Low-Temperature Photochemistry of Previtamin D: A Hula-Twist Isomerization of a Triene**

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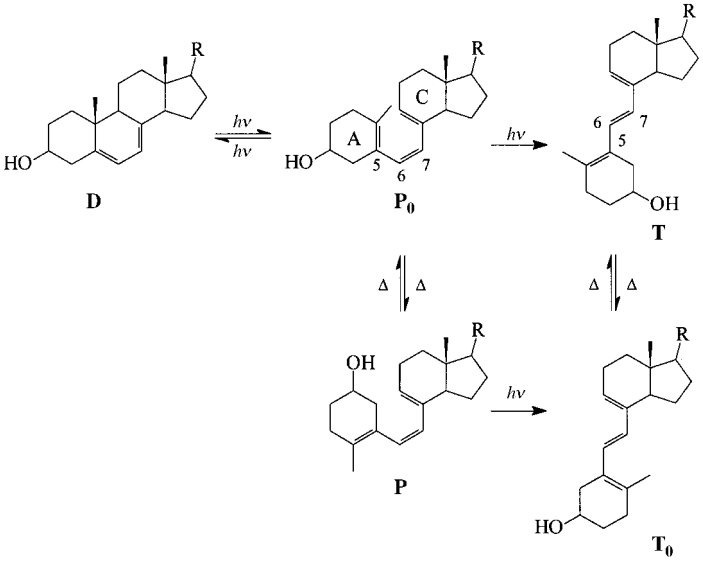
For the investigation of the stereochemistry of chemical reactions it is advantageous if the conformers of the compounds employed can be distinguished based on their substitution patterns. Previtamin D, a triene in the steroid series, offers this possibility. Thermal interconversion of the conformers **P** and $\mathbf{P_0}$ can be suppressed in a cold matrix. Already in 1983 Havinga and co-workers irradiated previtamin D in a matrix at 92 K and found that in the *cis–trans* isomerization an unstable conformer ($\mathbf{T_0}$) of tachysterol forms initially and converts to the stable form **T** only when warmed up (Scheme 1).[1] The two conformers, whose UV spectra are clearly different, were assigned based on their circular dichroism. Havinga et al.[1] assumed that $\mathbf{P_0}$ is the thermodynamically more stable form of previtamin D, that it dominates at low temperature, and hence that $\mathbf{T_0}$ forms from $\mathbf{P_0}$.



Scheme 1. Photochemical and thermal reactions in the previtamin D system. **D**: 7-dehydrocholesterol; $\mathbf{P_0}$ and **P**: s-*cis,Z,*s-*cis* and s-*trans,Z,*s-*cis* conformers of previtamin D, respectively; **T** and $\mathbf{T_0}$: s-*trans,E,*s-*cis* and s-*cis,E,*s-*cis* conformers of tachysterol, respectively. (Actually it is a group of conformers for each, because the molecules are not planar and can have different helical sense, and because in particular the A ring is flexible.[4]) The subscript 0 in $\mathbf{P_0}$ and $\mathbf{T_0}$ denotes the thermally less stable conformer. R = $CH(CH_3)CH_2CH_2CH_2CH(CH_3)_2$.

We have established by direct photochemical ring opening of 7-dehydrocholesterol **D** in the cold matrix that the starting material has a ringlike geometry (Scheme 1). We irradiated a solution of **D** in the solvent mixture "EPA" (diethyl ether/2-methylbutane/ethanol 5/5/2) at 90 K with UV pulses (70 μJ, 10 ns at 291, 293, 295, and 297.5 nm) from a frequency-doubled rhodamine 6G laser. The reaction was carried out in a 1-cm cell, which was cooled by liquid nitrogen and surrounded by a vacuum jacket, and was monitored in a UV spectrometer. Only the conversion rates of **D** and $\mathbf{P_0}$ were different at the different wavelengths used, in accord with their respective absorption cross sections. A spectrum of $\mathbf{P_0}$ was reported previously.[2]

