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Mechanisms of Photoisomerization of Polyenes in Confined Media: From Organic Glasses to Protein Binding Cavities†

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ABSTRACT

Photochemical reactivities of model organic systems (stilbene and diphenylbutadiene) in organic glasses were first examined and compared with those in solution and in organized media. These observations were in turn compared with reactivities of polyene chromophores in protein binding cavities (specifically PYP, rhodopsin and bacteriorhodopsin). The obvious conclusion is that the preference for the most volume-conserving Hula-twist mechanism isomerization in organic glasses is because of the close interaction between the guest and the host molecules. In organized media (zeolites, crystals and protein binding cavities), the residual empty space coupled with any specific guest–host interactions that are characteristic of a given system, could lead to involvement of the more volume-demanding one-bond-flip (*i.e.* torsional relaxation) or bicycle-pedal or an extended HT process in photoisomerization.

INTRODUCTION

Torsional relaxation according to the Mullikan's energy diagram for ground and excited states of ethylene has been the long accepted mechanism for photochemical *cis*,*trans* isomerization (1). However, ever since the first pico-second time-resolved study on rhodopsin photochemistry (2), the question how the very volume-demanding torsional relaxation process which involves turning over of at least one-half of the chromophore can take place in the rigid binding cavity was raised. The latter is particularly relevant in view of the short lifetime of the excited chromophore. Therefore, other mechanistic concepts have been introduced in recent decades that are not as volume-demanding as torsional relaxation. (To emphasize the rotation around one double bond in a polyene system, the latter process has also been labeled as one-bond-flip, OBF (3).) (Fig. 1) Warshel first introduced the bicycle-pedal process (BP) in which two alternating double bonds rotate simultaneously while keeping the remaining parts of the molecule in-plane (4). The predicted stereochemical consequence of one-photon-two-bond isomerization, however, was not in agreement with nearly all available experimental evidence obtained with protein bound or solubilized chromophores. Subsequently, the Hula-twist (HT) concept was introduced by the Hawaii group (3), in which a pair of adjacent double and single bonds, flanking a single C–H unit, rotates concertedly. The predicted stereochemical consequence is simultaneous configurational isomerization of a double bond and conformational isomerization of an adjacent single bond. The first unambiguous example demonstrating the predicted stereochemical consequence of HT was reported by Fuss and coworkers (5). Many more organic molecules executing HT photoisomerization in organic glasses have since been described in the literature (6–8).

There are, however, less definitive words concerning the exact mechanism of isomerization of photosensitive protein-bound polyene chromophores. Since, one by one, the primary photoproducts of many protein bound polyene chromophores are being defined by exact structural tools, now appears to be an appropriate time to examine the mechanisms of the primary processes in each case. Such questions are in fact part of a general issue of possible mechanisms of isomerization in different host systems (9). In this paper, we shall provide an over-view of mechanisms of photoisomerization conducted in a variety of media. While some new experimental evidence will be introduced, this paper is largely a critical review of existing information in the literature.

RESULTS

We have carried out photoisomerization of isomers of 1,4-diphenyl-1,3-butadiene (DPB) under three different experimental conditions: in solution, organic glass and in crystal. The results are described separately below.

Irradiation of DPB in solution. Detailed photoisomerization studies of isomers of DPB in solution are available in the literature (10). We have confirmed their conclusion that for direct irradiation, the isomerization takes place one double bond at a time starting from any one of the three isomers producing eventually a mixture of all three isomers. The data for the c,c isomer is shown in Fig. 2. Because of the efficient conversion of the c,t isomer to the t,t, the accumulation of the intermediate c,t isomer was not immediately obvious.

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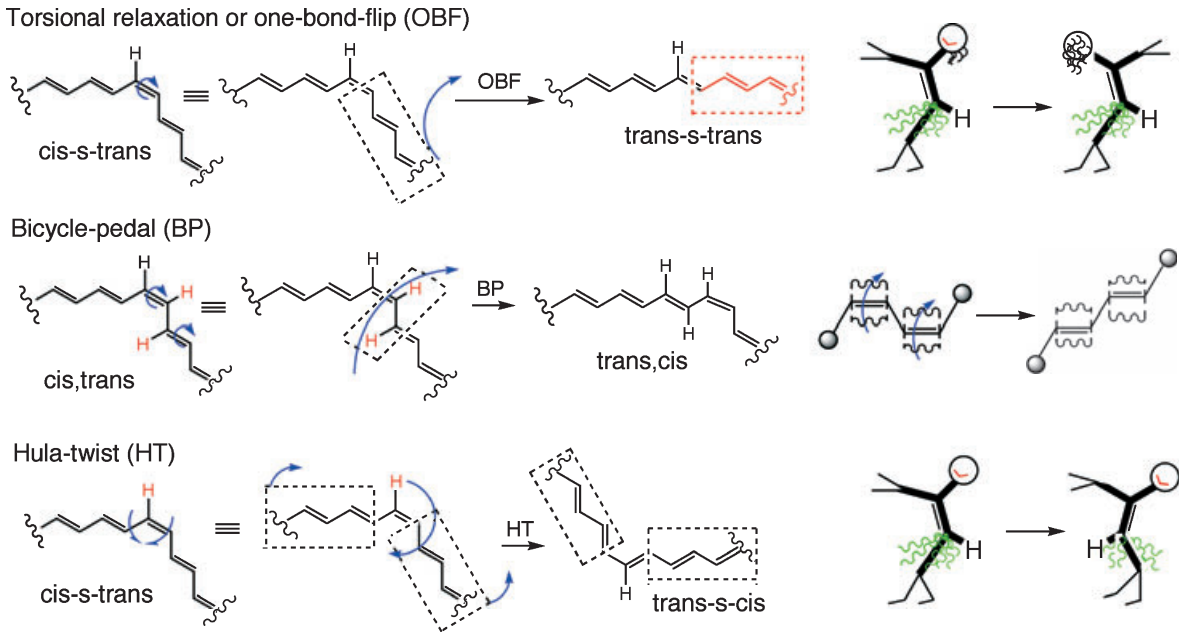


