An experimental and quantumchemical study on the mechanism and stereochemistry of photochemical [1,3] sigmatropic shifts

Citation for published version (APA):
Peijnenburg, W. J. G. M. (1988). *An experimental and quantumchemical study on the mechanism and stereochemistry of photochemical [1,3] sigmatropic shifts*. [Phd Thesis 1 (Research TU/e / Graduation TU/e), Chemical Engineering and Chemistry]. Technische Universiteit Eindhoven. https://doi.org/10.6100/IR284815

DOI:
10.6100/IR284815

Document status and date:
Published: 01/01/1988

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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AN EXPERIMENTAL AND QUANTUMCHEMICAL STUDY ON THE MECHANISM AND STEREOCHEMISTRY OF PHOTOCHEMICAL [1,3] SIGMATROPIC SHIFTS

W.J.G.M. PEIJNENBURG

AN EXPERIMENTAL AND QUANTUMCHEMICAL STUDY ON THE MECHANISM AND STEREOCHEMISTRY OF PHOTOCHEMICAL [1,3] SIGMATROPIC SHIFTS

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR
AAN DE TECHNISCHE UNIVERSITEIT EINDHOVEN,
OP GEZAG VAN DE RECTOR MAGNIFICUS,
PROF. DR. F.N. HOOGE, VOOR EEN COMMISSIE
AANGEWEZEN DOOR HET COLLEGE VAN DECANEN
IN HET OPENBAAR TE VERDEDIGEN OP DINSDAG
21 JUNI 1988 TE 16.00 UUR

door

WILHELMUS JOZEF GERARDUS MARIA PEIJNENBURG

geboren te Boxtel

DIT PROEFSCHRIFT IS GOEDGEKEURD DOOR

DE PROMOTOREN

PROF. DR. H.M. BUCK

EN

PROF. DR. J.W. VERHOEVEN

Aan mijn ouders

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Chapter 1

General Introduction.

1.1 Mechanistic Organic Photochemistry

In general photochemical processes may be defined as transitions from an electronically excited state to yield structures of different constitution or configuration than the original ground state molecule[1]. The essence of a photochemical process is that activation for reaction is provided by the absorption of a photon.
A photochemical reaction differs from a thermal reaction in at least two fundamental ways:

1. In general photochemical activation is more specific than thermal activation; a photon of particular energy, corresponding to a particular wavelength, will only excite a chromophore capable of absorbing at that specific wavelength. This chromophore in its turn may be only a small part of a large molecule.

2. The absorption of light by a molecule prepares it in a nonstationary state with a nonuniform distribution of the energy over several vibrational modes, whereas a ground state molecule is almost always in a state in which the distribution of energy is (nearly) uniform.

Besides this vibrational distribution, the excitation of a molecule leads to an essentially different electronic distribution from that in the ground state. For instance, a nonpolar ground state may be associated with a highly polar excited state. Hence, photochemical reaction mechanisms are often strikingly different from those obtained when the molecule is thermally activated.

The dynamics of a thermal process are mainly described by the energy and geometry of the reactant, transition state and the product.

However, for photodynamics the presence of avoided crossings and funnels through which an excited molecule may return to its ground state are as much of interest as barrier heights.

In Figure 1 a schematic representation is given of both a ground and an excited state potential surface.

From this figure we note some important generalizations:

a. -Absorption and emission of light tends to occur at nuclear geometries which correspond to minima in either the ground or in the excited state surface.

b. -Radiationless jumps are most facile for geometries for which two surfaces come close together in energy; generally this is the case for geometries which have high energies on the ground state

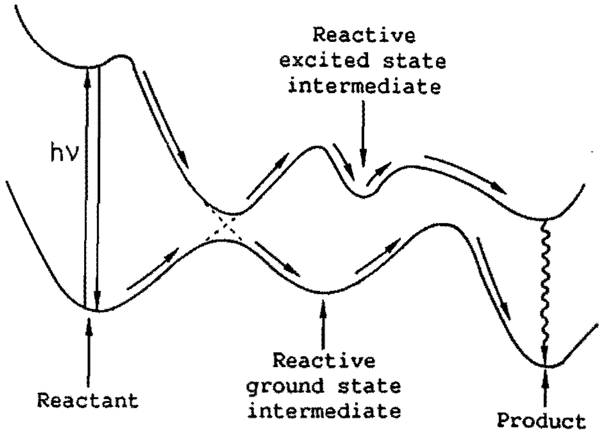

Figure 1. Schematic representation of a ground and excited state potential energy surface.

surface. These "high energy" points on the S_0 surface commonly correspond to extreme stretching of a σ-bond, extreme twisting of a π-bond or to orbitally forbidden ground state reactions.

c. -The location and heights of energy barriers on <u>both</u> the excited and ground state surface may determine the specific pathway of a photoreaction.

d. -The course of a photoreaction depends on competing photophysical as well as photochemical processes.

A thorough understanding of photochemical processes (such as absorptions and emission of light, vibronic interactions, intersystem crossings, internal conversions and chemical reactions in excited states) is very important since such processes play an essential role in many fields varying from laser techniques and photophysics via organic photochemistry to the biochemistry of visual perception and photosynthesis. Thus a detailed knowledge of potential energy surfaces, obtained via the interplay of experiment, qualitative arguments and more sophisticated quantumchemical calculations, is required.

Probably the first application of quantumchemistry to organic photoreactions originates from Mulliken[2], who offered an elegant explanation for the E-Z isomerization in acyclic alkenes from the potential energy curves of the four valence excited states of ethylene, which can be formed by distributing the two π-electrons over the bonding and antibonding π-molecular orbitals. Moreover, he noticed that the minimum on the excited state potential energy curve corresponds to a maximum on the ground state potential energy curve, thus creating a condition from which a radiationless transition is likely to occur (vide supra).

The next step forward in the interpretation of organic photochemistry was the recognition of the importance of orbital symmetry. Thus it was Havinga[3] who mentioned that the complementary stereochemistry of the thermal and photochemical octatriene - cyclohexadiene interconversion can be formalized in terms of the different symmetries of the highest occupied molecular orbitals for the ground and excited state processes. This theoretical prediction was based on a suggestion of Oosterhoff (vide infra). The concept of conservation of symmetry has been generalized by Woodward and Hoffmann[4] for the description of pericyclic reactions. They predicted that reactions which proceed with conservation of orbital symmetry would have an activation energy much lower than reactions which occur without this conservation of orbital symmetry. These predictions have thereafter been confirmed by many experiments, especially the thermal reactions. However, the application of this concept to photochemical reactions is less straightforward and it may be questioned why the course of such a reaction should be governed by the symmetry of a molecular orbital which is occupied by only one of the frontier electrons. The concept deals with strictly concerted reactions and, therefore, can not account for the fact that the absorption of a photon by a molecule causes an electronic redistribution which often results in the breaking of a former (double) bond leading to a diradicalar structure. It was found that many organic photoreactions can be interpreted assuming such diradicalar intermediates[5]. Another important feature in which this qualitative concept lacks, is the prediction of avoided crossings between excited states and the nonadiabatic interactions associated with them[6].

That the situation for photochemical reactions is more complicated, was nicely demonstrated by van der Lugt and Oosterhoff[7] via a complete π-electron MO and VB calculation of the intramolecular ring opening - ring closure of the cyclobutene - cis-butadiene system. They found that the mechanism of the photoreaction is not determined by the initially excited (π-π*)-state but by a second excited state which has a potential energy well at a nuclear conformation for which the ground state has a potential energy barrier.

An overall photochemical reaction can be thought of as to be composed of photophysical and strictly photochemical processes. It starts with the interaction of light with a molecule leading to the absorption of a photon. The electronically excited molecule will relax its geometry to a minimum on the excited state surface from which there are two processes possible. The first one is the emission of a photon (fluorescence or phosphorescence) after which the molecule relaxes in the ground state to its equilibrium geometry, so that no net reaction reaction has occurred.

An example of this type of reaction has been described by Dormans et al[8], who investigated the influence of the shape of the potential energy curves on the dynamics of the photochemical E-Z isomerization of a number of small polyenes. It was found that upon increasing the number of conjugated double bonds, the molecules show an increasing tendency to be planar in the excited state so that the driving force for a photochemical E-Z isomerization decreases. This observation seems to disagree with the remarkably rapid and efficient E-Z isomerization in the protonated schiff base of retinal. This molecule is the common chromophore in the light active protein systems rhodopsin and bacteriorhodopsin and consists of five carbon - carbon double bonds of which particularly one is found to exhibit a photoisomerization. Subsequent MNDO/CI calculations for protonated 1-imino-2,4-pentadiene showed[9] that this apparently contradictive behaviour arises from a strong stabilization of the 90° twisted structure in the excited state by an electron deficient protonated nitrogen atom. Besides this, calculations on a model compound of the protonated Schiff base of retinal showed that the extend of the stabilization of the twisted molecule can be directed by providing external point-charges around the molecule. In nature, these point-charges are provided by the protein opsin.

As an alternative to these photophysical processes, a photochemical reaction may take place, for which there is generally a potential energy barrier to be crossed. The driving force for this process is the excess kinetic energy of the excited molecule or a thermal activation in the excited state. Once the barrier has been crossed, the molecule will return to its ground state via a radiationless transition (internal conversion or intersystem crossing) at a point of the reaction coordinate for which the surfaces come close and the non-adiabatic interactions are strong.

An example of this type of reaction is provided by Fransen[10], who found a unique photochemical [1,3]-OR shift upon irradiation of the cyclic 1,5-diene systems 8-methoxy- and 8-hydroxy-germacrene B (germacrol).

Up till now relatively little attention in olefin photochemistry was devoted to the occurrence of sigmatropic shifts[11-20]. Most of this work was directed to photochemical [1,3]-C shifts, which were studied in detail by Cookson and co-workers[20]. They focused their attention on studying the stereochemical fate of both the migrating group and the allylic terminus. Products with different stereochemistry and loss of geometrical purity of the starting material were found. Apparently E-Z isomerization is faster than the [1,3]-allylic shift, and no conclusions regarding the stereochemistry of the reaction could be drawn.

The Woodward and Hoffmann rules of conservation of orbital symmetry[4] predict a concerted photochemical [1,3] shift to proceed in a suprafacial fashion. In this thesis a mechanism for photochemical [1,3] shifts is elaborated which is not governed by the symmetry of the highest (singly) occupied molecular orbital but by the energetically favourable E-Z isomerization of a double bond. From the (polarized) 90° twisted conformation of the molecule, an atom (or group) may now shift *in* the plane of the carbon skeleton (planar shift, vide infra). This mechanism is strongly supported by MNDO calculations with a minimal CI[21,22] and extensive ab initio CI calculations[23].

1.2 Outline of this Thesis

In this thesis the occurrence of a non-Woodward and Hoffmann reaction path for photochemical [1,3] sigmatropic shifts in acyclic alkenes is further refined. In chapter 2 the results of semi-empirical calculations of the exocyclic double bond isomerization in both germacrol and germacrene are presented. The different photochemistry of these compounds (a photochemical [1,3]-OH shift versus reactions of the endocyclic 1,5-diene moiety) could be well explained assuming an initial isomerization of the exocyclic double bond. It is shown that in case of germacrol the exocyclic double bond can reach a twisted conformation where the lowest excited state has a polarization favourable for a (planar) [1,3]-OH shift. For germacrene however this state is strongly coupled to two diradicalar states and therefore the corresponding [1,3]-H shift will not take place.

Chapters 3, 4 and 5 deal with the results of an experimental study on the mechanistic and stereochemical aspects of photochemical [1,3] sigmatropic shifts. In chapter 3 the first experimental evidence regarding the occurrence of a planar photochemical [1,3]-OH shift is presented. The photochemical behaviour of some 4-methyl, 4-ethyl disubstituted 3-alkylidene-2-naphthalenol derivatives is investigated. It is shown that occurrence of a [1,3]-OH shift is dependent only on the ground-state conformation of the substrate. The stereochemical outcome of this shift is in full agreement with the one expected in case of a planar mechanism. Further evidence in favour of the planar mechanism was obtained by studying the effects of both solvent polarity (chapter 4) and of substituents located at the exocyclic double bond (chapter 5). In chapter 4 it is shown that the yield of formation of the products derived from a photochemical [1,3]-OH shift is dependent on the polarity of the solvent employed. This result could be well explained in terms of a stabilization of the polarized 90° twisted intermediate formed upon irradiation of the substrate, by reorientation polarization of the dipole solvent molecules. In chapter 5 it is shown that dependent on the nature of the substituents at the exocyclic double bond either a photochemical [1,3]-OH or [1,3]-H shift takes place. This directive effect too could be well explained on the basis of a planar reaction mechanism.

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Chapter 2*

Quantumchemical Calculations on the Photochemistry of Germacrene and Germacrol. The Exclusive Role of the Exocyclic Double Bond Isomerization.

Abstract

The different photochemistry of the title compounds (reactions of the endocyclic 1,5-diene moiety versus a photochemical [1,3]-OH shift) can be explained assuming an initial isomerization of the exocyclic double bond. MNDO/CI calculations of the potential energy curves and nonadiabatic couplings for the rotation of this bond showed that the 90° twisted conformation can easily be reached. For germacrol the lowest excited state has a zwitterionic character which is favourable for a planar photochemical [1,3]-OH shift. For germacrene, this polarized state is strongly coupled to two diradicalar states. In these twisted diradicalar states a redistribution of the charges in the endocyclic double bonds is found which is eminently suited for intramolecular bond formation.

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*W.J.G.M. Peijnenburg, G.J.M. Dormans, H.M. Buck, Tetrahedron, accepted for publication.

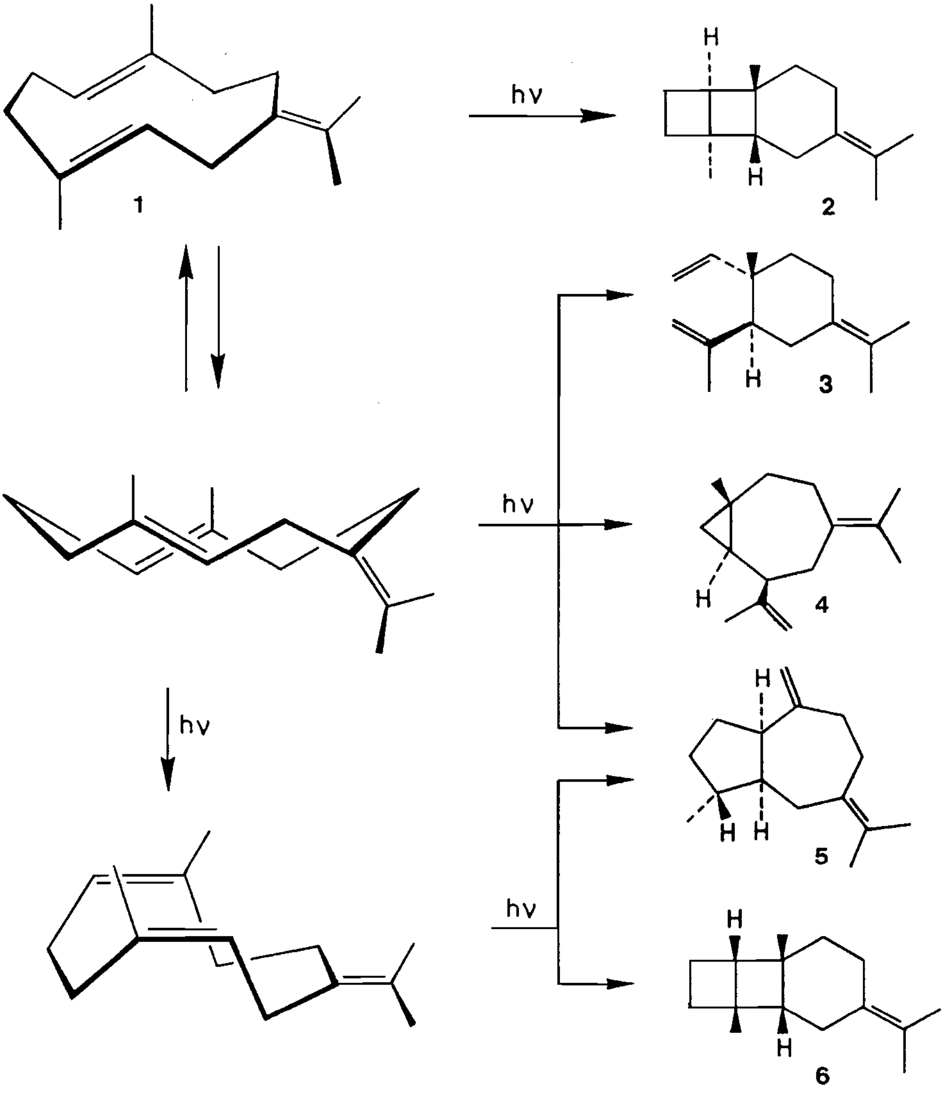

Figure 1. Photochemistry of (E,E)-germacrene (1).