After generation of $\mathbf{P_0}$ further irradiation directly yields the stable conformer **T** of tachysterol, which was identified by its structured UV spectrum[1] (Figure 1). Kinetic measurements

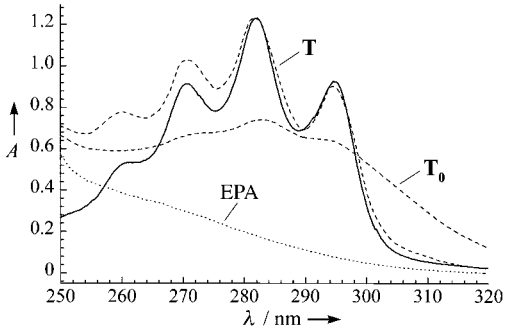


Figure 1. UV absorption of the two tachysterol conformers **T** and $\mathbf{T_0}$ according to ref.[1] (broken line; solvent absorption supposedly not subtracted, 92 K) and the spectrum of the final product of the irradiation at 90 K (solid line; absorption of EPA subtracted). *A*: absorbance; λ: wavelength.

on the previtamin D system indicate that thermal reactions are frozen out in the cold matrix.[3] Not the activation energy (16 kJ mol^{-1}) but rather the solvent viscosity η is mainly responsible for suppressing the conversion $\mathbf{P_0} \rightarrow \mathbf{P}$, whose rate is $\propto \eta^{-1}$.[3] The fact that we obtained a different product than Havinga et al.[1] implies that the starting compounds were different, too. Since the reaction we observed corresponds to $\mathbf{P_0} \rightarrow \mathbf{T}$, the process they observed[1] must be $\mathbf{P} \rightarrow \mathbf{T_0}$ (see Scheme 1). Furthermore it can be concluded that **P** is more stable than $\mathbf{P_0}$; this is consistent with the observed isomerization $\mathbf{P_0} \rightarrow \mathbf{P}$[3] and with some results[4, 5] of the force-field calculations.[4–6] Previous opinions about the relative stabilities of **P** and $\mathbf{P_0}$ were not uniform.[7] It should also be pointed out that tachysterol can form from both conformers of previtamin D, in contrast to the widespread opinion[4, 8] that $\mathbf{P_0}$ is only capable of ring closure.

It is evident from the positions of the methyl and hydroxyl groups that in the two *cis–trans* isomerizations the A ring reorients by 120° *without leaving the plane* (Scheme 1). This is reminiscent of the *cis–trans* isomerizations of Schiff bases by inversion at nitrogen. Inversion at carbon is, however, not possible. With the help of ball-and-stick models one can find another way (Scheme 2): Twisting C^6H and C^7H by about +45° and −45°, respectively, out of the plane only induces minor changes in the positions of the rings (Scheme 2b). When C^6H is turned a further 90° around the axis indicated by the broken line (Scheme 2c), the A ring reorients by 120° within the plane. Finally both CH groups can turn back into