Figure 1. Three possible mechanisms of photoisomerization. Top: torsional relaxation where one-half of the molecule flips around the formal double bond (or one-bond-flip, OBF). Middle: the bicycle-pedal (BP) process that results in isomerization at two formal double bonds. Bottom: the Hula-twist (HT) that results in configurational isomerization at one double bond and conformational isomerization at an adjacent single bond. The cartoon figures on the right emphasize the parts that change in space.

However, it is clear that the initial difference in spectrum was rather featureless (characteristic of a *cis* product) which is different from that of c,t (see Fig. 3 below).

Irradiation of 1,4-diphenyl-1,3-butadiene in organic glasses. Preliminary results on irradiation of 1,4-diphenyl-1,3-butadiene (DPB) isomers in organic glasses at liquid nitrogen temperature were reported earlier (11). Below we describe some of the observations on each isomer in detail.

The t,t isomer of DPB was found to be un-reactive in EPA (ether: isopentane: ethanol = 5 : 5 : 2) glass at 77 K. This observation is consistent with what is known for diarylethylenes (12). On the other hand, both the c,t or the c,c isomers of DPB were found to be reactive under the same condition. For c,t-DPB, the conversion to the t,t isomer was a clean one-to-one conversion (Fig. 3). On the other hand, for the c,c isomer the conversion to the t,t is clearly stepwise going through an initial product with a featureless absorption band (consistent with the c,t isomer) (Fig. 4).

Irradiation of DPB crystals. Small crystals of three isomers of DPB were irradiated with >300 nm light (Pyrex filter). Progress of reaction was followed by dissolving small amounts of the powder and analyzed by HPLC or by H NMR (10,11). Both the t,t and the c,t crystals were found to be un-reactive under the UV light. However, crystals of the c,c isomer were found to undergo stereospecific isomerization to the t,t isomer. We interrupted irradiation at early stages of irradiation with conversions ranging from 10–15%. It was clear that the c,t isomer was never present throughout these periods of irradiation (based on hplc and H NMR analyses of dissolved crystals). This photochemical behavior was also observed in isomers of two derivatives of DPB: *p,p′*-difluoro-DPB and *p,p′*-dimethoxy-DPB.

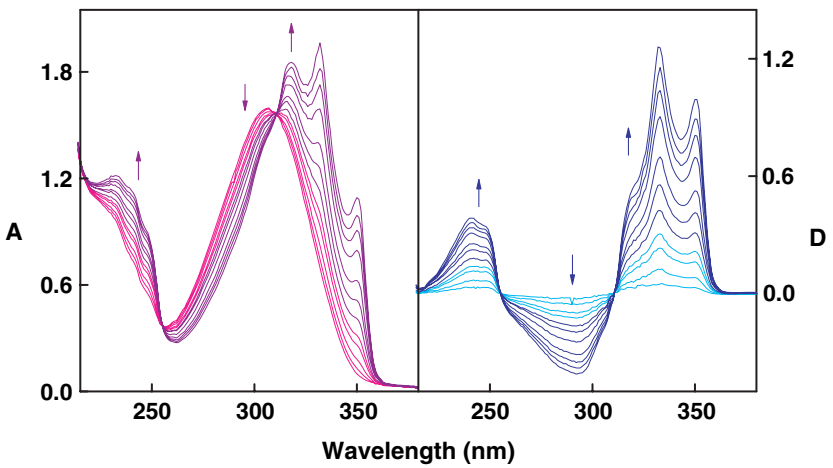


Figure 2. Changes in UV absorption spectra of c,c-DPB in EPA solution at 200 K with Corning O-54 filter (>310 nm). Left: absorption spectra. t = 0, 2, 4, 6, (in red) 8, 12, 17, 23, 43, 53, 73 s (in purple). Right: difference spectra from left (aqua for the early periods). Notice the featureless broad spectrum at the earliest stage of irradiation indicating possible formation of a *cis* isomer (*i.e.* c,t).