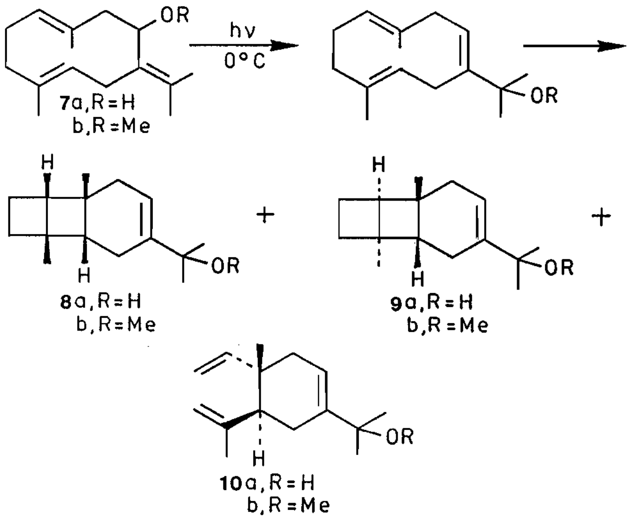

Figure 2. Photochemistry of germacrol (**7a**) and its methyl derivative **7b**.

2.1 Introduction

Our interest in the photochemistry of the germacrene system originates from the unique properties of a 1,5-diene chromophore enclosed in a medium sized ring[1-4].

Upon irradiation of (E,E)-germacra-1(10),4,7,(11)-triene (germacrene 1) under singlet conditions[2], the main photoproducts arise from a reaction of the 1,5-diene moiety. Products 2 and 6 are formed via a $[\pi^2_s + \pi^2_s]$ cycloaddition reaction of the two endocyclic double bonds, 5 from a biradicalar reaction, and 3 and 4 from respectively a Cope- and an Ohloff-rearrangement of the 1,5-diene system (see Figure 1).

On the other hand, irradiation of (E,E)-germacra-1(10),4,7(11)-triene-8-ol (germacrol **7a**) and its methyl derivative (**7b**) under the same conditions[3] reveals a remarkable [1,3]-OH ([1,3]-OMe) shift in the exocyclic part of the molecule as the primary photoprocess. In a subsequent step, the endocyclic double bonds react to form two cyclobutane derivatives (**8a**,**b**, **9a**,**b**) and a Cope rearranged product (**10a**,**b**) (see Figure 2).

The exclusive role of the 1,5-diene moiety follows from an experiment where the 4,5-double bond is selectively hydrogenated[4]. Irradiation of (4SR,8SR)- and (4SR,8RS)-4,5-dihydrogermacrol (**11** and **15**) leads only to E-Z isomerization of the endocyclic double bond (**12** and **16**) and to a photochemical [1,3]-allyl shift (**13**, **14** and **17**) along the same double bond (see Figure 3).

From these experiments two possible explanations arise for the observed behaviour of these germacrene systems.

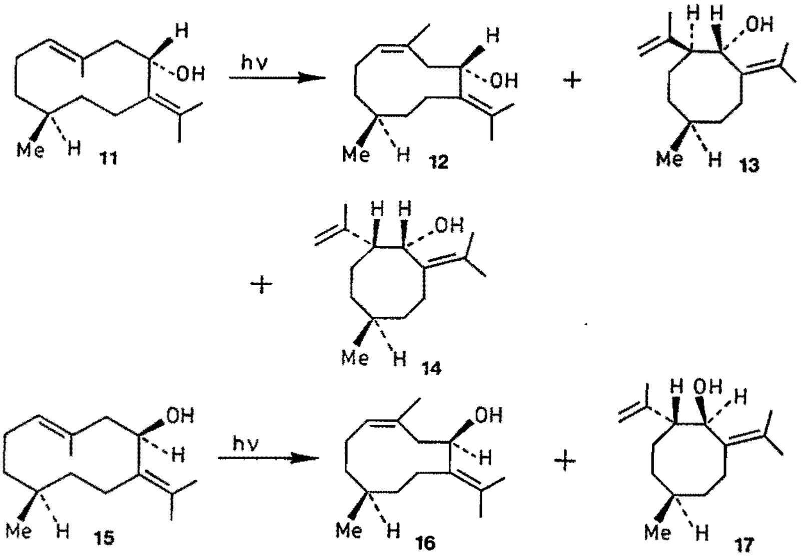

Figure 3. Photochemistry of (4SR,8SR)- and (4SR,8RS)-dihydrogermacrol (**11** and **15**).

First, the ground-state conformation of these molecules is known to play an important role in the observed photochemistry[1,2,4-6]. Due to the presence of three double bonds, the ring skeleton has a certain rigidity and consequently there are eight conformations possible[7]. MNDO-calculations for germacrol[7] (7a) revealed that the SSS-conformation[8] is the most stable one. This observation is supported by an X-ray analysis of a germacrene-silver nitrate adduct[9]. The preferential germacrol-conformation is depicted in Figure 4.

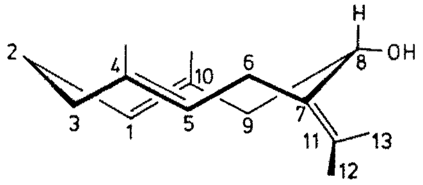

Figure 4. Preferential (SSS-) conformation of germacrol **(7a)**.

It is characterized by a crossed conformation of the two endocyclic double bonds. Another important feature is that the hydroxyl group is oriented almost in the plane spanned by the carbon atoms 7, 8 and 11. Such an orientation is a prerequisite for the occurrence of a planar [1,3]-OH shift, which we propose on the basis of quantumchemical calculations[10,11]. This mechanism can briefly be illustrated for the photochemical [1,3]-OH shift in propenol[10] (see Figure 5).

According to orbital symmetry considerations, this reaction is expected to proceed in a suprafacial fashion. MNDO-calculations reveal an activation enthalpy in the first singlet excited state of 57 kcal/mol. However, upon excitation an electron is promoted from a bonding to an antibonding π orbital, leading to a rotation of the excited double bond. This exothermic process is the essential step in the E-Z isomerization of alkenes. The twist of the double bond is accompanied by a relocalization of the electrons ("Sudden Polarization"[12]). In the 90° twist region there are two excited states (Z_1 and Z_2[13]) close in energy which exhibit an opposite polarization of charge since in these zwitterionic states the electrons may be located at either the central or the terminal carbon atom of the excited double bond.

For propenol, the configuration with the two electrons on the central carbon atom is best stabilized. The lowest excited state is thus positively charged at the terminal carbon atom and negatively charged at the central carbon atom. The partially negatively charged hydroxyl group now shifts towards the terminal carbon atom *in* the plane of the carbon skeleton via a transition state of C_{2v} symmetry.

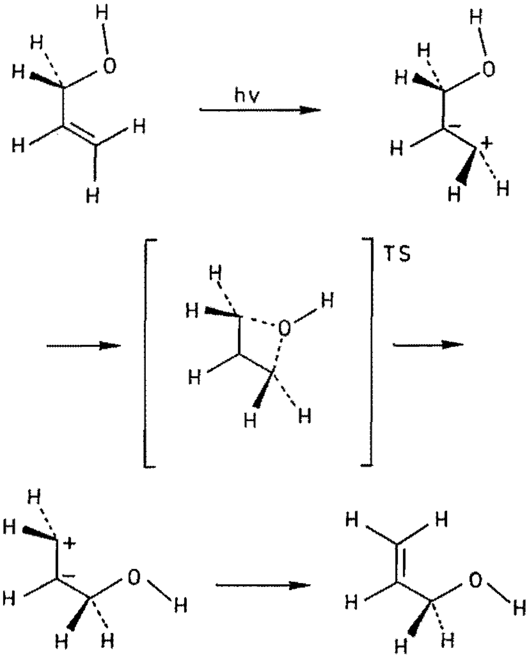

Figure 5. The proposed mechanism for the photochemical [1,3]-OH shift in propenol.

The calculated activation enthalpy for this planar reaction is 17 kcal/mol. The top of this barrier is still below the level of the vertical excited molecule. Comparable calculations for the planar [1,3]-H shift in propene yield an activation enthalpy of 35.5 kcal/mol.

The conclusion of the quantumchemical calculations is that photochemical sigmatropic shifts in acyclic alkenes proceed via such a planar mechanism which is initiated by a rotation of the excited double bond. Recently we were able to obtain the first experimental evidence in favour of the occurrence of a planar [1,3]-OH shift (chapter 3 of this thesis).

Due to the absence of one double bond in 4,5-dihydrogermacrol (11, 15) this system is much more flexible than germacrol (7a) itself and the favourable orientation of the hydroxyl group for a planar shift might be lost. To check this argument, the 4,5-endocyclic double bond was selectively replaced by a cyclopropyl group[14], thus maintaining the rigidity of the molecule while changing the chromophore. Irradiation of this molecule leads essentially to the same reactions as observed for compounds 11 and 15[15]. Clearly the rigidity of the molecule is not the only prerequisite for the occurrence of the [1,3]-OH shift.

In order to get a sigmatropic shift it is necessary that the exocyclic double bond is in an excited configuration. Therefore an interaction is needed between the endocyclic 1,5-diene chromophore and the exocyclic double bond. The presence of such an interaction is clear from the UV-absorption spectrum of germacrol and germacrene. Whereas compounds 11 and 15 show maxima near λ = 220 nm, the latter two compounds have their maxima near λ = 245 nm.

This bathochromic shift can partly be explained from an increased torsion of the endocyclic double bonds (vide infra), but must also be attributed to the above-mentioned interaction between these double bonds. In this way, the excitation energy can be transferred to the exocyclic moiety where it is used for an efficient photochemical reaction.

A question which remains is why germacrol exhibits a [1,3]-OH shift, whereas germacrene does not show a [1,3]-H shift despite their similar UV-absorption characteristics. Part of the answer is that the calculated activation enthalpy for a [1,3]-H shift is about twice the value for a [1,3]-OH shift for the planar mechanism (vide supra). This explanation is based on the assumption that the exocyclic double bond can reach a twisted conformation where the lowest excited state has a polarization favourable for a [1,3]-OH shift.

We have now performed semi-empirical calculations for the exocyclic double bond isomerization in both germacrol and germacrene which confirm this assumption and give an additional explanation for their typical difference in photochemistry.

2.2 Results and Discussion

The calculations have been performed starting from a MNDO-SCF calculation followed by a full CI treatment (170 configurations) for the highest three occupied and first three virtual MOs. These six MOs are mainly built up from the AOs which form the three π-bonds.

Each electronic state is characterized by calculating the bond orders (P_{AB}) and atomic charge densities (P_{AA}) in the basis of natural orbitals from the final multiconfigurational wavefunctions for this state.

$$P_{AB} = \sum_{p \in A} \sum_{q \in B} D_{pq} S_{pq}$$

$$D_{pq} = \sum_{i=1}^{N} \eta_i C_{pi} C_{qi}$$

S_{pq} is the overlap integral between the AOs p and q (belonging to the atoms A and B respectively) and D_{pq} the spinless density matrix in the basis of the natural orbitals (i) with coefficients C_{pi}, C_{qi} and an occupation number η_i (η_i = 0, 1 or 2). N runs over all natural orbitals.

All calculations were performed for the optimized structure of SSS-germacrol[7] (Figure 4) with the only difference that the CC distance of the twisted bond was chosen as 1.40 Å. Germacrene was assumed to have the same geometry as germacrol.

In Figures 6 and 7 we present the potential energy curves for the twist of the exocyclic double bond in the interval $0° \leq \Theta \leq 90°$ for germacrol and germacrene. In Tables I and II the lowest electronic states are characterized by their π bond orders and atomic charge densities.

We start the discussion with the vertical excited molecules. The distribution of the electronic excitation over the molecule can be determined by comparing the bond orders of the excited states with those of the ground state[16]. A decrease in bond order going from the ground to the excited state indicates that this particular bond is more antibonding (energy rich) and therefore more reactive. When the

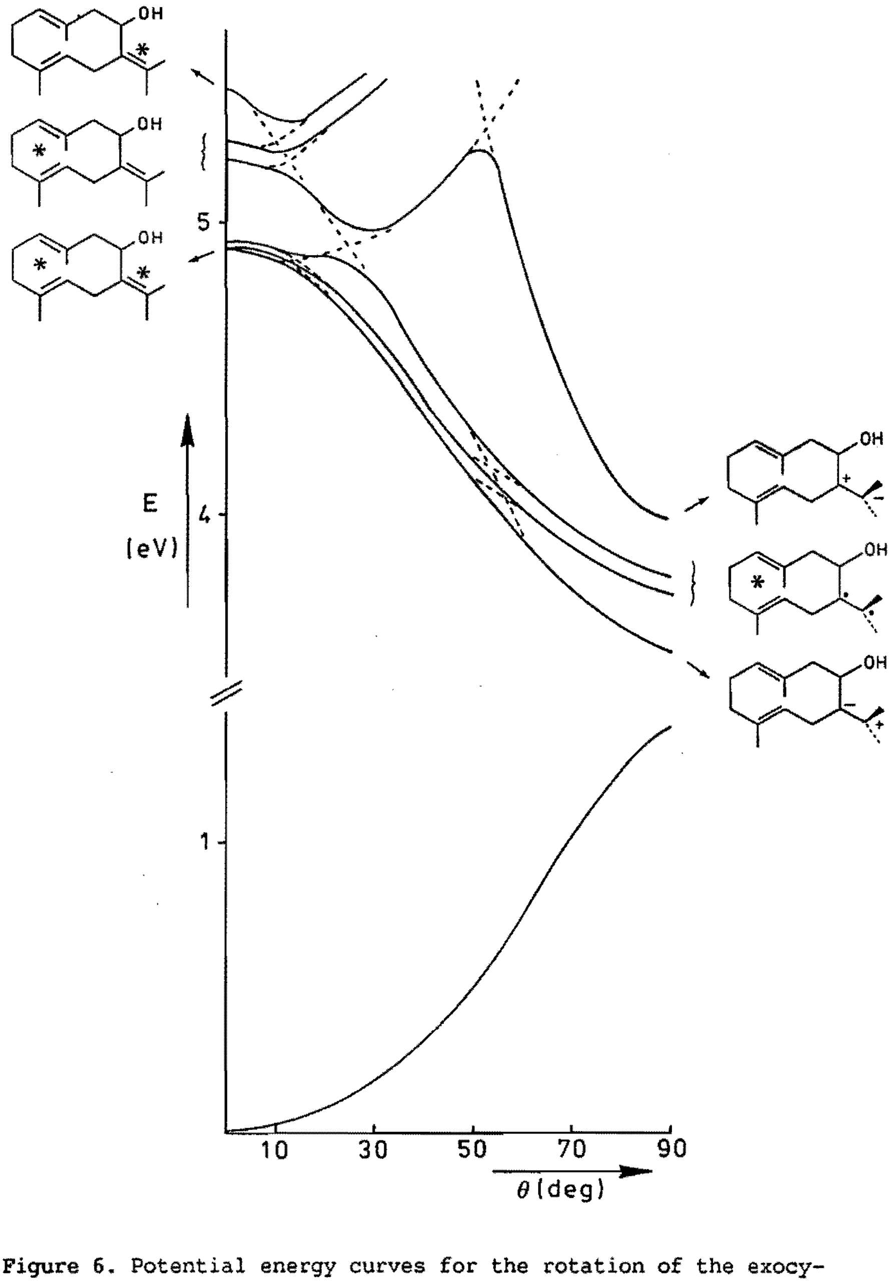

Figure 6. Potential energy curves for the rotation of the exocyclic double bond in germacrol. The localization of the excitation in a certain excited state is indicated by an asteriks.

