3388.