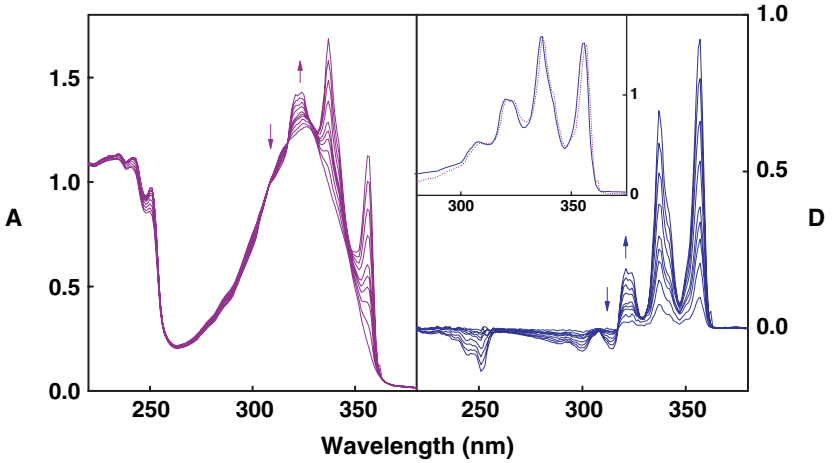


Figure 3. Changes in UV absorption spectra recorded during irradiation of c,t-DPB in EPA glass at 77 K with O-54 filter. Left: absorption spectra. t = 0, 30, 80, 140, 220, 310, 550, 790, 1030 and 1250 s. Right: difference spectra after the same time intervals. Notice the appearance of fine structure at the earliest stage of irradiation (blue) showing formation of the t,t-isomer. Insert: absorption spectra of the photoproduct before (solid line) and after (dashed) warming to room temperature and re-cooling to 77 K.

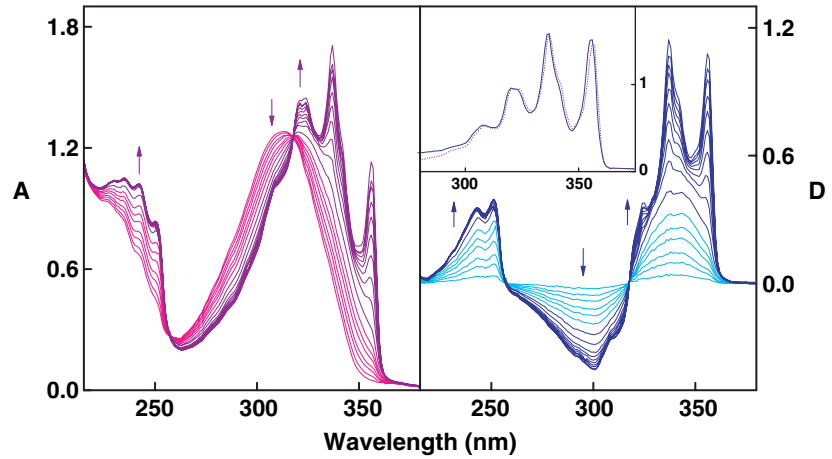


Figure 4. Changes in UV absorption spectra of c,c-DPB recorded during its irradiation in EPA glass at 77 K with >310 nm light. Left: absorption spectra. t = 2, 6, 10, 20, 30, 50, 110 (in red), 230, 350, 470, 590, 710, 830, 950, 1010 and 1250 s (purple). Right: difference spectra. Aqua, early stage of irradiation; blue, late stage of irradiation. Notice that the fine structures only appeared at later stages. Insert: absorption spectra of photoproduct before (solid) and after (dashed) warming to rt and re-cooling to 77 K.

Since the unusual two-bond isomerization of the c,c isomer is different from that of the crystals, we proceeded to determine the crystal structures of two c,c-DPB's (Figs. 5 and 6).

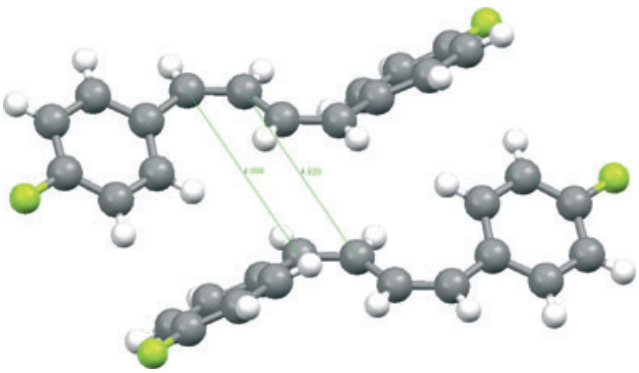


Figure 5. The X-ray crystal structure of c,c-*p,p'*-difluoro-DPB. The distance between the diene units in two molecules is 4.908 Å.

DISCUSSION

Formation of unstable products during irradiation of isomers of DPB only in a low temperature glass (Figs. 3 and 4) showed that these unique photochemical properties are associated with the restricting media. Similar unstable products were also obtained for styrenes (7) and dienes (8) in organic glasses. It became logical to ask whether such photochemical observations are to be expected in other confining media such as zeolite, crystals and even the binding cavities of proteins. Earlier, one of us (9) reasoned that the reaction sites within the amorphous media of organic glasses are very different from those of the organized media. The collapsing solvent cage surrounding a substrate during the course of freezing must be constantly changing in shape accompanied by a decrease in the size of the enclosed cavity. On the other hand, for an organized medium, the shape of the cavity is defined by the unique architecture of the host molecule. It is usually rigid in shape and the confined cavity is not likely to change much with temperature or after occupancy of a substrate molecule or