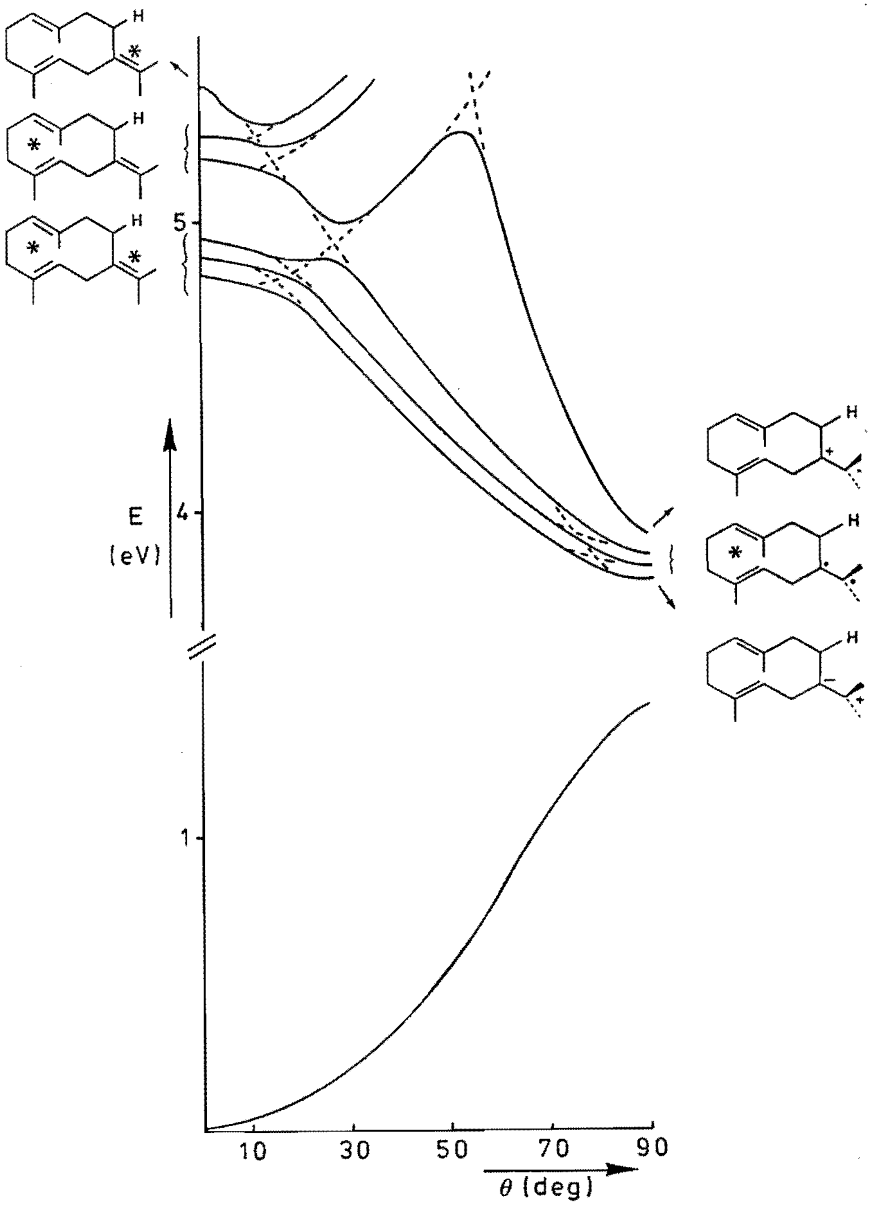

Figure 7. Potential energy curves for the rotation of the exocyclic double bond in germacrene. The localization of the excitation in a certain excited state is indicated by an asteriks.

Table I. Calculated π bond orders and atomic charges of the lowest electronic states of germacrol.

			Atomic charges[a]						P_{AB}[b]		
θ	$\vert\psi_K\rangle$	$\Delta E^c(f_{osc}{}^d)$	C_1	C_{10}	C_4	C_5	C_7	C_{11}	1,10	4,5	7,11
0°	S_0	0	−0.09	−0.15	−0.14	−0.08	−0.14	−0.12	0.91	0.91	0.91
	S_1	4.89(0.004)	−0.06	−0.11	−0.18	−0.10	−0.19	−0.18	0.81	0.76	0.85
	S_2	4.89(0.000)	−0.17	−0.14	−0.09	−0.02	−0.12	−0.17	0.77	0.87	0.76
	S_3	4.93(0.001)	−0.04	−0.12	−0.21	−0.15	−0.14	−0.17	0.85	0.79	0.77
	S_4	5.17(0.519)	−0.06	−0.16	−0.17	−0.09	−0.15	−0.13	0.91	0.80	0.85
	S_5	5.21(0.365)	−0.05	−0.21	−0.15	−0.08	−0.15	−0.12	0.78	0.91	0.88
	S_6	5.47(0.167)	−0.06	−0.16	−0.17	−0.07	−0.17	−0.12	0.88	0.87	0.79
90°	S_0	1.38	−0.07	−0.15	−0.15	−0.08	−0.14	−0.16	0.91	0.91	0.81
	Z_1	3.53	−0.09	−0.13	−0.14	−0.08	−0.71	+0.39	0.91	0.91	0.81
	D_1	3.77	−0.24	−0.31	+0.00	+0.09	−0.14	−0.17	0.87	0.80	0.81
	D_2	3.78	+0.09	+0.00	−0.32	−0.27	−0.14	−0.16	0.80	0.87	0.81
	Z_2	3.98	−0.06	−0.16	−0.13	−0.09	+0.46	−0.74	0.91	0.91	0.81

[a] Atomic charges calculated from P_{AA}. [b] Bond order. [c] Energy difference in eV. [d] Oscillator strength.

bond order remains unchanged, this bond is unaffected by the electronic excitation. Using this concept, we may qualitatively characterize the excited states of germacrol (and germacrene, which are fully comparable).

As can be seen from Tables I and II the lowest three excited states are each excited mainly in two double bonds. The ordening of these biexcited states can be explained from the reactivity of the three

Table II. Calculated π bond orders and atomic charges of the lowest electronic states of germacrene.

			Atomic charges[a]						P_{AB}[b]		
θ	$\vert\psi_K\rangle$	$\Delta E^c(f_{osc}{}^d)$	C_1	C_{10}	C_4	C_5	C_7	C_{11}	1,10	4,5	7,11
0°	S_0	0	−0.07	−0.14	−0.15	−0.08	−0.10	−0.15	0.91	0.91	0.90
	S_1	4.82(0.002)	−0.12	−0.16	−0.09	−0.11	−0.09	−0.13	0.77	0.76	0.88
	S_2	4.88(0.000)	−0.12	−0.18	−0.13	−0.06	−0.13	−0.16	0.76	0.89	0.76
	S_3	4.92(0.001)	−0.06	−0.12	−0.20	−0.13	−0.13	−0.16	0.88	0.77	0.76
	S_4	5.18(0.598)	−0.05	−0.16	−0.17	−0.08	−0.10	−0.17	0.91	0.81	0.84
	S_5	5.22(0.262)	−0.06	−0.19	−0.15	−0.08	−0.10	−0.15	0.79	0.90	0.88
	S_6	5.47(0.189)	−0.06	−0.17	−0.17	−0.08	−0.11	−0.16	0.88	0.86	0.80
90°	S_0	1.45	−0.07	−0.14	−0.15	−0.08	−0.13	−0.16	0.91	0.91	0.81
	Z_1	3.79	−0.12	−0.23	+0.01	−0.10	+0.23	−0,52	0.91	0.88	0.81
	D_1	3.81	−0.31	+0.00	+0.09	−0.04	−0.25	−0.17	0.90	0.83	0.81
	D_2	3.82	+0.18	+0.16	−0.46	−0.40	−0.13	−0.17	0.76	0.90	0.81
	Z_2	3.90	−0.14	−0.21	−0.16	−0.05	−0.58	+0.28	0.91	0.87	0.81

[a] Atomic charges calculated from P_{AA}. [b] Bond order. [c] Energy difference in eV. [d] Oscillator strength.

double bonds due to their torsional strain. So it was found[7] that the 4,5 double bond is more reactive than the 1,10 double bond, whereas the torsional strain for the exocyclic double bond is negligible. The energy difference between the π and π^* orbital of the 4,5 double bond is thus smallest, followed by the 1,10 and 7,11 double bonds respectively. Therefore the electronic state which involves an excitation to the endocyclic double bonds has the lowest excitation energy.

Of course the situation is more complicated as the various π orbitals are strongly mixed up at the MO level. This is why the wavefunctions are built up from several configurations with large coefficients. The fact that these states are biexcited species explains why the oscillator strengths for these transitions are negligible (see Tables I and II).

On the other hand, the next three excited states are predominantly described by a single excitation into one particular double bond and are therefore photoactive. The energy ordening can again be explained from the reactivity of the three double bonds. The calculated absorption spectrum starts at about λ = 238 nm (5.2 eV, see Tables I and II) for both molecules, in reasonable agreement with the observed absorption maximum at λ = 245 nm.

The behaviour of an excited state upon twisting the exocyclic double bond is directly related to its bond order. For those states in which this value is near to the ground state value of 0.90 (S_1, S_4 and S_5) this double bond has no antibonding character and a rotation is highly unfavourable. These electronic states therefore show a strong increase in energy (indicated by the dashed lines in Figures 6 and 7) comparable with that of the ground state.

For S_2 and S_3 the electronic excitation is distributed partly in one endocyclic double bond and partly in the exocyclic double bond. In this case the twisting results in a decrease of the potential energy. For S_6 the excitation is located merely in the exocyclic double bond and for this configuration twisting leads to a strong decrease in energy, thereby crossing the energy curves of the lower excited states (see Figures 6 and 7).

However, due to avoided crossings the excited molecule does not follow these diabatic curves (dashed lines) but the adiabatic curves (full lines, these are in fact the calculated potential energy curves). From these curves it is seen that the molecule would never reach the 90° twisted structure without passing a potential energy barrier when it is excited to one of the states bearing oscillator strength.

The situation however is more complicated as the Born Oppenheimer approximation becomes less valid in regions where the adiabatic curves come close in energy. In this particular case, the nonadiabatic coupling (g_{KL}) between two electronic wavefunctions ($|\psi_K\rangle$ and $|\psi_L\rangle$) is induced by the operator $\partial/\partial\theta$, where θ is the twisting motion around the excited double bond of the molecule:

$$g_{KL} = \langle\psi_K|\frac{\partial}{\partial\theta}|\psi_L\rangle$$

The value of g_{KL} is a measure for the transfer of population from one electronic state to another[17]. In regions where g_{KL} is large and ΔE_{KL} is small, the lower electronic state becomes rapidly populated (within fractions of picoseconds[18]). In this case the molecule merely follows the diabatic curve rather than the adiabatic curve.

We have calculated these nonadiabatic couplings for the twist of the exocyclic double bond using the method of finite differences, which is described in detail elsewhere[19]. The stepsize for the numerical procedure was $\Delta\theta = 0.02°$. A selection of the coupling curves for both germacrol and germacrene is presented in the Figures 8 and 9.

As can be seen from these figures, the nonadiabatic couplings are indeed very large (several au^{-1}) in regions where the adiabatic curves show an avoided crossing.

The dynamics of the excited molecule can now be described as follows. The molecule is excited to one of the states S_4, S_5 or S_6, of which the former two induce an increased reactivity in the endocyclic part of the molecule. These states might lead to E-Z isomerization or other photochemical reactions of these double bonds. Due to the constraints of the ring it is expected that these reactions demand a certain activation energy. On the other hand, an E-Z isomerization of the exocyclic double bond is very feasible as the diabatic curve for this motion monotonically decreases till θ = 90°. Even in the case of a rapid internal conversion to the lower singlet

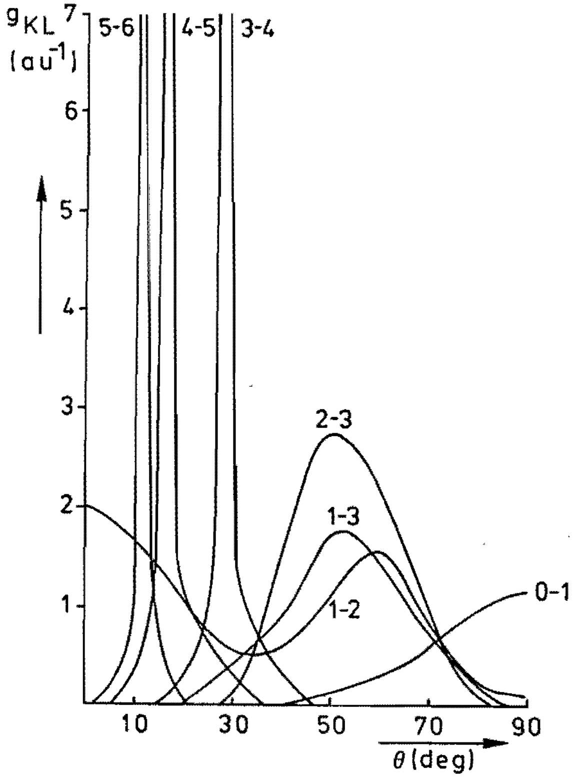

Figure 8. Selection of the nonadiabatic coupling curves for rotation of the exocyclic double bond of germacrol.

excited states, their energy curves show that the 90° twisted structure can be reached.

So far, the situation is comparable for germacrol and germacrene. The main differences arise in the 90° region. They are a direct consequence of the presence of the hydroxyl group in germacrol. The perturbing effect of this substituent on the stability of the two zwitterionic states (Z_1 and Z_2) is larger than for the hydrogen atom in germacrene. Consequently, the energy splitting between these two states is larger (0.46 eV in germacrol, 0.11 eV in germacrene). The lowest excited state at θ = 90° for germacrol is the one with a posi-

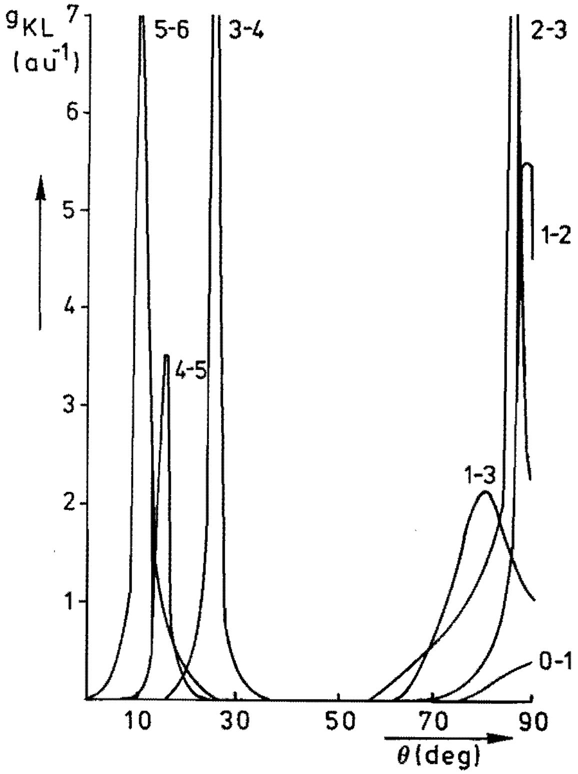

Figure 9. Selection of the nonadiabatic coupling curves for rotation of the exocyclic double bond of germacrene.

tively charged exocyclic carbon atom. The situation is reversed in germacrene (see Tables I and II).

For both molecules there are two diradicalar states (D_1 and D_2) which lie in between the two zwitterionic states. For germacrene these four states not only lie in an interval of only 0.11 eV but their mutual nonadiabatic couplings are very large as well (see Figure 9). The properties (e.g. polarization) of these states are therefore strongly mixed. For germacrol the energy splitting between Z_1 and D_1 is 0.24 eV and the coupling is small (see Figure 8). Therefore at least the lowest vibrational level of Z_1 will show the properties of this electronic configuration: a polarization which is favourable for a planar [1,3]-OH shift i.e. a negative charge at the central carbon atom C_7 and a positive charge at the terminal carbon atom C_{11}.

The nonadiabatic coupling between Z_1 and the ground state is in the order of 1 au^{-1}. From this value it may be concluded that the molecule will not convert directly to the ground state potential energy curve once the twisted conformation is reached[11,17b,18]. It will start to oscillate in this minimum thereby having a certain probability for a radiationless transition to the ground state in competition with the photochemical [1,3]-OH shift. We estimated the activation energy for this shift in the order of 17 kcal/mol, which is less than the increase of kinetic energy obtained from the twisting of the double bond (approximately 35 kcal/mol). The estimated activation energy for a planar [1,3]-H shift was calculated to be twice as large (35.5 kcal/mol). The top of the energy barrier for this shift in germacrene will lie above the level of the vertical excited molecule. This makes this reaction rather unlikely to occur.

Looking at the charge densities of the twisted diradical states (Tables I and II), a redistribution of the charges in the two endocyclic double bonds is found. The charges at the carbon atoms of the anti-bonding double bond become more positive whereas a more negative character of the carbon atoms of the other endocyclic double bond is perceptible. This is a situation which is eminently suited for an intramolecular bond formation in this part of the molecule. These twisted diradicalar states can thus be seen as precursors for the observed photoproducts of germacrene.

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Chapter 3*

An Experimental Study on the Mechanism and Stereochemistry of a Photochemical [1,3]-OH Shift. A Non-Woodward and Hoffmann Reaction Path for Photochemical Sigmatropic Reactions.

Abstract

An experimental study on the photochemistry of the 4-methyl, 4-ethyl disubstituted 3-alkylidene-2-naphthalenol derivatives **1a,b** and **5a,b** is presented. It is shown that occurrence of a [1,3]-OH shift is dependent only on the ground-state conformation of the substrate. This conformation in its turn is fixed by the chirality at C_2 and C_4. In case of compounds **1a,b** the hydroxyl group is located in the plane of the exocyclic double bond. Excitation of this favourable conformation results in a 90° twist of the exocyclic double bond. Due to the interaction between the substituents at C_4 and C_9 preferential formation of just one twisted geometry takes place. The stereochemical outcome of the resulting [1,3]-OH shift agrees well with the one expected in case of a planar shift. Further evidence in favour of the occurrence of a non-Woodward and Hoffmann reaction path is obtained from the irradiation of 5a,b; despite a favourable

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*W.J.G.M. Peijnenburg, H.M. Buck, Tetrahedron, submitted for publication.

ground-state conformation for a suprafacial shift to occur, this shift does not take place. Instead a 90° twisted intermediate is formed, from which solely a radiationless transition to the ground state is observable. The stereostructure of the photoproducts formed was established by means of low temperature NOE measurements.