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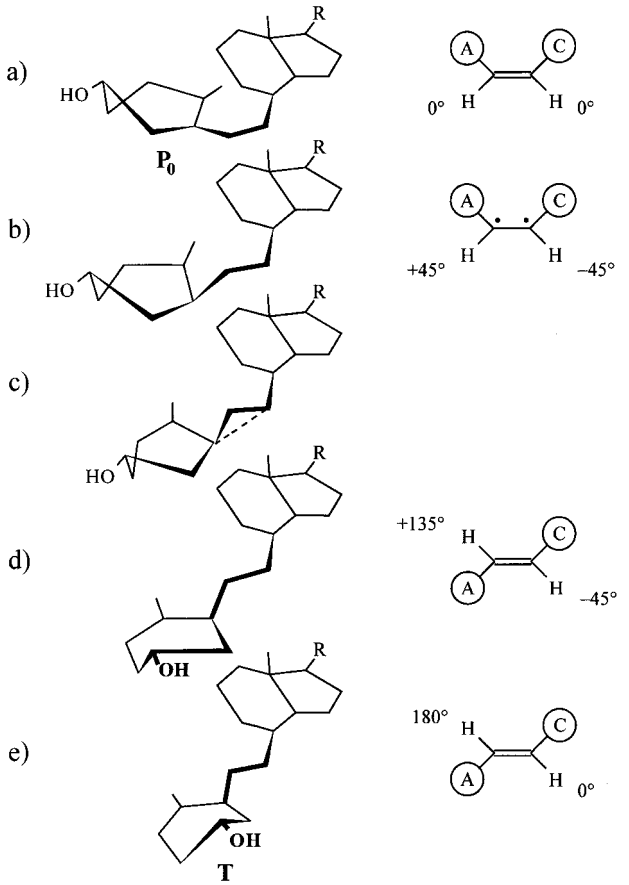

Scheme 2. Proposed geometrical pathway for the *cis–trans* isomerization. Only the C^6H group rotates substantially out of the plane, whereas the remaining parts of the molecule stay more or less in the plane while they reorient. The angles 0° and 180° only denote the planar reference geometry; the actual molecules in a) and e) are twisted for steric reasons.[4] The remaining angles are also only approximate.

the plane. A characteristic feature of this process is that only C^6H rotates substantially out of the plane. An equivalent description invokes the simultaneous rotation of the double bond and an adjacent single bond.

Our proposed mode of motion requires substantially less volume than the conventional concept, in which the terminal ligands move along a cone with an aperture of 120°. Hence this mode is possible even in a matrix. It was also postulated for rhodopsin[9, 10] and called a hula-twist isomerization, since only the central part of the molecule rotates. This mode of isomerization was proposed to rationalize how in the restricted opsin matrix the stiff polyene chain of the retinal chromophore can isomerize around a central double bond.[9, 10] The example presented here is the first experimental demonstration of the hula-twist isomerization.

Since the reaction $\mathbf{P_0} \rightarrow \mathbf{T}$ proceeds in a cold matrix, the hula-twist isomerization apparently has no appreciable activation energy. (The formation of tachysterol at low temperature is irreversible;[9] in other words, the back reaction seems to have an activation energy.) Hence the isomerization can also occur at higher temperatures and outside of a matrix. We assume that it probably corresponds to the normal path of *cis–trans* isomerization based on the following consideration.

Ultrafast photoreactions, including the *cis–trans* isomerization of hexatriene[11–13] and other polyenes, proceed along a continuous path from the upper (S_1) to the lower (S_0) potential energy surface. The transition from S_1 to S_0 occurs at a cone-shaped intersection of the two surfaces.[14–16] The molecular geometry at the conical intersection can be calculated by quantum chemistry. Remarkably, such calculations predict that this point on the potential energy surface (of 1,3,5-hexatriene) corresponds to a triangular substructure of the molecule similar to that in Scheme 2c, in which all the ligands are outside of the plane of the triangle and a bonding interaction exists between C^5 and C^7 (broken line in Scheme 2c).[17, 18] This prediction is shown in Figure 2 for (*Z*)-hexatriene. Thus quantum chemistry also

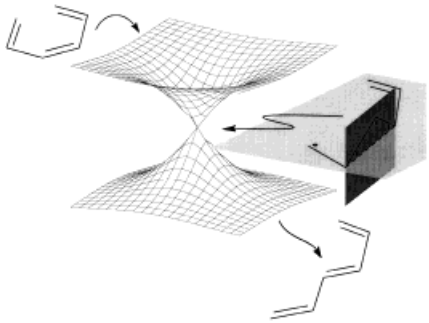

Figure 2. Transition from the excited to the ground state potential energy surface and associated geometries of (*Z*)-hexatriene.[17, 18]

supports the hula-twist mechanism and links it to the conical intersection and thus to electronic rather than steric effects. Since this three-center bond was found as an intermediate substructure for all polyenes calculated (butadiene to octatetraene),[18] it must be assumed that this pathway is standard for the *cis–trans* isomerization of nonpolar polyenes. Furthermore it is worth noting that the observed stereochemistry is the first experimental confirmation of the geometry predicted for a conical intersection.