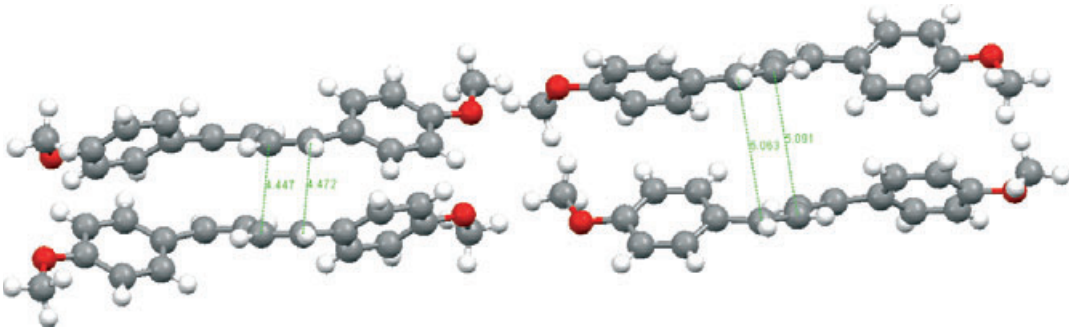


Figure 6. The X-ray crystal structure of c,c-*p,p′*-dimethoxy-DPB. The distances between the double bonds of two sets of non-equivalent molecules average: 4.46 and 5.08 Å.

other (*e.g.* solvent) molecules. In most cases, the guest molecules are usually introduced into the cavity through diffusion. There is no reason to suspect that the binding cavity can be fully occupied (unless there are unique specific attractive interactions), leaving the possibility of substantial unfilled space. The residual space can be filled by solvent molecules if they were present at the time when the substrate was introduced. This would suggest that for an organized host, the inhibiting effect of the wall of the host cavity is likely to be less than that of an amorphous organic glass. However, it should also be recognized that specific interactions between part of the "walls" of the organized hosts with the substrate molecules could dictate the manner of photochemical transformation of the substrate (specifically the isomerization pathway) in that particular guest-host pair. We would like to examine available experimental evidence that might shed light to these generalizations.

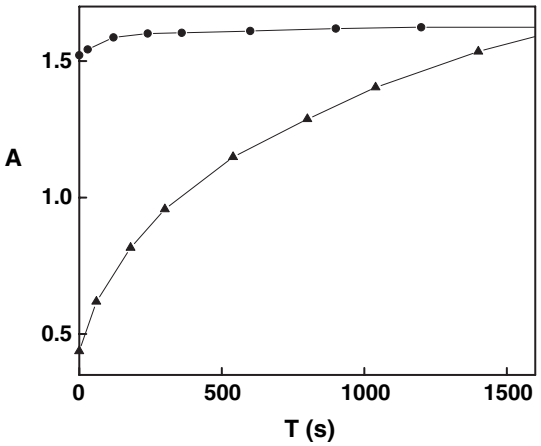


Figure 7. Changes of absorbance at 305 nm during irradiation (>310 nm) of isomers of stilbene at 77 K in EPA glass: round dots, *trans* isomer; triangles, *cis* isomer. The slight rise in absorption during early stage of irradiation of the *trans* isomer was probably due to local thawing and re-freezing (15).

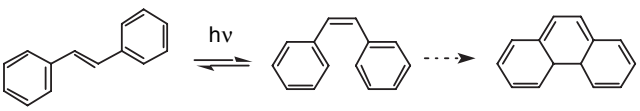
Photoisomerization of simple organic polyenes

Stilbenes and 1,4-diphenylbutadienes. 1,2-Diphenylethylene, or stilbene and 1,4-diphenylbutadiene (DPB) are model organic compounds frequently used for studies of the photoisomerization reaction. It will be of interest to compare their photochemical behavior in solution and in various confined media.

In the case of the stilbene, ample data are available in the literature (13). In solution, its two isomers, upon direct irradiation, undergo ready inter-conversion giving a photostationary state containing the two isomers. Additionally, there is a slower 6e-cyclization reaction from the *cis* isomer giving the colored dihydrophenanthrene (not formed in low temperature glass). Upon increase of solvent viscosity, it is known that the *trans* to *cis* photoisomerization becomes progressively less efficient (14). Eventually, in frozen media, the reaction stopped completely giving way to a high fluorescence yield of the *trans* isomer. The *cis* isomer, however, retained partly (~30% at 77 K in EPA) (6) its photoreactivity. Hence, in a low temperature glass, the eventual product mixture, or the photostationary state mixture, contained only the *trans* isomer (Fig. 7).

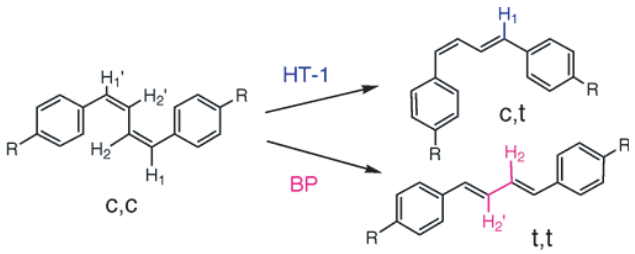
Because of its symmetrically substituted rings, for stilbene, it is not possible to ascertain whether the low temperature isomerization of the *cis* isomer proceeds by way of the OBF process (torsional relaxation) or the volume-conserving HT process. However, if one infers from the results of *o*-substituted stilbenes (6,15), it seems safe to conclude that in a low temperature glass *cis*-stilbene also isomerizes by way of HT.

Ramamurthy *et al.* described results of photoisomerization of stilbene imbedded in the Na Y zeolite (16), prepared by the interaction of the vacuum heated zeolite with a hexane solution of *t*-stilbene. Ready photoisomerization was observed, yielding an eventual photostationary state mixture identical to that of a hexane solution of stilbene. In other words, confinement did not lead to reduced efficiency of *trans* to *cis* isomerization. It is a clear indication that the wall of the zeolite must be too remote to provide any inhibiting effects to the stilbene substrate. And, any void space in the zeolite cavity must have been filled by hexane molecules.