3.1 Introduction

During our investigations on the photochemistry of rigid 1,5-dienes it was found that irradiation of 8-hydroxygermacrene B leads to an exclusive [1,3]-OH shift[1]. Following the Woodward and Hoffmann rules of conservation of orbital symmetry[2], a photochemical [1,3] sigmatropic shift is expected to proceed in a suprafacial way. However, the orbital symmetry arguments deal only with strictly concerted conversions and no attention is paid to local geometry changes which effectuate the course of the overall process. Yet it is well-known in alkene photochemistry that twisting of the excited double bond occurs in order to diminish electronic repulsion between the antibonding p-orbitals. In unsymmetrically substituted alkenes this twist will be accompanied by a complete charge separation in the orthogonal situation[3]. Based on this phenomenon, known as "Sudden Polarization", we proposed a mechanism for photochemical sigmatropic reactions as depicted in Figure 1 for the photochemical [1,3]-OH shift in 2-propen-1-ol[4].

For 2-propen-1-ol (I) this polarization leads to a positive charge on the terminal carbon atom and a negative charge on the central carbon atom (II). The hydroxyl group, which has a partially negative charge, may now shift towards the positively charged terminus *in* the

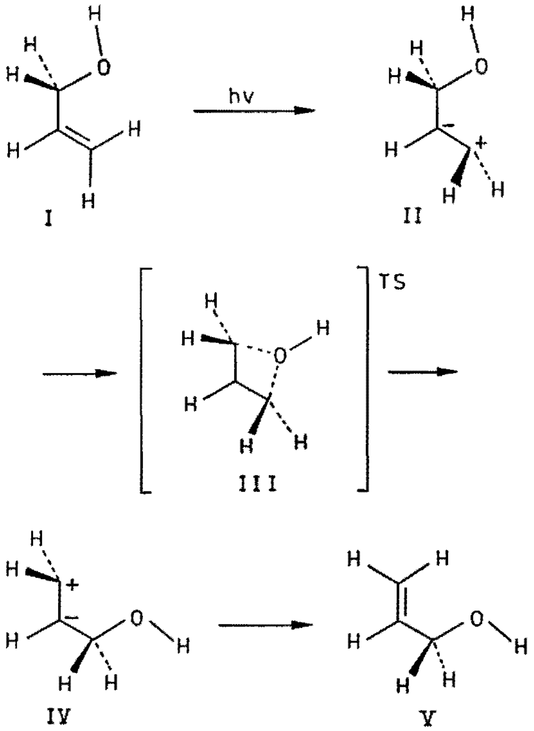


Figure 1. The proposed mechanism of the planar [1,3]-OH shift in 2-propen-1-ol.

plane of the carbon atoms via a transition state of C_{2v}-symmetry (III). After a radiationless transition from a second twisted conformation (IV) the reaction proceeds on the ground state potential surface towards the shifted product (V). MNDO-CI calculations for various photochemical shifts showed the activation energy for this planar mechanism to be considerably smaller than for the mechanism based on the Woodward and Hoffmann rules[5].

Up to now relatively little attention has been paid to the stereochemical aspects of photochemical sigmatropic rearrangements. Most of this work was directed to [1,3]-C shifts, which were studied in detail by Cookson and co-workers[6]. They demonstrated that the photochemical [1,3]-benzylic shift in (3SR,5RS)- and (3RS,5RS)-3-methyl-5-phenyldicyanocyclohexylidene is completely stereospecific with retention of configuration of the migrating benzylic centre (see Figure 2), which is consistent with both the suprafacial and the planar mechanism[5].

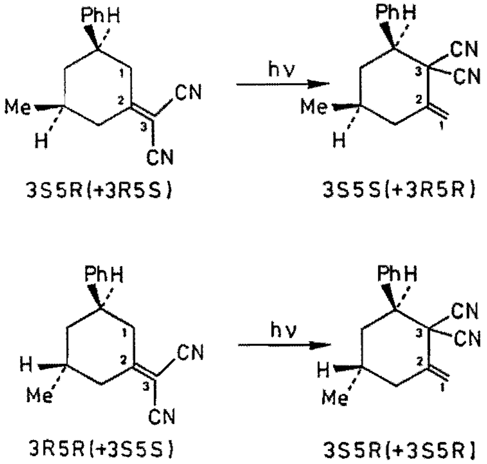


Figure 2. Photochemistry of (3SR,5RS)- and (3RS,5RS)-3-methyl-5-phenyldicyanocyclohexylidene.

Irradiation of cyano-3-phenylcyclohexylidene methylacetate showed that E-Z equilibration is faster than the [1,3]-benzylic shift and therefore no conclusions regarding the stereochemical fate of the allylic terminus could be obtained (see Figure 3).

In the abscence of steric factors the twisting motion of the exocyclic double bond takes place in two opposite directions, thus accounting for the scrambling of the chirality at the terminal carbon atoms.

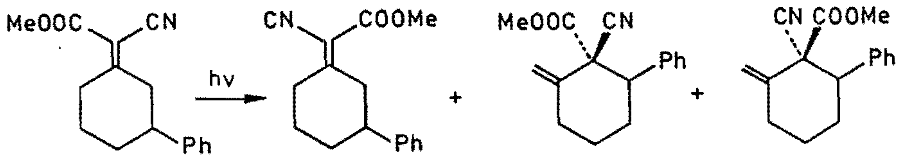


Figure 3. Photochemistry of cyano-3-phenylcyclohexylidene methylacetate.

We now wish to report the results of an experimental study on the photochemistry of the 4-methyl, 4-ethyl disubstituted 3-alkylidene-2-naphthalenol derivatives **1a,b** and **5a,b**. Irradiation of these diastereoisomeric compounds leads, because of the large steric interaction between the allylic ethyl group and the vinylic alkyl group, to a preferential twisting of the exocyclic double bond into *one* direction. The stereochemical outcome of the subsequent [1,3]-OH shift delivers to our knowledge the first experimental evidence of the occurrence of a planar photochemical [1,3] sigmatropic shift in acyclic alkenes.

3.2 Results

Upon direct irradiation of (2RS,4SR)-**1a** in n-hexane fast E-Z isomerization around the exocyclic double bond could be observed. This led to the formation of a mixture of the E- and Z-isomers **2a** and **1a** respectively in a ratio of approximately 50:50. Further irradiation of this mixture resulted in the clean formation of the diastereoisomeric product mixtures 3a and **4a** in a ratio of 85:15.

The influence of the C_9-alkyl group becomes clear from the observed photochemical behaviour of the product formed by substitution of the C_9(Me) by the more bulky ethyl group (compound **1b**). Irradiation of the rapidly formed 50:50 mixture of **1b** and **2b** results in an even more stereoselective [1,3]-OH shift, yielding **3b** and **4b** in a ratio of 93:7 (see Figure 4).

Irradiation of either (2SR,4SR)-**5a** or (2SR,4SR)-**5b** in n-hexane also gave rise to the initial formation of a 50:50 mixture of the E- and Z-isomers **6a,b** and **5a,b** respectively. However, upon prolonged irradiation no further photoproducts were formed. This clearly demonstra-

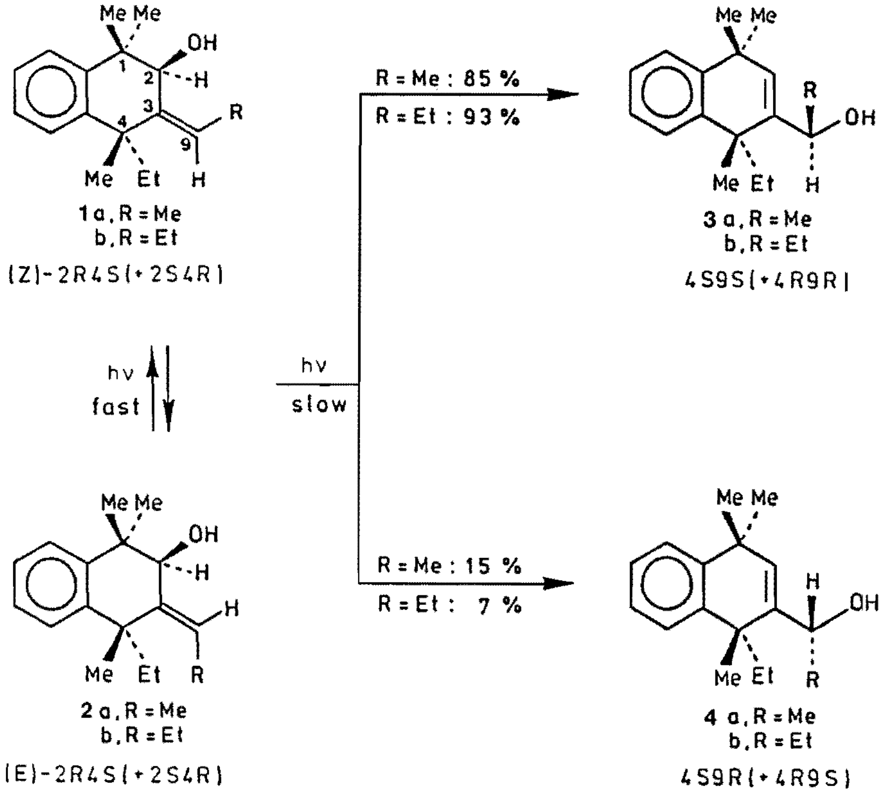


Figure 4. Photochemistry of (2RS,4SR)-**1a,b** upon irradiation in n-hexane.

tes the unique properties of the compounds studied. Dependent on the chirality at C_2 and C_4, either a highly stereospecific [1,3]-OH shift takes place or no shift at all is observed. Initial formation of a 50:50 mixture of **5a,b** and **6a,b** was also observed upon irradiation of 5a,b in methanol. Besides this general behaviour the two additional photoproducts **7a,b** and **8a,b** were formed in ratios of 60:40. These products arise from the addition of methanol to the excited double bond of either 5a,b or 6a,b. No [1,3]-OH shift could be established (see Figure 5).

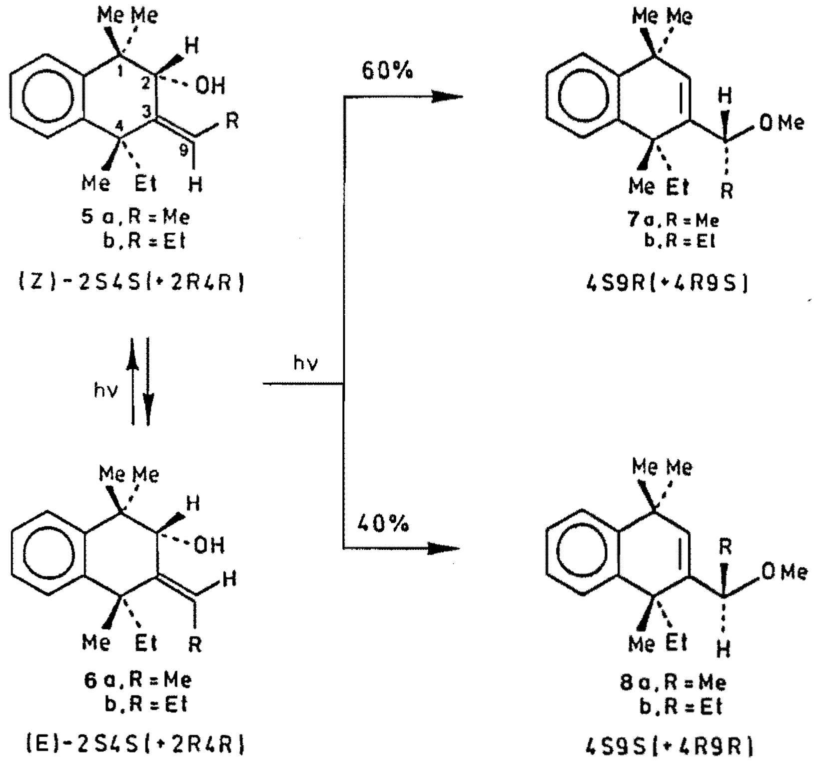


Figure 5. Photochemistry of (2SR,4SR)-5a,b upon irradiation in methanol.

The fact that the [1,3]-OH shift does not occur for compounds **5a,b** and **6a,b** in n-hexane indicates a lower reactivity than for compounds **1a,b** and **2a,b**, but does not exclude the possibility of its appearance in methanol. Therefore a control experiment was set up in order to make sure no photochemical substitution reaction occurs which would convert **3a,b** and **4a,b** into **7a,b** and **8a,b**. No reaction could be observed upon prolonged irradiation of both **3a,b** and **4a,b** in methanol.

3.3 Discussion

The observation of an unequal product distribution upon irradiation of the 50:50 mixture of **1a,b** and **2a,b** clearly indicates the occurrence of a non-Woodward and Hoffmann reaction path for photochemical sigmatropic [1,3]-OH shifts. For following the Woodward and Hoffmann rules of conservation of orbital symmetry, a photochemical [1,3]-OH shift is predicted to proceed in a suprafacial fashion. A suprafacial [1,3]-OH shift will always be accompanied with complete transfer of the chirality at C_2 in the starting products towards C_9 in the photoproducts **3a,b** and **4a,b**.

As shown in Figure 6 a relative configuration of 2R4S(2S4R) of the Z-isomers **1a,b** will lead to the formation of a 4S9R(4R9S)-configuration of the products formed upon suprafacial migration of the hydroxyl group. Similarly the same relative configuration of 2R4S(2S4R) of the E-isomers **2a,b** will result in a 4S9S(4R9R)-configuration of the photoproducts.

Because of the presence of the unequal substituents at C_2 and C_4 the

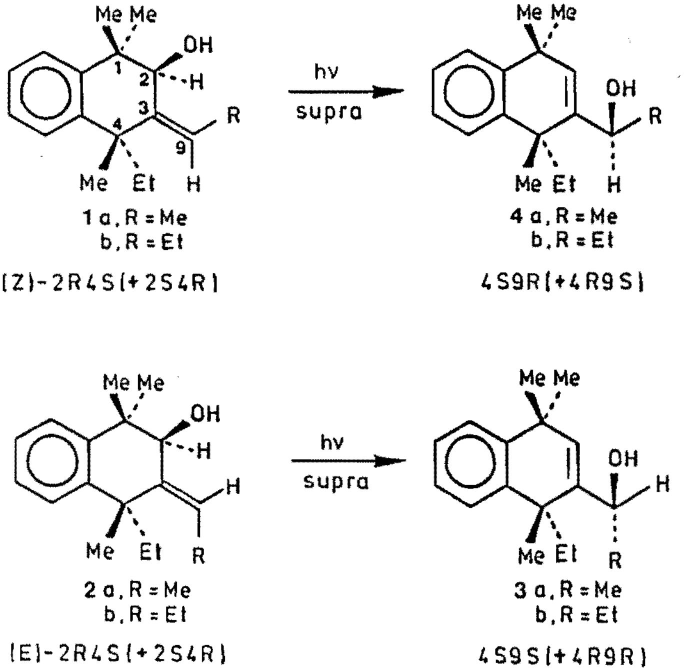


Figure 6. Products expected from a suprafacial [1,3]-OH shift in **1a,b** and **2a,b**.

transition states for these two suprafacial shifts would be diastereoisomeric of nature. Going from the starting geometry to the transition state, the interaction between the trans oriented vinylic substituent at C_9 and the alkyl substituents at C_4 will increase. This interaction will be largest in case of a trans oriented methyl or ethyl group (compounds **2a,b**). Therefore, the activation energy of a suprafacial [1,3]-OH shift will be lowest for compounds **1a,b**, thus leading to excess formation of **4a,b**. From this it may be concluded that, apart from conformational aspects (vide infra), the observed stereoselectivity (yielding predominantly 3a,b) makes a suprafacial mechanism rather improbable.