A previous alternative proposal for a volume-saving isomerization ("bicycle-pedal mechanism") postulated the simultaneaous twist of two *double* bonds.[19] Our experiments do not allow a conclusion about this pathway since the terminal double bonds in previtamin D are sterically fixed. However, semiempirical calculations predict that the barrier for this path is higher in the excited state than in the ground state.[20] One argument against the hula-twist mechanism was that the expected conformer of bathorhodopsin, an intermediate of the rhodopsin isomerization, was not found by resonance Raman spectroscopy.[21] However, according to a previous proposal[22] the initial product is photorhodopsin which forms within about 100 fs,[23] whereas bathorhodopsin appears only within picoseconds.[24, 25] This period of time is long enough for single-bond isomerization in the ground state; therefore, a modified bicycle-pedal rotation of two single bonds can minimize the spatial demands according to ref. [10c]. Recent quantum chemical calculations indicate that the pentadieniminium cation has a conical S_1/S_0 intersection with a structure in which only the central double bond is

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twisted by 90°.[27] This ion can serve as a model for the protonated Schiff base of retinal present in rhodopsin. In contrast to nonpolar polyenes, in highly polar double-bond systems no electronic reason exists for a hula-twist pathway, although steric reasons for it persist.

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[25] In work other than ref. [23] (for example in ref. [26]) it is observed that in the 100-fs range a "hot" primary product initially forms which then assumes a more stable conformation and simultaneously cools down in the ps range. According to experience with hexatriene[12] the internal rotation in the hot primary product cannot be suppressed by cold solvent. We propose denoting only the (freezable) conformationally relaxed product as bathorhodopsin; only this product has been shown to have an all-*trans* configuration.[21]
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Activation of P_4 and P_2 by Transition Metal Complexes at Room Temperature**

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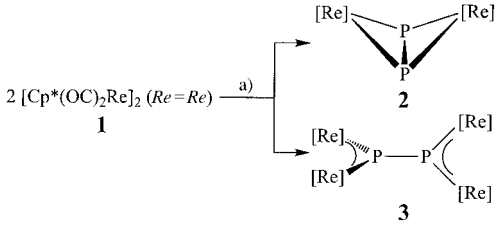
Dedicated to Professor Achim Müller on the occasion of his 60th birthday

The most important source of phosphorus for the preparation of complexes with P_n ligands[1] is white phosphorus P_4. The activation and cleavage of its P – P bonds[2] can be achieved in the presence of transition metal complex fragments both thermally at 60 – 190 °C as well as photochemically.[1]

The dropwise addition of a solution of white phosphorus in toluene to the dirhenium complex **1**[3] (Scheme 1) at room temperature gave, in addition to traces of complex **2**,[4] the tetranuclear complex **3** with a diphosphinidene ligand in approximately 40 % yield.



Scheme 1. P_4 activation at room temperature. a) P_4 (0.5 equiv), toluene, room temperature. [Re] = $Cp^*(CO)_2Re$.

The structures of **2** and **3** can be generally formulated as **C** (P_2 formally as a four-electron donor) and **D** (P_2 formally as an eight-electron donor), respectively. The structure type **C** with a P_2M_2 butterfly framework is relatively rare; it is observed for ML_n transition metal complex fragments with 14 and 16 valence electrons (VE).[1, 4] With 15-VE-ML_n complex fragments, polyhedra with P_2M_2 tetrahedrane frameworks are formed, which have been studied in detail.[1] In both cases the P_2 ligand is coordinated side-on as a π-electron donor

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[+] X-ray crystal structure analyses.

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