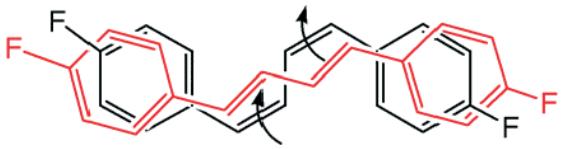


For DPB isomers, the three isomers are known to undergo ready photochemical inter-conversion in solution giving a photostationary state mixture containing all three isomers (10). For direct irradiation, the isomerization takes place one double bond at a time. However, under the confined condition of organic glass, the t,t isomer is photostable while the c,t and c,c

isomers isomerize readily. Thus, prolonged irradiation resulted in exclusive formation of the t,t isomer. That a stable t,t isomer was obtained from c,t-DPB (insert of Fig. 3) indicates that the reaction did not proceed by the way of HT-2 isomerization. The HT-1 process however gives the same stable t,t isomer as the OBF process. Only after the use of *o,o′*-disubstituted DPBs (11), the latter was successfully eliminated. Therefore, same as *cis*-stilbene, the isomerization reaction has taken place in the least volume-demanding HT manner for the more restricting media of organic glasses. And, for c,c-DPB in EPA glass, the reaction proceeded sequentially first yielding the stable c,t isomer then the t,t isomer culminated with the structured absorption band that is characteristic of the t,t isomer (Fig. 4).



In organic crystals, the isomers of DPB exhibited different photoreactivities: the c,t isomer being photostable while the c,c isomer isomerizing stereospecifically to the t,t isomer. The cause for the latter new photochemical reactivity becomes evident when one compares the crystal structure of c,c-DPB with different conformers of t,t-DPB. Only the s-*trans* conformer (red) is close in shape with that of the stable conformer of the c,c isomer (black). In crystals, the molecule is likely to be "anchored" at the two bulky ends (no room for rotation of the phenyl groups), leaving considerable intermolecular space between the connecting butadiene chains (Figs. 5 and 6). It allows rotational motions of these atoms in the form of volume-conserving bicycle-pedal (BP) process for the conversion of c,c-isomer directly to the t,t-isomer. As no flipping over of the phenyl rings is involved, it is a least motion process in the chemical transformation.



It should be noted that bond order reversal upon light excitation facilitates this two-bond isomerization process. Furthermore, the observed reaction is an energy down-hill c,c to t,t conversion that conveniently overcomes any activation energy suspected to be present in a BP process of an excited polyene as shown by the MNDO calculations (17).

The bulky phenyl end groups in the crystal prevents the molecule from undergoing the OBF process of which one of the two phenyl rings must turn over. The HT process is also not favored, most likely due to the substantial lateral displacement of the phenyl ring involved in such a process (Fig. 1). Consequently, the BP process presents itself as a least motion compromise, uniquely fitting within the intermolecular empty space present in c,c-DPB crystals.

Other organic examples of bicycle-pedal process motion in the literature. There are, in fact, other examples of two-bond isomerization in the literature. Several years ago, the direct conversion of c,c muconate salt (**1**) to its t,t isomer was reported (18) (Fig. 8c), the first example of two-bond BP isomerization. It is closely related to the current case of c,c-DPB in that both involve stereospecific conversion from the higher energy c,c isomer to the t,t isomer. In 2003, the surprising result of conformation flexibility in crystals of *trans*-stilbene and *trans*-azobenzene was described (19). The rotation of the ethylenic unit is in fact a BP motion (Fig. 8a) turning simultaneously, in this case, two alternating single bonds (for a ground state process). These observations underscore the large intermolecular space present around the ethylenic unit, made possible by the bulky end groups (the phenyl groups), a situation similar to those in crystals of c,c-DPB and muconate salt.

It should also be pointed out that the photoisomerization observed in crystals of the photochromic salicylideneaniline (**3**) (20) and *trans*-dibenzoylethylene (**4**), crystals (21) are likely the result of BP motion of the ethylenic bond coupled with a nearby single bond (see red arrows). (HT was proposed for the