The observed stereospecificity agrees well with the one expected in case of a planar [1,3]-OH shift. Bearing in mind the knowledge about the photochemical behaviour of excited alkenes, direct irradiation of either **1a** or 2a will lead to a 90° twist of the exocyclic double bond in order to diminish the electronic repulsion between the antibonding p-orbitals. This twist will be accompanied by a complete charge separation in the orthogonal situation ("Sudden Polarization", vide supra). In view of the inequality of the substituents at both C_4 and C_9, twisting of the exocyclic double bond may take place in two opposite directions. Due to the in case of compounds **1a** and **2a** large steric interaction between the C_4(Et) and the C_9(Me), preferential formation of just one twisted geometry will take place i.e. the one in which the vinylic methyl group is turned away from the

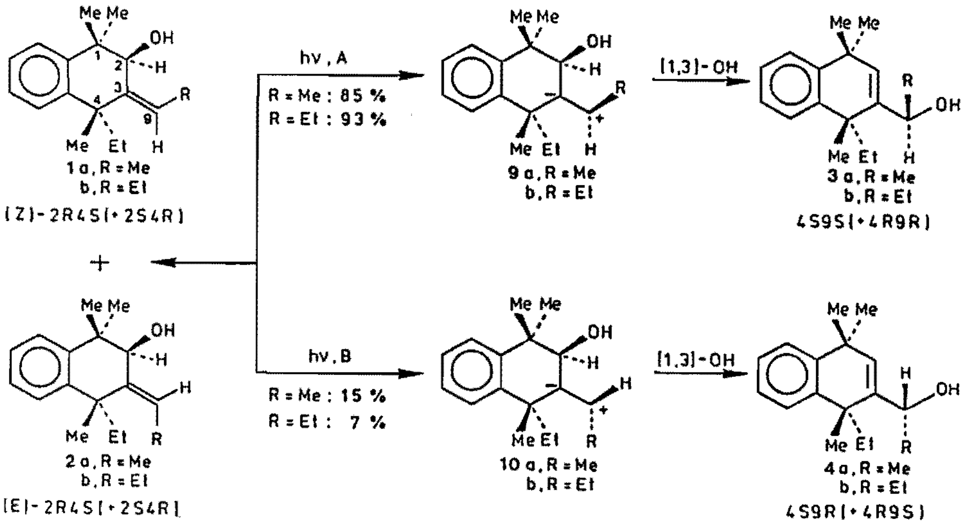


Figure 7. Products resulting from a planar [1,3]-OH shift in **1a,b** and **2a,b**.

allylic ethyl group (reaction route A in Figure 7).

Thereupon, MNDO-calculations on the preferential conformation of **1a** and **2a** show that in the ground state a small sp^2-sp^2 torsion around the exocyclic double bond of 3° respectively 8° is present. Again this distortion is caused by the interaction between the C_4(Et) and the C_9(Me) and is directed in the same way as in the case of structure **9a**. Thus it is evident that excitation of these slightly distorted conformations will lead to the preferential formation of the 90° twisted geometry **9a**. From this polarized structure either a radiationless transition to the ground state, yielding the (isomerized) reactants 1a and 2a, or a planar [1,3]-OH shift may occur. As shown in Figure 7, there is now only one way in which the migrating hydroxyl group can approach C_9. This will lead to the formation of a relative (4SR,9SR)-configuration in the thus formed product **3a**.

Likewise, formation of **4a** to a smaller extent can in the framework of a planar [1,3]-OH shift be explained by assuming a planar shift starting from the 90° twisted geometry **10a** (route B, Figure 7). Due to the in this case *un*favourable ground-state distorsion of the exocyclic double bond in the starting products **1a** and **2a** and because of the interaction between the C_4(Et) and the C_9(Me), formation of this intermediate will hardly take place.

The planar mechanism is strongly supported by the observed photochemistry of **1b** and **2b**. In case of compounds **1b** and **2b** an even larger interaction between the substituents at C_4 and C_9 exists. Because of this large interaction intermediate **10b** will be formed to an even lesser extend, thereby explaining the observed increase in stereoselectivity of the [1,3]-OH shift upon substitution of the vinylic methyl group by the more bulky ethyl group.

Besides this, the photochemical behaviour of (2RS,4RS)-**5a**,**b** delivers additional evidence for the occurrence of a planar [1,3]-OH shift. Irradiation of these compounds in n-hexane or methanol does not result in the occurrence of a [1,3]-OH shift. In order to give an explanation for this apparent contradictory behaviour a conformational analysis of both **5a** and **6a**, using the semi-empirical MNDO-method[7], was performed. In these compounds the exocyclic double bond can adapt two possible orientations leading to a stable conformer, one in which the hydroxyl group is located in the plane of the exocyclic double bond and one in which the hydroxyl group is situated out of this plane. These conformers can be denoted as S respectively R[8]. First of all the steric energy of the conformers was minimized by means of MM2 calculations[9]. Coordinates found in this way were used as starting values for the MNDO-calculations. The heats of formation and relative populations of the fully relaxed geometries for both **5a** and **6a** are given in the Tables I and II.

The calculations clearly show a preferential ground state conformation in which the hydroxyl group is located out of the plane of the exocyclic double bond. Again this is caused by the large steric interaction between the substituents at the exocyclic double bond and the C_4(Et). In Figure 8 the preferential ground-state conformation of **5a** is depicted. Dreiding molecular models clearly show the corresponding 3-propylidene derivatives **5b** and **6b** to possess a similar preferential conformation.

Concerning the mechanism of a photochemical [1,3]-OH shift, the conformation in which the hydroxyl group is located in the plane of the exocyclic double bond is in favour for a planar shift to occur.

Table I. Heats of Formation (ΔH_f) and Relative Populations (at 0 °C) of All Stable Conformers of (Z)-(2S4S)-5a.

Conformer	ΔH (Kcal mol^{-1})	Relative Populations (%)
S	-0.121	$4.4 \cdot 10^{-3}$
R	-5.542	99.9956

Table II. Heats of Formation (ΔH_f) and Relative Populations (at 0 °C) of All Stable Conformers of (E)-(2S4S)-**6a**.

Conformer	ΔH (Kcal mol^{-1})	Relative Populations (%)
S	1.865	0.03
R	-2.447	99.97

Regarding the very low relative populations of this (S)-conformation in both 5a and 6a (<0.03%), a planar [1,3]-OH shift is not very likely in these compounds. On the other hand, a location of the hydroxyl group out of the plane of the exocyclic bond favours a suprafacial shift to take place. Thus the non-occurrence of a [1,3]-OH shift upon irradiation of a 50:50 mixture of **5a,b** and **6a,b** gives an extra indication in favour of a non-Woodward and Hoffmann reaction path. Despite the favourable ground-state conformation of **5a,b** and **6a,b** for a suprafacial shift to occur, this shift does not take place. Instead a 90° twisted (polarized) intermediate is formed (as could be proven by irradiation of **5a,b** in methanol), from which solely a radiationless transition to the ground state is observable. Besides this, the absence of products derived from a [1,3]-OH shift in the irradiation of **5a,b** and **6a,b** likely indicates the occurrence

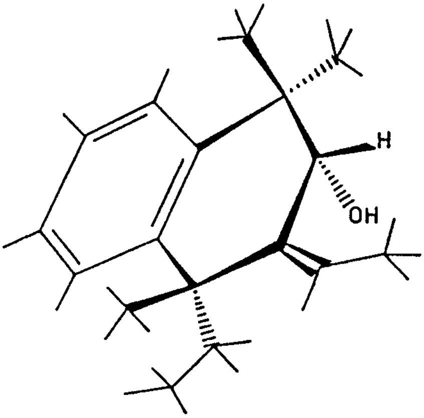


Figure 8. Preferential conformation of (Z)-2S4S-**5a**.

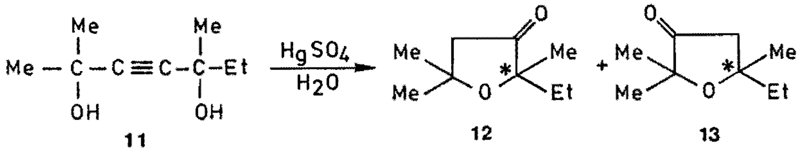
of a non-radical process. For in that case cleavage of the C_2-hydroxyl bond will be followed by recombination of the hereby formed (bi)radicals. This recombination is independent of the conformation of the substrate. Hence formation of a biradicalar intermediate is expected to give rise to the occurrence of a photochemical [1,3]-OH shift in all substrates.

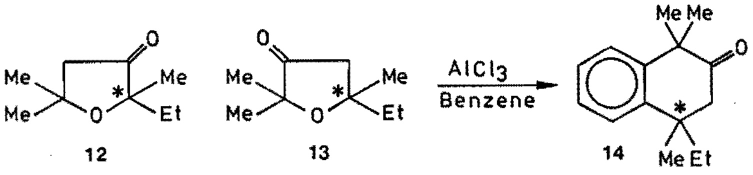
3.4 Experimental Section

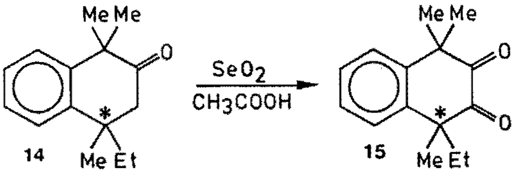
3.4.1 Synthesis of Reactants of Interest

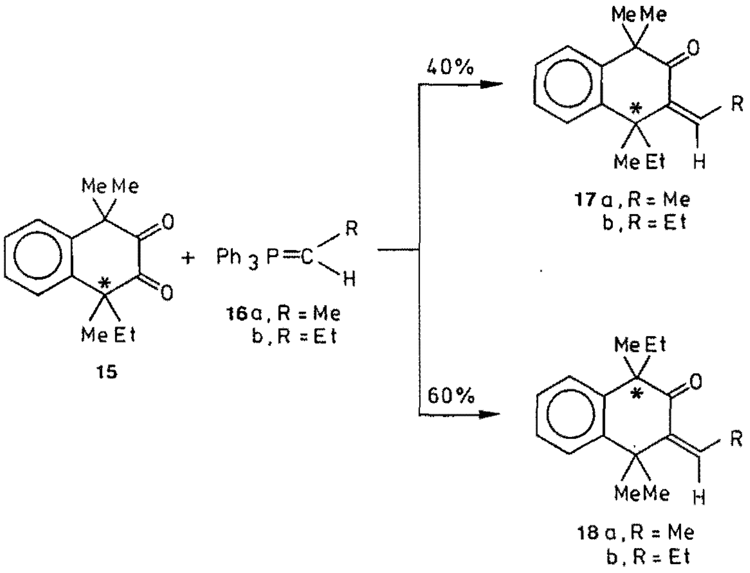
The reaction route for the synthesis of the diastereoisomeric mixtures of (2RS,4SR)- and (2RS,4RS)-3,4-dihydro-4-ethyl-1,1,4-trimethyl-(Z)-3-ethylidene-2(1H)-naphthalenol (**1a** and **5a** respectively), (2RS,4SR)- and (2RS,4RS)-3,4-dihydro-4-ethyl-1,1,4-trimethyl-(Z)-3-propylidene-2(1H)-naphthalenol (**1b** and **5b** respectively) is outlined in Scheme I.

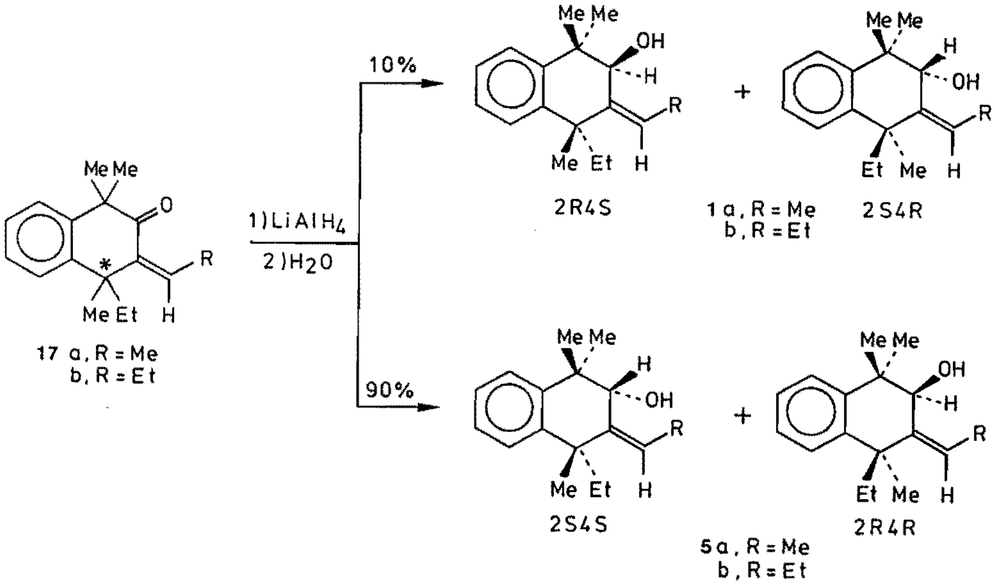
Hydration of the acetylenic γ-diol **11** in the presence of $HgSO_4$


Me
Me
Me
C
C
C
C
Et
OH
OH
11
HgSO4
H2O
O
Me
Me
Me
Et
O
*
12
+
O
Me
Me
Me
Et
O
*
13


O
Me
Me
Me
Et
O
*
12
O
Me
Me
Me
Et
O
*
13
AlCl3
Benzene
Me Me
O
*
14
Me Et


Me Me
O
*
14
Me Et
SeO2
CH3COOH
Me Me
O
O
*
15
Me Et


Me Me
O
O
*
Me Et
15
+
Ph3P=C
R
H
16a, R = Me
b, R = Et
40%
Me Me
O
R
*
Me Et
H
17a, R = Me
b, R = Et
60%
Me Et
*
O
R
Me Me
H
18a, R = Me
b, R = Et



Scheme I. Reaction Route for the Synthesis of the Photochemical Reactants **1a,b** and **5a,b**.

yielded a mixture of the isomeric tetrahydrofuranones **12** and **13** in an equal ratio. Upon Friedel-Crafts cyclialkylation of this mixture with benzene in the presence of $AlCl_3$, the tetrasubstituted naphthalenone derivative **14** could be isolated. Upon SeO_2-oxidation and subsequent Wittig-reaction of the resulting diketone **15**, using the alkylidenephosphoranes **16a** and **16b**, the isomeric α,β-unsaturated ketones **17a,b** and **18a,b** were obtained in ratios of 40:60. In order to distinguish the 1-ethyl-1,4,4-trimethyl and 4-ethyl-1,1,4-trimethyl derivatives, ^1H NMR $Eu(fod)_3$ shift experiments were carried out.

As indicated in Figure 9 for the 3-ethylidene derivatives **17a** and **18a**, the results show clearly that the C_1-methylene protons in case of compound **18a** display a larger shift than the corresponding C_4-

methylene protons of compound **17a**.

Besides this, addition of $Eu(fod)_3$ to compound **17a** causes a rather large shift of the two $C_1(Me)$ groups. In case of compound **18a** however only one $C_1(Me)$ group displays this behaviour. As $Eu(fod)_3$ is known to form stable complexes with the carbonyl group, these results strongly confirm the proposed structures. Thereupon, a Z-configuration of both exocyclic double bonds could be deduced from comparison of the induced chemical shifts of the vinylic methyl and hydrogen substituents upon addition of $Eu(fod)_3$ (see Figure 9).

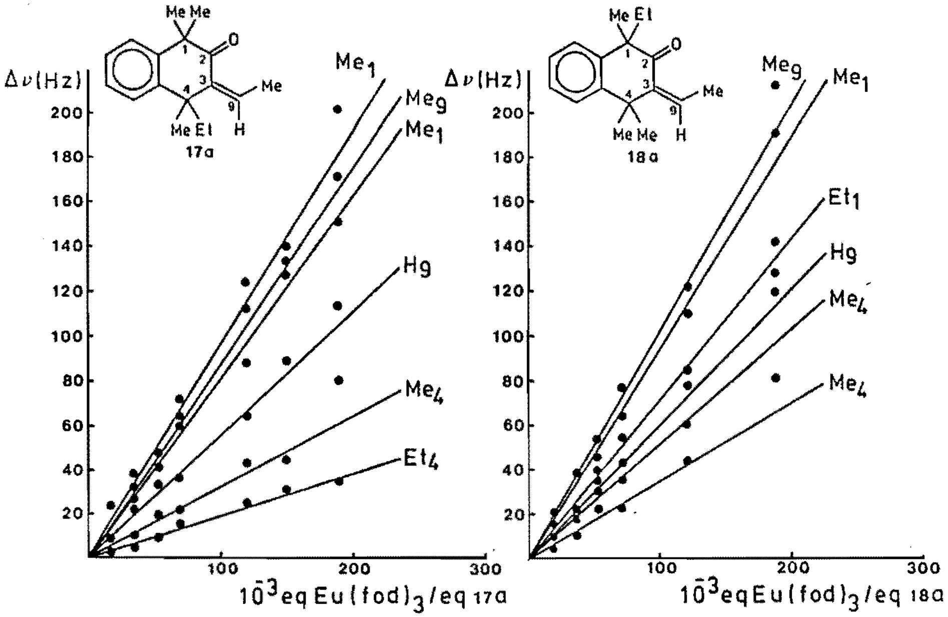


Figure 9. Plot of the induced chemical shift, Δν, versus the amount of added shift reagent for protons of **17a** and **18a**.

Similarly, ^1H NMR Eu(fod)$_3$ shift experiments on **17b** and **18b** enabled an unambiguous structure determination of these compounds.

Separation of the isomeric ketones 17a,**b** and 18a,**b** could be accomplished by using argentation chromatography. Upon LiAlH$_4$-reduction of the racemic mixture of **17a** (**17b**), the diastereoisomeric allylic alcohols **1a** (**1b**) and **5a** (**5b**) were formed in ratios of 10:90. Thus nearly complete asymmetric induction occurs. An explanation of this phenomenon is based on the conformation of the substrate. As the bulky ethyl group shields one side of the plane of the carbonyl group, hydride-attack is more likely to occur from the opposite side. This implies that a R(S)-configuration on C$_4$ results in a preferential hydride-attack yielding predominantly a R(S)-configuration on C$_2$.