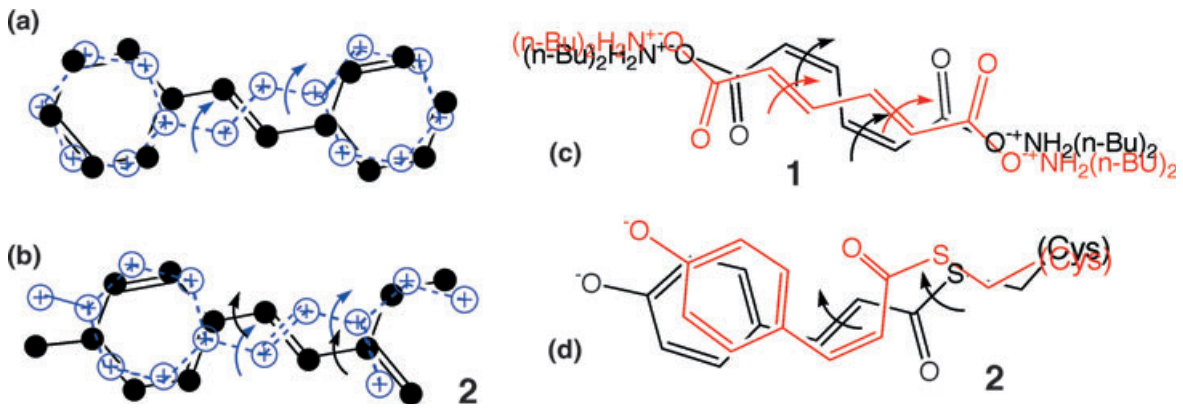
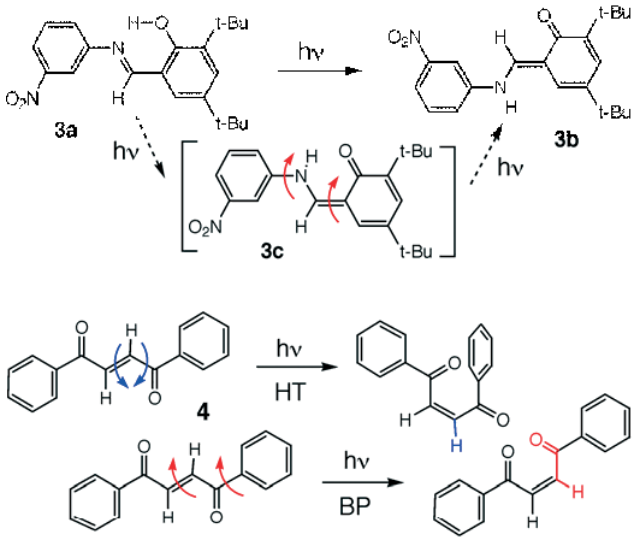


Figure 8. The common bicycle-pedal-like motion in four different systems. Ground state conformational equilibration in crystals of (a) t-stilbene (19) and (b) the *trans* thiocinnamate (**2**) chromophore in crystals of PYP (26); (c) photoisomerization of c,c-muconate salt (**1**), black, to the t,t-isomer, red (18) and (d) photoisomerization of the thiocinnamate chromophore of PYP (**2**), black, to the *cis* isomer, red (24,25).

latter (21).) Both examples are in reality a double bond twist coupled with a nearby single bond twist, however, rotating the middle two-carbon fragment in a manner similar to a BP process. We might add that in a recent conference report, Harada reached the similar conclusion in their X-ray crystal study of (**4**) (22).

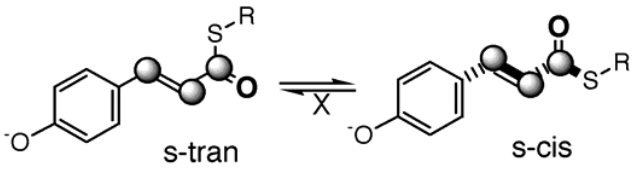


Photoisomerization of polyene chromophore within protein binding cavities

Protein binding cavities are also host systems with rigid, well-defined structural framework. Hence, they are similar to cavities in organic crystals that are usually larger than the substrates that they accept. Thus even when a protein binding site is "filled," there should still be empty space surrounding the trapped substrate for reaction. Hence, the surrounding environments cannot be as restrictive as the collapsing solvent molecules in formation of organic glasses. We would like to show below that the recently reported photochemical structural studies of three photoactive pigments (photoactive yellow protein, rhodopsin and bacteriorhodopsin) revealed larger empty space available for reaction for each case. In fact, their primary photochemical reactions are often dictated by the need to execute a least motion of the chromophore so as not to disturb the anchors that position the chromophore at the unique, defined position. (See below on implication of specific model of protein–substrate interactions.)

The photoactive yellow protein. The facile *trans* to *cis* isomerization of the small and anchored thiocinnamate chromophore (**2**) of photoactive yellow protein (PYP) within its binding cavity remains an exciting and unexpected observation. The specific nature of this conversion has become increasingly clear through several elegant steady state (23,24) and time-resolved X-ray crystallographic studies (25) on this protein.

The thiocinnamate chromophore was shown to exist exclusively in the s-*cis* ene-ester conformation. It is remarkably close in shape to those of *trans*-stilbene and azobenzene (Fig. 8a). Therefore, it is perhaps not surprising that a recent re-investigation of the crystal structure of PYP at low temperature revealed the presence of two conformers of the cinnamate chromophore which inter-convert at slightly elevated temperature (26). It involves the motion of connecting ethylenic unit only (around the dotted single bonds), equivalent to the BP-like motion in t-stilbene and t-azobenzene (see Fig. 8b). We emphasize that this observation again revealed a large empty space surrounding the ethylenic unit of the PYP chromophore.