3.4.2 Structural Assignment of Photoproducts

The structure elucidation of the various photoproducts was accomplished by comparison of the relative positions and multiplicities of the ^1H- and ^{13}C-NMR resonances. The relative configurations at C$_4$ and C$_9$ of the products derived from a [1,3]-OH shift, **3a,b** and **4a,b**, were deduced from the relative configurations of the corresponding methyl ethers **7a,b** and **8a,b**. In order to correlate these products, the allylic alcohols 3a,**b** and 4a,**b** were separately methylated to yield 8a,**b** and 7a,**b** respectively (as shown by GLC). Since this reaction does not affect the chirality at either C$_4$ or C$_9$, the correlation between 3a,b, 8a,b and 4a,b, 7a,b is evident. In order to establish the stereostructure of both 7a,b and 8a,b, low temperature difference nuclear Overhauser enhancement (NOE) measurements were performed[10,11]. Irradiation of the methoxy group produced

Table III. Observed NOE (%) of $C_2(H)$ upon Irradiation of $C_9(OMe)$ at Several Temperatures for Compounds **7a** and **8a**.

Temperature (K)	Compound **7a**	Compound **8a**
293	1.3	0.2
273	0.9	0.6
253	3.2	0.3
233	4.8	0.9
213	7.4	1.1
203	9.3	0.8

Table IV. Observed NOE (%) of $C_2(H)$ upon Irradiation of $C_9(OMe)$ at Several Temperatures for Compounds **7b** and **8b**.

Temperature (K)	Compound **7b**	Compound **8b**
293	-0.3	0.2
273	0.6	0.4
253	1.5	0.3
233	3.6	1.0
213	5.3	0.8
203	6.8	0.9

enhancement of several other proton resonances in each case. As shown in Tables III and IV, the most significant result of these measurements is the observation of enhancement of the vinylic $C_2(H)$ in **7a,b** and not in **8a,b**, at temperatures below -20 °C.

Since a linear relationship between the observed NOE and the sixth power of the internuclear distance has been established by Bell and Saunders[12], these results indicate that at low temperatures the internuclear C_2(H)-C_9(OMe) distance in compounds **7a,b** is considerably smaller than in case of compounds **8a,b**. Dreiding molecular models show that in the preferential conformation of both **7a,b** and **8a,b** the C_9(H) is located in an anti-position to the C_2-C_3 double bond, thereby minimizing the interaction between the substituents at C_9 and C_4. In case of a relative (4SR,9SR)-configuration, C_9(OMe) and C_4(Et) are located on the same side of the plane of the C_2-C_3 double bond. A relative (4SR,9RS)-configuration on the other hand implies a location of the C_9(OMe) and the C_4(Et) on opposite sides of the plane of the C_2-C_3 double bond. Dependent on the chirality at C_4 the C_4(Et) shields one side of this plane. This means that in case of a relative (4SR,9SR)-configuration the C_9(OMe) is directed away from the C_4(Et), which leads to an increase of the C_2(H)-C_9(OMe) internuclear distance. Thus, based on the results of the low temperature NOE experiments, a (4SR,9SR)-configuration can be assigned to compounds **8a,b** and **3a,b**. As in case of a relative (4SR,9RS)-configuration the C_4(Et)-C_9(OMe) internuclear distance is much larger, the C_9(OMe) will hardly be influenced by this substituent. This implies that in the preferential conformation the C_9(OMe) is located near the vinylic C_2(H), thus accounting for the observed enhancement of the ^{1}H NMR signal of this proton upon irradiation of the C_9(OMe) resonance. So compounds **7a,b** and **4a,b** have a (4SR,9RS)-configuration.

3.4.3 Materials and Methods. Preparation of Compounds

^1H and ^{13}C NMR spectra were recorded at 200 respectively 50 MHz on a Bruker AC 200 NMR spectrometer, interfaced with an ASPECT 3000 computer. An internal field-frequency lock was used. Chemical shifts were referenced against tetramethylsilane (δ = 0 ppm), which was added as a small trace. NOE difference spectra were obtained using the method of Hall and Sanders[10] with the following timings: preirradiation (5 sec), delay (50 msec), 90° pulse (3 μsec) and acquire one transient (2.7 sec). Eight transients were collected at each site during each pass around the full frequency list until 200 transients had been accumulated at every site. Thoroughly degassed CD_2Cl_2 was used as a solvent. Gas chromatograms were recorded using a Kipp Analytica 8200 equipped with a flame-ionization detector. Columns used were Chrompack fused silica wall, open tubular columns with CP Wax 51 as liquid phase (25 m x 0.23 mm). The UV measurements were performed on a Perkin-Elmer 124 spectrofotometer. Argentation chromatography was performed using impregnated silica, prepared by evaporating to dryness of a slurry of silica (type 60, Merck) and 10% $AgNO_3$ in CH_3CN.

3.4.4 Irradiation Procedure

Irradiations were performed using a 500 Watt medium pressure mercury lamp (Hanau TQ718) through quartz. Cooling of the lamp and the reaction vessel was accomplished by means of a closed circuit filled with methanol. The temperature in the reaction vessel was maintained at ± 0 °C. A 6×10^{-3} molar solution of the various compounds in n-hexane or methanol (both p.a.) was used. Before and during irradiation, the reaction mixture was purged by a stream of dry nitrogen in order to remove all traces of oxygen. All irradiations were followed by means of GLC. Upon GLC indicating the presence of sufficient amounts of photoproducts to be identified by means of ^1H and ^{13}C NMR spectroscopy (usually at approximately 5% conversion), the irradiation was stopped and the solvent removed on a rotatory evaporator. The crude reaction mixture was separated by means of repeated argentation chromatography.

2-Ethyldihydro-2,5,5-trimethyl-3(2H)-furanone (12) and 5-ethyldihydro-2,2,5-trimethyl-3(2H)-furanone (13)[13]**.**

To a mixture of 27 g of HgO, 30 mL of conc. H_2SO_4 and 100 mL of water was added with cooling 300 g (1.92 mol) 2,5-dimethyl-3-heptyn-2,5-diol (11). The mixture was stirred for 2h at 70 °C. After cooling to room temperature and filtration, the aqueous layer was extracted with two 300-mL portions of ether. The combined organic extracts were neutralized with a saturated $NaHCO_3$-solution, washed with brine, dried over $MgSO_4$ and evaporated. Distillation (20 mm, 73-74 °C) afforded 208 g (69%) of 12 and 13 in a ratio of 50:50 (as indicated by GLC).

^1H NMR ($CDCl_3$) δ .85 (t,3H), 0.94 (t,3H), 1.23 (s,6H), 1.24 (s,3H), 1.31 (s,3H), 1.34 (s,3H), 1.40 (s,3H), 1.56 (m,4H), 2.43 (m,4H); ^{13}C NMR ($CDCl_3$) δ 214.49 (s), 214.15 (s), 83.72 (s), 80.48 (s), 78.64 (s), 75.98 (s), 49.72 (t), 46.44 (t), 35.26 (t), 32.34 (t), 30.66 (q), 30.31 (q), 27.79 (q), 26.66 (q), 26.27 (q), 24.61 (q), 8.79 (q), 8.51 (q).

3,4-Dihydro-4-ethyl-1,1,4-trimethyl-2(1H)-naphthalenone (14)[14]. To a stirred solution of 208 g (1.33 mol) of **12** and **13** in 750 mL of anhydrous benzene was added gradually anhydrous, powdered $AlCl_3$ (316 g, 2.37 mol) while maintaining the temperature between 40 and 50 °C by external cooling. The solution was then heated at reflux for 2h, cooled and poured into one liter of ice and water containing 150 mL of conc. HCl. The aqueous layer was washed with four 200-mL portions of ether. The combined organic layers were washed with a saturated $NaHCO_3$-solution, dried over $MgSO_4$ and concentrated in vacuo. Chromatography (silica 60, n-hexane-ether 3:1 (v/v)) afforded 50.7 g (18%) of **14**.

^1H NMR ($CDCl_3$) δ .60 (t,3H), 1.27 (s,3H), 1.30 (s,3H), 1.40 (s,3H), 1.79 (q,2H), 2.57 (AB-q, A 2.50, B 2.64, J_{AB}= 12.8 Hz, 2H), 7.09-7.45 (m,4H); ^{13}C NMR ($CDCl_3$) δ 213.89 (s), 145.19 (s), 142.36 (s), 127.82 (d), 127.68 (d), 127.33 (d), 125.49 (d), 53.32 (s), 53.22 (s), 38.85 (t), 34.79 (t), 32.10 (q), 31.47 (q), 29.26 (q), 10.79 (q).

1,4-Dihydro-1-ethyl-1,4,4-trimethyl-2,3-naphthalenedione (15). To a solution of 50.7 g (0.23 mol) of **14** in 250 mL of glacial acetic acid was added 30 g (0.27 mol) SeO_2. The mixture was heated at reflux for 4h. The cooled solution was thoroughly filtered and the solvent removed in vacuo. The residu was dissolved in 200 mL of ether, washed with water and a saturated $NaHCO_3$-solution. The organic layer was dried over $MgSO_4$ and concentrated under reduced pressure. This afforded 52.8 g (97%) of **15**.

^1H NMR ($CDCl_3$) δ .71 (t,3H), 1.43 (s,3H), 1.48 (s,3H), 1.54 (s,3H), 1.87 (m,2H), 7.13-7.48 (m,4H); ^{13}C NMR ($CDCl_3$) δ 206.32 (s), 206.10 (s), 141.84 (s), 139.80 (s), 128.91 (d), 128.81 (d), 127.33 (d), 127.15 (d), 56.34 (s), 51.74 (s), 35.40 (t), 28.73 (q), 26.00 (q), 23.96 (q), 9.97 (q).

3,4-Dihydro-4-ethyl-1,1,4-trimethyl-(Z)-3-ethylidene-2(1H)-naphthalenone and 3,4-dihydro-1-ethyl-1,4,4-trimethyl-(Z)-3-ethylidene-2(1H)-naphthalenone (**17a** and **18a** respectively).
n-Butyllithium (187 mL of a 1.6 M solution in n-hexane, 0.30 mol) was added dropwise to a stirred suspension of 102.2 g (0.28 mol) (ethyl)triphenylphosphonium bromide in 200 mL of anhydrous ether, whereupon the deep red color of the ethylidenephosphorane **16a** was produced. The mixture was then stirred for 2h at room temperature. At the end of this period 52.8 g (0.23 mol) of **15** was added dropwise, whereupon a white precipitate formed. The mixture was then cooled and filtered by suction. The filtrate was washed with water, the organic layer separated and dried over $MgSO_4$. Removal of ether left a residue which was separated by repeated argentation chromatography using n-hexane-ether 95:5 (v/v) as eluent. Thus 3.2 g of **17a** and 4.5 g of **18a** could be obtained (total yield = 14%). The corresponding E-isomers were not detected as byproducts. GLC showed the original product mixture to contain **17a** and **18a** in a ratio of 40:60.

17a; ^{1}H NMR ($CDCl_3$) δ .70(t,3H), 1.38 (s,3H), 1.40 (s,3H), 1.46 (s,3H), 1.78 (d,3H), 2.05 (q,2H), 5.74 (q,1H), 7.10-7.46 (m,4H); ^{13}C NMR ($CDCl_3$) δ 209.98 (s), 145.27 (s), 144.08 (s), 143.83 (s), 129.05 (d), 127.73 (d), 127.63 (d), 125.52 (d), 125.30 (d), 50.19 (s), 43.08 (s), 38.89 (t), 30.63 (q), 28.66 (q), 24.16 (q), 16.13 (q), 9.77 (q).

18a; ^{1}H NMR ($CDCl_3$) δ .63 (t,3H), 1.37 (s,3H), 1.42 (s,3H), 1.49 (s,3H), 1.80 (d,3H), 2.09 (q,2H), 5.81 (q,1H), 7.10-7.49 (m,4H); ^{13}C NMR ($CDCl_3$) δ 210.25 (s), 147.09 (s), 144.87 (s), 141.92 (s), 129.30 (d), 127.79 (d), 127.40 (d), 126.00 (d), 125.75 (d), 54.49 (s), 46.84 (s), 35.09 (t), 31.61 (q), 30.60 (q), 27.03 (q), 16.02 (q), 10.72 (q).

3,4-Dihydro-4-ethyl-1,1,4-trimethyl-(Z)-3-propylidene-2(1H)-naphthalenone and 3,4-dihydro-1-ethyl-1,4,4-trimethyl-(Z)-3-propylidene-2(1H)-naphthalenone (17b and 18b respectively).

The same procedure was used as for the preparation of **17a** and **18a**. Starting from 50.0 g (0.22 mol) of **15**, 3.0 g of **17b** and 3.9 g of **18b** were obtained after repeated argentation chromatography using n-hexane-ether 9:1 (v/v) as eluent.

17b; ^{1}H NMR ($CDCl_3$) δ .63 (t,3H), 1.00 (t,3H), 1.40 (s,3H), 1.43 (s,3H), 1.49 (s,3H), 2.10 (q,2H), 2.20 (m,2H), 5.63 (t,1H), 7.09-7.48 (m,4H); ^{13}C NMR ($CDCl_3$) δ 209.73 (s), 145.17 (s), 143.78 (s), 141.88 (s), 127.87 (d), 127.72 (d), 126.93 (d), 126.13 (d), 125.35 (d), 54.30 (s), 42.86 (s), 34.89 (t), 32.18 (t), 29.39 (q), 24.31 (q), 23.55 (q), 15.27 (q), 10.62 (q).

18b; ^{1}H NMR ($CDCl_3$) δ .67 (t,3H), 1.00 (t,3H), 1.42 (s,3H), 1.43 (s,3H), 1.50 (s,3H), 2.12 (q,2H), 2.19 (m,2H), 5.67 (t,1H), 7.14-7.53 (m,4H); ^{13}C NMR ($CDCl_3$) δ 210.12 (s), 145.58 (s), 144.01 (s), 143.24 (s), 128.79 (d), 127.70 (d), 127.30 (d), 125.94 (d), 124.16 (d), 53.55 (s), 49.92 (s), 38.84 (t), 31.24 (t), 30.79 (q), 27.50 (q), 23.62 (q), 15.54 (q), 9.63 (q).

(2RS,4SR)- and (2RS,4RS)-3,4-Dihydro-4-ethyl-1,1,4-trimethyl-(Z)-3-ethylidene-2(1H)-naphthalenol (**1a** and **5a** respectively).
To a stirred suspension of 0.5 g (13.2 mmol) of $LiAlH_4$ in 50 mL of anhydrous ether was added dropwise, at 0 °C, a solution of 3.2 g (13.2 mmol) of **17a** in 25 mL ether. After 30 min. additional stirring the reaction mixture was allowed to warm to room temperature. After addition of respectively 1 mL of water, 1 mL of a 5N NaOH solution and 5 mL of water, filtration, separation of the organic layer and removal of the solvent afforded 3.0 g (94%) of a mixture of **1a** and **5a**. GLC showed a composition of 10% of **1a** and 90% of **5a**. Separation was accomplished by using repeated argentation chromatography with n-hexane-ether 9:1 (v/v) as eluent.

1a; ^{1}H NMR ($CDCl_3$) δ .73 (t,3H), 1.24 (s,3H), 1.32 (s,3H), 1.40 (s,3H), 1.80 (d,3H), 2.03 (q,2H), 4.53 (s,1H), 5.80 (q,1H), 7.03-7.33 (m,4H); ^{13}C NMR ($CDCl_3$) δ 145.13 (s), 143.78 (s), 142.73 (s), 128.43 (d), 127.81 (d), 127.50 (d), 127.02 (d), 126.36 (d), 75.50 (d), 43.49 (s), 40.63 (s), 36.20 (t), 32.62 (q), 29.40 (q), 20.31 (q), 15.14 (q), 10.17 (q).
UV (EtOH) λ_{max} 240 nm.

5a; ^{1}H NMR ($CDCl_3$) δ .87 (t,3H), 1.28 (s,3H), 1.35 (s,3H), 1.49 (s,3H), 1.81 (d,3H), 1.97 (q,2H), 4.47 (s,1H), 5.69 (q,1H), 7.07-7.38 (m,4H); ^{13}C NMR ($CDCl_3$) δ 144.57 (s), 143.04 (s), 141.94 (s), 129.23 (d), 127.87 (d), 127.58 (d), 127.14 (d), 127.01 (d), 75.02 (d), 45.65 (s), 43.64 (s), 39.05 (t), 31.10 (q), 27.07 (q), 23.89 (q), 14.21 (q), 10.89 (q).

UV (EtOH) λ_{max} 245 nm.

(2RS,4SR)- and (2RS,4RS)-3,4-Dihydro-4-ethyl-1,1,4-trimethyl-(Z)-3-propylidene-2(1H)-naphthalenol (1b and 5b respectively).

The same procedure was used as for the reduction of **17a**. Starting from 3.0 g (11.7 mmol) of **17b**, 3.0 g of a mixture of **1b** and **5b** was obtained. GLC showed this mixture to contain 10% of **1b** and 90% of **5b**. Separation was accomplished using repeated argentation chromatography with n-hexane-ether 9:1 (v/v) as eluent.

1b; ^{1}H NMR ($CDCl_3$) δ .86 (t,3H), 1.05 (t,3H), 1.20 (s,3H), 1.41 (s,3H), 1.51 (s,3H), 2.03 (q,2H), 2.22 (m,2H), 4.47 (s,1H), 5.53 (t,1H), 6.97-7.33 (m,4H); ^{13}C NMR ($CDCl_3$) δ 143.64 (s), 142.82 (s), 140.74 (s), 129.63 (d), 128.61 (d), 128.39 (d), 127.85 (d), 126.79 (d), 75.65 (d), 44.26 (s), 40.22 (s), 38.69 (t), 36.81 (t), 31.06 (q), 27.62 (q), 21.71 (q), 15.81 (q), 10.57 (q).

UV (EtOH) λ_{max} 250 nm.

5b; ^{1}H NMR ($CDCl_3$) δ 1.05 (t,3H), 1.10 (t,3H), 1.15 (s,3H), 1.45 (s,3H), 1.57 (s,3H), 2.00 (q,2H), 2.23 (m,2H), 4.75 (s,1H), 5.69 (t,1H), 7.08-7.43 (m,4H); ^{13}C NMR ($CDCl_3$) δ 145.43 (s), 144.58 (s), 143.20 (s), 130.07 (d), 128.39 (d), 127.47 (d), 127.26 (d), 126.48

(d), 70.29 (d), 42.23 (s), 39.45 (s), 37.82 (t), 34.30 (t), 30.57 (q), 27.65 (q), 21.71 (q), 15.99 (q), 9.36 (q).

UV (EtOH) λ_{max} 240 nm.

(1SR,9RS)-1,4-Dihydro-1-ethyl-1,4,4-trimethyl-2(1-methoxyethyl)-naphthalene (7a).

A mixture of 0.015 g (0.63 mmol) of NaH and 15 mL of THF was heated to 40 °C, followed by addition of 0.1 g (0.7 mmol) of CH_3I. A solution of 0.1 g (0.41 mmol) of **4a** in 10 mL of THF was added dropwise. Then the mixture was kept at 40 °C for 90 min. After cooling the reaction mixture, hydrolysis was performed by dropwise addition of excess of water. The aqueous layer was separated and extracted twice with ether. The combined organic layers were washed with brine and dried over $MgSO_4$. GLC showed **7a** to be the main product present. No traces of **8a** could be detected. Evaporation and subsequent column chromatography (Woelm silica, n-hexane-ether 95:5 (v/v)) yielded 0.055 g (52%) of **7a**.

^{1}H NMR ($CDCl_3$) δ .50 (t,3H), 1.26 (s,3H), 1.32 (d,3H), 1.35 (s,3H), 1.42 (s,3H), 1.79 (q,2H), 3.23 (s,3H), 3.91 (q,1H), 5.84 (s,1H), 7.11-7.38 (m,4H); ^{13}C NMR ($CDCl_3$) δ 148.54 (s), 143.25 (s), 138.73 (s), 133.49 (d), 127.43 (d), 127.10 (d,2x), 126.98 (d), 75.74 (d), 57.05 (q), 43.16 (s), 41.92 (s), 34.92 (t), 34.57 (q), 33.88 (q), 24.99 (q), 23.75 (q), 11.02 (q).

(1SR,9SR)-1,4-Dihydro-1-ethyl-1,4,4-trimethyl-2(1-methoxyethyl)-naphthalene (8a).

Starting from 0.14 g (0.58 mmol) of **3a**, the same procedure was used as for the methylation of **4a**. GLC indicated **8a** to be the main product formed, no traces of **7a** could be detected. Column chromatography (Woelm silica, n-hexane-ether 95:5 (v/v)) yielded 0.09 g (61%) of **8a**.

^{1}H NMR ($CDCl_3$) δ .43 (t,3H), 1.28 (s,3H), 1.34 (d,3H), 1.36 (s,3H), 1.42 (s,3H), 1.76 (q,2H), 3.28 (s,3H), 3.97 (q,1H), 5.87 (s,1H), 7.15-7.40 (m,4H); ^{13}C NMR ($CDCl_3$) δ 146.78 (s), 141.56 (s), 139.51 (s), 134.12 (d), 128.11 (d), 127.31 (d), 126.98 (d), 126.78 (d), 74.92 (d), 56.33 (q), 44.03 (s), 39.86 (s), 35.13 (t), 34.11 (q), 33.70 (q), 24.40 (q), 23.47 (q), 10.81 (q).

(1SR,9RS)-1,4-Dihydro-1-ethyl-1,4,4-trimethyl-2(1-methoxypropyl)-naphthalene (7b).

The same procedure was used as for the preparation of compounds **7a** and **8a**. Starting from 0.1 g (0.39 mmol) of **4b**, a 20 % conversion was achieved after stirring for 5 h. GLC indicated **7b** to be the main product present, **8b** could not be detected. Column chromatography (Woelm silica, n-hexane-ether 99:1 (v/v)) yielded 0.01g (46%) of **7b**.

^{1}H NMR ($CDCl_3$) δ .59 (t,3H), .87 (t,3H), 1.25 (s,3H), 1.36 (s,3H), 1.43 (s,3H), 1.73 (q,2H), 2.01 (m,2H), 3.27 (s,3H), 4.06 (t,1H), 5.57 (s,1H), 7.13-7.42 (m,4H); ^{13}C NMR ($CDCl_3$) δ 145.37 (s), 142.11 (s), 141.47 (s), 133.57 (d), 131.94 (d), 129.88 (d), 126.94 (d), 126.73 (d), 78.32 (d), 57.16 (q), 40.85 (s), 38.17 (s), 33.54 (t), 32.72 (t), 31.23 (q), 30.02 (q), 24.07 (q), 15.19 (q), 12.33 (q).

(1SR,9SR)-1,4-Dihydro-1-ethyl-1,4,4-trimethyl-2(1-methoxypropyl)-naphthalene (8b).

Compound **8b** was prepared in the same way as compounds **7a,b** and **8a**. Starting from 0.2 g of 3b, column chromatography (Woelm silica, n-hexane-ether 99:1 (v/v)) yielded 0.04 g (20%) of **8b**. As indicated by GLC, **8a** was not present in the crude reaction mixture.

^{1}H NMR ($CDCl_3$) δ .52 (t,3H), .95 (t,3H), 1.28 (s,3H), 1.39 (s,3H), 1.48 (s,3H), 1.69 (q,2H), 2.06 (m,2H), 3.24 (s,3H), 4.03 (t,1H), 5.55 (s,1H), 7.10-7.38 (m,4H); ^{13}C NMR ($CDCl_3$) δ 145.85 (s), 142.06 (s), 140.80 (s), 132.68 (d), 131.86 (d), 130.14 (d), 127.98 (d), 125.61 (d), 77.92 (d), 56.77 (q), 40.89 (s), 37.82 (s), 33.35 (t), 33.01 (t), 31.55 (q), 30.52 (q), 24.85 (q), 15.37 (q), 11.96 (q).

3.4.5 Spectral Data for the Remaining Photoproducts

2a; ^{1}H NMR ($CDCl_3$) δ .63 (t,3H), 1.21 (s,3H), 1.27 (s,3H), 1.43 (s,3H), 1.88 (d,3H), 2.13 (q,2H), 4.29 (s,1H), 5.73 (q,1H), 7.11-7.35 (m,4H); ^{13}C NMR ($CDCl_3$) δ 144.23 (s), 143.53 (s), 143.48 (s), 129.24 (d), 128.93 (d), 127.85 (d), 127.04 (d), 126.62 (d), 78.32 (d), 45.31 (s), 42.44 (s), 40.46 (t), 28.00 (q), 24.51 (q), 21.78 (q), 15.20 (q), 11.50 (q).

3a; ^{1}H NMR ($CDCl_3$) δ .47 (t,3H), 1.30 (s,3H), 1.31 (d,3H), 1.33 (s,3H), 1.36 (s,3H), 1.81 (q,2H), 3.89 (q,1H), 5.58 (s,1H), 7.10-7.40 (m,4H); ^{13}C NMR ($CDCl_3$) δ 145.54 (s), 142.09 (s), 140.16 (s), 132.16 (d), 128.32 (d), 127.26 (d), 126.85 (d), 126.74 (d), 72.98 (d), 43.83 (s), 40.37 (s), 35.07 (t), 33.81 (q), 33.12 (q), 25.06 (q), 24.21 (q), 11.16 (q).

4a; ^{1}H NMR ($CDCl_3$) δ .49 (t,3H), 1.24 (s,3H), 1.30 (d,3H), 1.36 (s,3H), 1.39 (s,3H), 1.82 (q,2H), 3.94 (q,1H), 5.81 (s,1H), 7.13-7.39 (m,4H); ^{13}C NMR ($CDCl_3$) δ 146.39 (s), 143.87 (s), 139.96 (s), 132.76 (d), 127.83 (d), 127.51 (d), 127.06 (d), 126.54 (d), 73.14 (d), 43.27 (s), 40.83 (s), 35.01 (t), 34.36 (q), 33.67 (q), 25.48 (q), 23.73 (q), 11.05 (q).

6a; ^{1}H NMR ($CDCl_3$) δ .70 (t,3H), 1.20 (s,3H), 1.25 (s,3H), 1.41 (s,3H), 1.79 (d,3H), 2.11 (q,2H), 4.21 (s,1H), 5.64 (q,1H), 7.05-7.40 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 145.64 (s), 143.92 (s), 142.83 (s), 129.77 (d), 128.79 (d), 127.27 (d), 127.06 (d), 126.83 (d), 77.06 (d), 45.09 (s), 43.09 (s), 37.64 (t), 30.56 (q), 26.63 (q), 23.47 (q), 13.95 (q), 10.43 (q).

2b; ^{1}H NMR ($CDCl_3$) δ .97 (t,3H), 1.10 (t,3H), 1.22 (s,3H), 1.38 (s,3H), 1.45 (s,3H), 2.05 (q,2H), 2.37 (m,2H), 3.95 (s,1H), 5.44 (t,1H), 7.00-7.43 (m,4H); ^{13}C NMR ($CDCl_3$) δ 144.02 (s), 141.77 (s), 141.58 (s), 129.15 (d), 128.19 (d), 127.69 (d), 126.92 (d), 125.02 (d), 77.38 (d), 45.86 (s), 43.36 (s), 40.29 (t), 37.84 (t), 29.03 (q), 26.49 (q), 22.36 (q), 15.89 (q), 10.23 (q).

3b; ^{1}H NMR ($CDCl_3$) δ .62 (t,3H), .98 (t,3H), 1.21 (s,3H), 1.31 (s,3H), 1.48 (s,3H), 1.65 (q,2H), 1.89 (m,2H), 3.86 (t,1H), 5.49 (s,1H), 7.10-7.36 (m,4H); ^{13}C NMR ($CDCl_3$) δ 146.13 (s), 143.62 (s), 140.17 (s), 130.81 (d), 129.36 (d), 129.21 (d), 128.60 (d), 126.81 (d), 75.41 (d), 42.32 (s), 39.86 (s), 37.18

(t), 34.36 (q), 34.25 (t), 31.27 (q), 25.13 (q), 15.88 (q), 12.02 (q).

4b; ^{1}H NMR (CDCl$_3$) δ .65 (t,3H), 1.01 (t,3H), 1.17 (s,3H), 1.33 (s,3H), 1.41 (s,3H), 1.71 (q,2H), 1.93 (m,2H), 3.91 (t,1H), 5.51 (s,1H), 7.08-7.32 (m,4H); ^{13}C NMR (CDCl$_3$) δ 145.51 (s), 144.51 (s), 140.86 (s), 131.35 (d), 130.10 (d), 129.63 (d), 127.98 (d), 126.47 (d), 74.92 (d), 41.81 (s), 39.23 (s), 6.73 (t), 33.92 (t), 33.71 (q), 31.61 (q), 25.01 (q), 16.12 (q), 12.23 (q).

6b; ^{1}H NMR (CDCl$_3$) δ 1.01 (t,3H), 1.19 (t,3H), 1.22 (s,3H), 1.41 (s,3H), 1.59 (s,3H), 2.12 (q,2H), 2.30 (m,2H), 4.05 (s,1H), 5.45 (t,1H), 7.10-7.40 (m,4H); ^{13}C NMR (CDCl$_3$) δ 144.45 (s), 142.95 (s), 141.59 (s), 130.10 (d), 128.22 (d), 127.77 (d), 127.50 (d), 126.93 (d), 75.31 (d), 43.52 (s), 40.44 (s), 39.03 (t), 34.81 (t), 31.34 (q), 27.02 (q), 21.84 (q), 15.10 (q), 10.79 (q).

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Chapter 4*

The Effect of Solvent Polarity on Photochemical [1,3] Sigmatropic Shifts. Experimental Evidence in Favour of the Occurrence of Sudden Polarization in Acyclic Alkenes.

Abstract

In this chapter further experimental evidence regarding the occurrence of sudden polarization in acyclic alkenes is presented. It is shown that the yield of formation of the product derived from an intramolecular photochemical [1,3]-OH shift in 1 is dependent only on the polarity of the solvent employed. This result could be well explained in terms of a stabilization of the zwitterionic intermediate formed upon irradiation of 1 by reorientation polarization of the dipole solvent molecules.

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*W.J.G.M. Peijnenburg, H.M. Buck, Tetrahedron, accepted for publication.

4.1 Introduction

In the preceding chapter the first experimental evidence regarding the occurrence of a planar photochemical [1,3] sigmatropic shift in unsaturated hydrocarbons was presented. A central role in this planar mechanism is taken by the relaxation of an excited double bond towards a 90° twisted intermediate. In the case of non-symmetrical alkenes the twisting motion is accompanied by a relocalization of the electrons. This "Sudden Polarization" effect has first been described theoretically by Salem and co-workers[1] and has thereafter been found to persist by many theoretical calculations at different levels of sophistication[2]. Up till now however, only the excited state reactivities of ß-t-butylstyrene derivatives and of some substituted cycloheptatrienes have been well elucidated on the basis of the sudden polarization model[3,4]. On the other hand as in the case of the intramolecular cycloaddition in which a triene is converted into a bicyclo[3.1.0]hexene, no experimental support regarding the proposed two step mechanism based upon the concept of sudden polarization was found[5]. Instead recent publications even strengthen the arguments against the validity of the sudden polarization model in this specific case; the theoretically predicted[6] effects of substituents on the charge distribution in the zwitterionic states found no experimental support[7].

In this chapter further experimental evidence in favour of the occurrence of sudden polarization in excited unmsymmetrical alkenes is presented. The yield of formation of the products derived from a planar photochemical [1,3]-OH shift in 3,4-dihydro-1,1,4,4-tetramethyl-(Z)-3-ethylidene-2(1H)-naphthalenol (1) was determined as a function of solvent polarity. A similar study on the effects of solvent polarity on photoinduced chemical reactions was performed by Verhoeven and co-workers, who elegantly studied the effect of solvent dynamics on the rate of electron transfer in an extensive series of molecules containing electron donor and acceptor groups separated by an elongated paraffinic spacer[8].

4.2 Results and Discussion

Upon direct irradiation of 1 in various solvents, fast E-Z isomerization around the exocyclic double bond could be observed. This led to the formation of a 50:50 mixture of 1 and 2. Further irradiation of this mixture resulted in the clean formation of 3, the product derived from a photochemical [1,3]-OH shift in either 1 or 2 (see Figure 1).

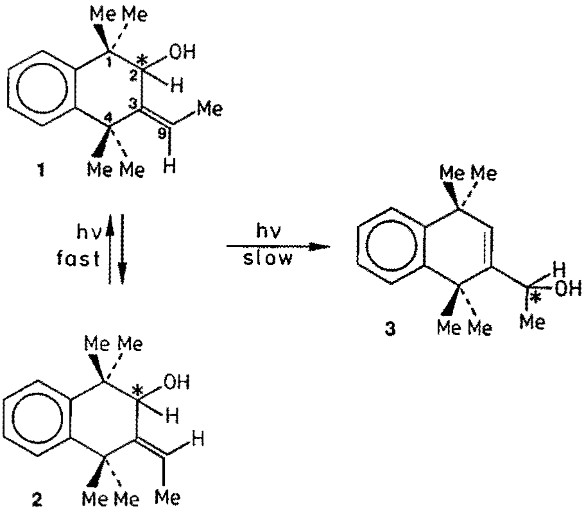

Figure 1. Photochemistry of compound 1 upon irradiation in various solvents.

It should be noted that, as shown in the preceding chapter, a location of the hydroxyl group *in* the plane of the exocyclic double bond is a prerequisite for a photochemical planar [1,3]-OH shift to take place. Clearly, in compounds 1 and 2 the presence of the four equivalent alkyl substituents at C_1 and C_4, will make the occurrence of such a conformation quite feasible.