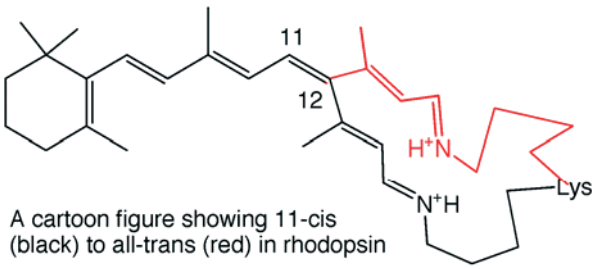


The exact nature of the photochemical transformation was made clear by the crystal structure of its primary photoproduct (24,25). The process takes advantage of the s-*cis* ene-ester conformation present in the pigment, that makes the single bond thioester linkage parallel to the alkene double bond (bold lines), a pre-requisite for BP-like motion. The structures of the chromophore before and after irradiation (according to crystallographic data) are shown in the form of overlaid bond-line structures (Fig. 8d): the *trans* to *cis* isomerization accompanied by flipping over of the carbonyl group of the thioester, an expected consequence of the BP-like motion. The motion is clearly shown in the overlaid structures (Fig. 8d). It involves motion only of the middle two-carbon fragment (an ethylenic carbon and the carbonyl carbon). It is a motion closely similar to that in t-stilbene except in this case a concerted rotation of only one formal double bond along with a single bond is involved (Fig. 8d). The clear advantage of such a transformation is that it does not lead to disruption of the cysteine (covalent) and phenoxy (ionic) anchors at the two ends. (Since only one double bond changes its configuration one might also label this process a modified OBF.) This isomerization mechanism is apparently uniquely fitting for the short, anchored chromophore of PYP. It should also be clear that the short Cys tether and the short chromophore do not permit a HT process that would lead to significant lateral displacement of either one of the anchors.¶

Rhodopsin photoisomerization. The HT concept was originally introduced (3) to account for the facile isomerization of the confined 11-*cis*-retinyl chromophore (black) in rhodopsin to the all *trans* form (red). (See structures below for the confined and anchored chromophores.) It requires the formation of an s-*cis* linkage (whether 10-s-*cis* or 12-s-*cis*) in the all-*trans* photoproduct. However, such a conformation was not detected in vibrational structural analyses of the stable photoproduct bathorhodopsin (28). Whether such an unstable conformation can be present in the unstable earlier intermediate photorhodopsin (29), as suggested by Fuss (5), remained

¶During the early stage of development of the concept of medium directed isomerization, one of us (Liu, 27) incorrectly suggested the involvement of HT process in the primary process of PYP pigment. The mistake was partly due to an incorrect interpretation, on his part, of the crystal structure of the photoproduct.

unanswerable. Subsequent theoretical studies (30,31) also suggested direct formation of the all-*trans* photoproduct with an s-*cis* linkage present only at the 6,7-single bond.



The crystal structure of rhodopsin became available in 2000 (32). In spite of the fact that its resolutions (2.8 and 2.5 Å) (33) are far from being sufficient in providing finer structural information such as exact conformational properties of the 11-*cis*-retinyl chromophore, there is much interesting new information derived from the structure.

A most unusual feature is the location of the retinyl chromophore. Instead of the anticipated location in the middle of the heptahelical bundle of the opsin binding site, it sits close to one end of the helical bundle (34,35). One side of it faces helix-3 and the other side faces the large trans-membrane loop that connects helices 4 and 5 (TM-4, 5). The loop, however, is rather rigid because of the presence of two disulfide linkages. Encircled by this large loop is a sizable empty space that was revealed in the crystal structure, as shown in Fig. 9. Only protein residues within 4.0 Å of either side of the 11-*cis* retinyl chromophore are shown. On the left side, the 11,12-*cis* linkage leans against helix-3 while on the right side, it faces virtually an empty space. It is known that the isomerization process starts

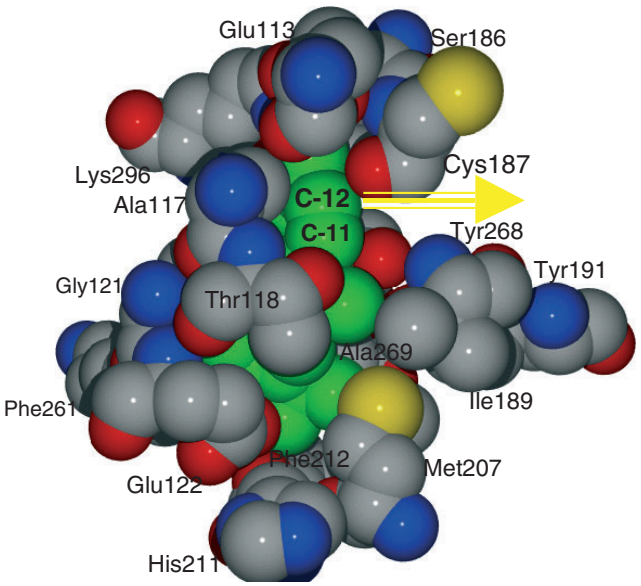


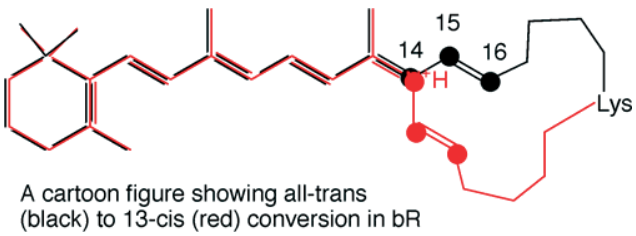
Figure 9. Partial crystal structure of rhodopsin (32) showing the amino acid residues surrounding the 11-*cis*-retinyl chromophore (green). Only atoms within 4.0 Å of the chromophore are shown. It is clear that the chromophore leans against helix-3 (amino acids 113–122) on the left while facing an open space on the right. The yellow arrow indicates the preferred direction of isomerization.

with the motion of the C–H_{12} fragment (36), a process made clear in the most recent ultrafast time-resolved RR study (37). The preferred direction of rotation of the C_{12}–H fragment to initiate isomerization must be into the empty space encircled by TM-4,5 (yellow arrow in Fig. 9). Again, we emphasize the presence of a large empty space surrounding the retinyl chromophore.

A crystal structure of bathorhodopsin, the primary product, has recently become available (38). A comparison of the structures of the 11-*cis*-retinyl chromophore in rhodopsin and the all-*trans*-retinyl chromophore in bathorhodopsin from the crystal structures revealed several interesting features. First, the 11,12 *cis* linkage, twisted even in rhodopsin (−41°) (27,28), rotates by 115° to another twisted structure in bathorhodopsin (−152°), much less than the usual 180° rotation in a *cis* to *trans* isomerization. This twist is negated by many small twists in the opposite direction of the nearby single and double bonds. As a result, it is possible for this lengthy chromophore to execute the OBF motion without disrupting either end of the anchors (the hydrophobic pocket for the cyclohexenyl ring or the lysine-iminium terminal). Given the empty space surrounding the chromophore mentioned above, the possibility of carrying out the usually volume-demanding OBF process is perhaps not surprising.

The empty space revealed by the crystal studies also required modification of the view on the underlying causes for the highly stereoselective recognition of the 11-*cis* retinal by the binding pocket of opsin. It is clearly not because of the snug interactions between the binding cavity and the substrate (the lock-&-key model). Rather, the recognition is achieved through the fulfillment of several key contact points (the lysine anchor, the hydrophobic pocket recognizing the ring, the 9-methyl recognition site, the protein wall near C-12 and the chiral twists of the polyene chain) as pointed out in a recent paper (39).

Bacteriorhodopsin (bR) photoisomerization. The primary photochemical process for bR is the all-*trans* (black) to 13-*cis* (red) isomerization of the imbedded retinyl chromophore (see structures below). An s-*cis* conformation was also suspected to be present in the primary photoproduct of bR (40). However, the more recent crystal structure of the stable early intermediate K (41) showed an absence of such a conformation.



We have now superimposed the crystal structure of the all-*trans*-retinyl chromophore structure of bR (42) with that of K (13-*cis*) (41) in Fig. 10. It is clear that the butyl tether is not fully extended in bR (especially twists at the 16,17 and 17,18 single bonds) which allows the conversion of the longer all-*trans* geometry (43) to the shorter 13-*cis* of the early K

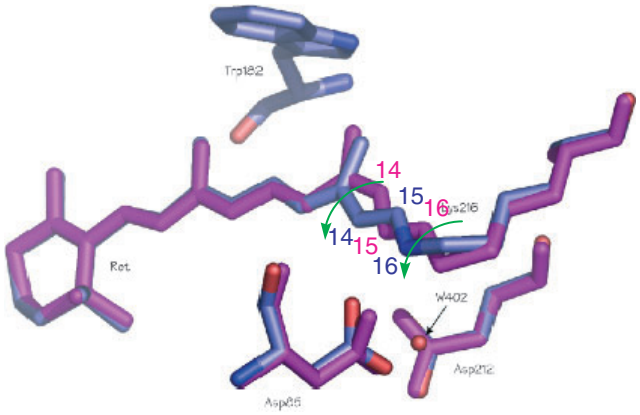


Figure 10. The all-*trans*-retinyl chromophore from crystal structure of bR (blue) (42) superimposed with the 13-*cis* chromophore from the crystal structure of the K intermediate (maroon) (41). Most of the atoms remain unperturbed with the exception of the marked 14, 15 and 16 segment of the conjugated chromophore that turned over during the transition from bR to K, through rotation at the two bonds shown (green arrows). Three of the closest amino acid residues are also shown.

intermediate, compensated by the stretching of butyl tether. The process involves significant movement of primarily C-14 and the 15,16-imino bond by turning over this segment of the conjugated system. In other words, it must have involved the rotation of the 13,14 formal double bond and the 16,17 single bond. The process can be viewed as an extended HT process (turning over of a three-carbon fragment rather than a one-carbon fragment). Apparently, the curved and anchored nature of the butyl side chain and the empty space surrounding the imino end of the conjugated system have made this unique process of photoisomerization the preferred one in bR.

CONCLUSION

Photoisomerization from the excited singlet state is a diabatic process proceeding directly from the excited potential surface to the ground state product. Different mechanisms of reactions are possible under different confined conditions for the reacting polyene. We argued that the close interactions between host molecules and the substrate in amorphous organic glasses have made the most volume-conserving HT process a preferred process of isomerization in such media. It differs from the common OBF process for photoisomerization under the non-restrictive condition of common solutions. In organized media (zeolites, crystal, protein binding cavities, *etc*.), the rigid host structures are likely to retain some empty space even when the cavity is occupied by a substrate. This residual empty space plus other specific interactions between the host and the substrate (*e.g*. specific points of recognition and the rigid anchors as well as the length of the chromophore and the appended tether) could lead to uniquely different photoisomerization mechanism(s) suitable for that particular pair of guest and host molecules. When coupled with a second single bond rotation, the usual volume-demanding OBF process can become part of a least motion process. Interestingly, for each of the three well-known photosensitive biopigments, a different mechanism of photoisomerization is involved: modified BP for PYP, OBF for rhodopsin and extended HT for bR. Thus, it is not surprising that the new photochemical results obtained in crystals of diphenylbutadienes and other reported studies of organic crystals are similar to that of a protein (specifically that of PYP).

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