In order to investigate the influence of solvent polarity on a photochemical [1,3]-OH shift, the irradiation was performed in a variety of solvents. A 0.01 molar solution of 1 in the differential solvents was irradiated during four hours. At regular intervals of time and at the end of this period the composition of the resulting product mixture was analyzed by means of GLC. In Table I the relative yields of formation of compound 3 after four hours of irradiation are depicted for several solvents; the yield of formation of compound 3 upon irradiation of 1 in n-hexane is given the reference value of 1. The in comparison to acetonitrile even more polar solvents methanol and

Table I. Relative yields of formation of 3 upon irradiation of a 50:50 mixture of 1 and 2 in various solvents.

Solvent	E_T[a]	Relative yield
n-hexane	30.9	1
cyclohexane	31.2	0.98
diethylether	34.6	0.65
2-Me-tetrahydrofuran	36.5	0.49
acetonitrile	46.0	0.15

[a] The solvent parameter E_T is based on the solvatochromism of pyridinium-N-phenolbetaine in various solvents[9].

ethanol could not be used since in these solvents a disturbing addition of solvent to the exocyclic double bond will take place (see chapter 5).

From this Table it may be concluded that the yield of formation of compound 3 decreases going from a highly apolar solvent like n-hexane to the in this series most polar solvent, acetonitrile. This result is a clear support in favour of the sudden polarization model. Excitation of either 1 or 2 will be followed by a 90° twist around the exocyclic double bond, accompanied with a complete separation of charge in the orthogonal situation. In the case of allylic alcohols this polarization leads to a negative charge on the central carbon atom C_3 and a positive charge on the terminal carbon atom C_9[10]. In case of a polar solvent this positive charge will be partly shielded by reorientation polarization of dipolar solvent molecules, thus lowering the total energy contents of the zwitterionic intermediate. This implies that in the orthogonal situation the energy difference between the S_1 and the S_0 will decrease upon transfer from an apolar to a polar solvent. However, since the nonadiabatic coupling between these states is inversely proportional to their energy difference (see chapter 2), a radiationless transition from the 90° twisted intermediate to the ground state will become more likely to occur in polar solvents, thus decreasing the yield of formation of 3 in these solvents.

Another effect of performing the irradiation of 1 and 2 in polar solvents will be an increase of the activation enthalpy for the planar [1,3]-OH shift in these compounds. Schematically the potential energy profiles for a planar [1,3]-OH shift in both a polar

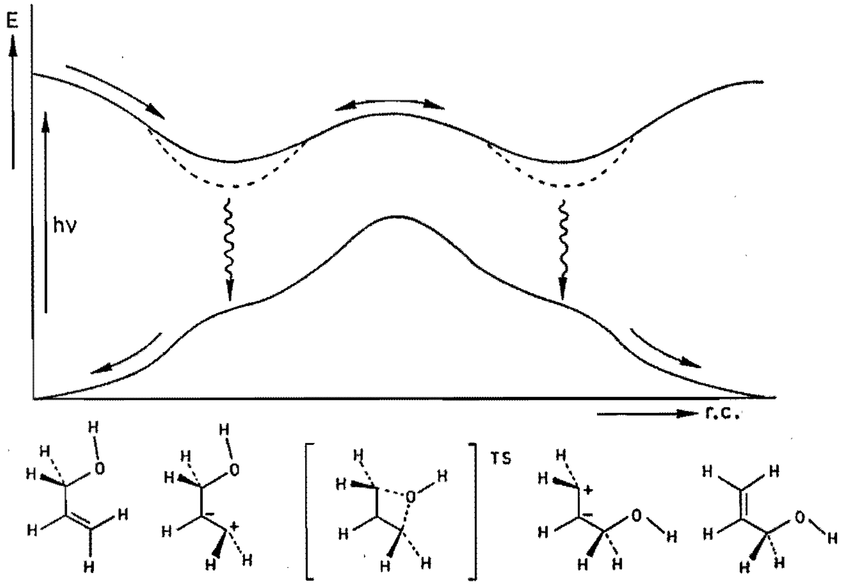

Figure 2. Potential energy curves of the ground and first singlet excited state for a photochemical planar [1,3]-OH shift in both a polar (---) and an apolar (——) solvent.

(---) and an apolar (——) solvent are depicted in Figure 2.

Since the planar transition state bears no polar character[10], the polarity of the solvent applied will not affect its energy contents. Hence, as can be seen from Figure 2, the potential energy difference between the stabilized 90° twisted conformation and the transition state will increase upon increasing solvent polarity, thus again decreasing the yield of formation of compound 3.

Taking into account the two effects described above, an estimate can be made of the maximum difference of the activation enthalpy, $\Delta(E_{akt})_{max}$, for the planar [1,3]-OH shift in a polar solvent like acetonitrile and an apolar solvent like n-hexane. Regarding the observed relative yields of formation of 3 depicted in Table I (1 and 0.15 respectively), the $\Delta(E_{akt})_{max}$ is calculated to amount 1.5 kcal/mol.

Summarizing it may be concluded that the results reported in this chapter strongly support the mechanism of a planar photochemical [1,3]-OH shift whereas they contradict the mechanism of a suprafacial shift. For in that case, since no polar intermediate is involved, no solvent effect at all would be observable.

4.3 Experimental Section

4.3.1 Synthesis of Reactants of Interest

For the preparation of 3,4-dihydro-1,1,4,4-tetramethyl-(Z)-3-ethylidene-2(1H)-naphthalenol 1 the same reaction route was used as for the synthesis of the corresponding 4-ethyl-1,1,4-trimethyl-2(1H)-naphthalenol derivatives described in section 3.4.1[11,12]. A Z-configuration of the exocyclic double bond could be deduced from ^1H NMR $Eu(fod)_3$ shift experiments.

4.3.2 Materials and Methods. Preparation of compounds

^1H and ^{13}C NMR spectra were recorded at 200 respectively 50 MHz on a Bruker AC 200 NMR spectrometer, interfaced with an ASPECT 3000 computer. An internal field-frequency lock was used. Chemical shifts were referenced against tetramethylsilane (δ = 0 ppm), which was added as a small trace. Gas chromatograms were recorded using a Kipp Analytica 8200 equipped with a flame-ionization detector. Columns used were Chrompack fused silica wall, open tubular columns with CP Wax 51 as liquid phase (25 m x 0.23 mm). The UV measurements were performed on a Perkin-Elmer 124 spectrofotometer.

4.3.3 Irradiation Procedure

Irradiations were carried out according to the general irradiation procedure described in chapter 3. Products were separated by column chromatography (silica gel, type 60 Merck, or silica Woelm as stationary phase), using n-hexane-ether 8:2 (v/v) as eluent.

The structure elucidation of the photoproducts **2** and **3** was accomplished by comparison of the relative positions and multiplicities of the ^{1}H- and ^{13}C-NMR resonances.

3,4-Dihydro-1,1,4,4-tetramethyl-2(1H)-naphthalenone.

This compound was prepared according to a somewhat modified procedure described by Bruson and co-workers[12]. To a stirred solution of 200 g (1.41 mol) of 2,2,5,5-tetramethyl-3(2H)-furanone in 750 mL of anhydrous benzene was added gradually anhydrous, powdered $AlCl_3$ (283 g, 2.12 mol) while maintaining the temperature between 40 and 50 °C by external cooling. The solution was then heated at reflux for 1h, cooled and poured into one liter of ice and water containing 175 mL of conc. HCl. The aqueous layer was washed with four 200-mL portions of ether. The combined organic layers were washed with a saturated $NaHCO_3$-solution, dried over $MgSO_4$ and concentrated in vacuo.

Chromatography (silica 60, n-hexane-ether 5:1 (v/v)) afforded 115.3 g (41%) of 3,4-dihydro-1,1,4,4-tetramethyl-2(1H)-naphthalenone. ^1H NMR ($CDCl_3$) δ 1.17 (s,6H), 1.32 (s,6H), 2.48 (s,2H), 6.87-7.35 (m,4H).

1,4-Dihydro-1,1,4,4-tetramethyl-2,3-naphthalenedione.

To a solution of 115.3 g (0.57 mol) of 3,4-dihydro-1,1,4,4-tetramethyl-2(1H)-naphthalenone in 250 mL of glacial acetic acid was added 72 g (0.60 mol) SeO_2. The mixture was heated at reflux for 3h. The cooled solution was thoroughly filtered and the solvent removed in vacuo. The residu was dissolved in 250 mL of ether, washed with water, a saturated $NaHCO_3$-solution and again with water. The organic layer was dried over $MgSO_4$ and concentrated under reduced pressure. This afforded 115 g (92%) of 1,4-dihydro-1,1,4,4-tetramethyl-2,3-naphthalenedione.
^1H NMR ($CDCl_3$) δ 1.14 (s,6H), 1.22 (s,6H), 7.00-7.33 (m,4H); ^{13}C NMR ($CDCl_3$) δ 204.47 (s), 140.54 (s), 128.35 (d), 126.41 (d), 51.61 (s), 27.10 (q).

3,4-Dihydro-1,1,4,4-tetramethyl-(Z)-3-ethylidene-2(1H)-naphthalenone.

n-Butyllithium (160 mL of a 1.6 M solution in n-hexane, 0.26 mol) was added dropwise to a stirred suspension of 88.6 g (0.24 mol) (ethyl)triphenylphosphonium bromide in 200 mL of anhydrous ether. The dark red coloured mixture was then stirred for 2h at room temperature. At the end of this period 38.3 g (0.18 mol) of 1,4-dihydro-1,1,4,4-tetramethyl-2,3-naphthalenedione was added dropwise, whereupon a white precipitate formed. The mixture was then cooled and filtered by suction. The filtrate was washed with water, the organic layer separated and dried over $MgSO_4$. Removal of ether left a residue which was separated by repeated column chromatography using n-hexane-ether 85:15 (v/v) as eluent. Thus 9.8 g (24%) of 3,4-dihydro-1,1,4,4-tetramethyl-(Z)-3-ethylidene-2(1H)-naphthalenone was isolated. The corresponding E-isomer could not be detected as a byproduct.

^1H NMR ($CDCl_3$) δ 1.30 (s,6H), 1.36 (s,6H), 1.64 (d,3H), 5.55 (q,1H), 6.81-7.23 (m,4H); ^{13}C NMR ($CDCl_3$) δ 209.77 (s), 146.51 (s), 144.39 (s), 143.59 (s), 130.25 (d), 128.30 (d,2x), 125.12 (d), 124.42 (d), 50.29 (s), 42.86 (s), 30.54 (q,2x), 28.82 (q,2x), 15.83 (q).

3,4-Dihydro-1,1,4,4-tetramethyl-(Z)-3-ethylidene-2(1H)-naphthalenol (1).

To a stirred suspension of 2.5 g (66 mmol) of $LiAlH_4$ in 150 mL of anhydrous ether was added dropwise, at 0 °C, a solution of 15 g (65.2 mmol) of 3,4-dihydro-1,1,4,4-tetramethyl-(Z)-3-ethylidene-2(1H)-naphthalenone in 100 mL ether. After 30 min. additional stirring the reaction mixture was allowed to warm to room temperature. After addition of respectively 5 mL of water, 5 mL of a 5 N NaOH solution and 30 mL of water, filtration, separation of the organic layer and removal of the solvent afforded 14.5 g (96%) of **1**.

^1H NMR ($CDCl_3$) δ .90 (s,3H), 1.29 (s,3H), 1.39 (s,3H), 1.41 (s,3H), 1.65 (d,3H), 4.34 (s,1H), 5.60 (q,1H), 6.80-7.21 (m,4H); ^{13}C NMR ($CDCl_3$) δ 146.03 (s), 145.12 (s), 142.19 (s), 128.08 (d), 127.43 (d), 127.08 (d), 126.60 (d), 122.01 (d), 75.32 (d), 40.48 (s), 39.74 (s), 37.48 (q), 34.01 (q), 31.07 (q), 26.70 (q), 14.00 (q).

UV (EtOH) λ_{max} 260 nm.

4.3.4 Spectral Data for the Photoproducts

2; ^1H NMR ($CDCl_3$) δ 1.03 (s,3H), 1.28 (s,3H), 1.40 (s,3H), 1.49 (s,3H), 1.73 (d,3H), 3.64 (s,1H), 5.37 (q,1H), 6.78-7.23 (m,4H); ^{13}C NMR ($CDCl_3$) δ 146.92 (s), 146.05 (s), 142.30 (s), 128.89 (d), 128.83 (d), 127.59 (d), 126.84 (d), 124.95 (d), 75.45 (d), 40.54 (s), 39.80 (s), 35.39 (q), 33.26 (q), 32.32 (q), 26.56 (q), 16.59 (q).

3; ^1H NMR ($CDCl_3$) δ 1.35 (s,12H), 1.41 (d,3H), 3.75 (q,1H), 5.63 (s,1H), 6.91-7.27 (m,4H); ^{13}C NMR ($CDCl_3$) δ 144.72 (s), 142.96 (s), 139.67 (s), 128.49 (d), 128.04 (d), 127.36 (d), 126.89 (d), 126.15 (d), 73.51 (d), 44.06 (s), 41.58 (s), 32.36 (q), 30.22 (q), 26.38 (q).

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Chapter 5

The Effect of Substituents on Photochemical [1,3] Sigmatropic Shifts. Further Experimental Evidence in Favour of the Occurrence of Sudden Polarization in Acyclic Alkenes.

Abstract

A directive effect of the substituents at the exocyclic C_3–C_9 double bond of a number of model compounds is reported. It is shown that, dependent on the nature of these substituents, either a photochemical [1,3]-H or [1,3]-OH shift may take place. This directive effect could be well explained on the basis of the sudden polarization model.

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*W.J.G.M. Peijnenburg, H.M. Buck, Tetrahedron, accepted for publication.

5.1 Introduction

In the preceding chapters 3 and 4 the photochemical behaviour of some 3-alkylidene-2-naphthalenol derivatives having an alkyl substituent at C_9 was described. It was shown that upon irradiation of these derivatives, dependent on the ground-state conformation of the substrate, a highly stereoselective [1,3]-OH shift takes place. Thus experimental evidence in favour of a planar reaction mechanism was obtained. This mechanism is based on the occurrence of sudden polarization in excited acyclic alkenes. Measurements of the yield of formation of the products derived from a photochemical [1,3]-OH shift as a function of solvent polarity gave further support in favour of the sudden polarization model. In this chapter it is shown that replacement of the C_9-alkyl substituent by a phenyl group causes a rather radical change in the photochemical behaviour of the thus obtained 3-phenylmethylene-2-naphthalenol derivatives. These results too could be well explained using the concept of sudden polarization.

5.2 Results and Discussion

In first instance again fast E-Z isomerization around the exocyclic double bond was observed upon irradiation of 1 in either n-hexane or acetonitrile, which led to the formation of an approximately 50:50 mixture of 1 and 2. In contradistinction to the 3-alkylidene-2-naphthalenol derivatives described in chapters 3 and 4 no photochemical [1,3]-OH shift was observed upon further irradiation of this mixture. Instead the clean formation of 3 was perceptible (see Figure 1).

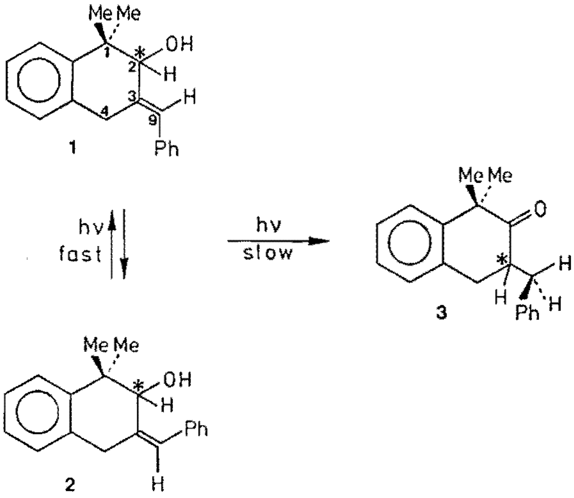


Figure 1. Photochemistry of compound 1 upon irradiation in either n-hexane or acetonitrile.

In compounds 1 and 2 two chromophoric phenyl groups are present whereas it is to be expected that the presence of just one phenylmethylene fragment will suffice in order to initiate the photochemical reactions of the thus obtained cyclohexanol derivatives. Indeed the same reactions as in the case of compound 1 took place upon irradiation of (E)-2-phenylmethylene-cyclohexanol **4a** in either n-hexane or acetonitrile (see Figure 2).

Formation of the products 3 and **6a** is initiated by a photochemical [1,3]-H shift in either 1,2 or 4a,5a. This shift will be followed by keto-enol tautomerism of the resulting enol, as indicated in Figure 3 for the cyclohexanol derivative **4a**.

Thus a clear directive effect of the substituents at the exocyclic double bond is perceptible. This directive effect can be well explained using the concept of sudden polarization. Excitation of either

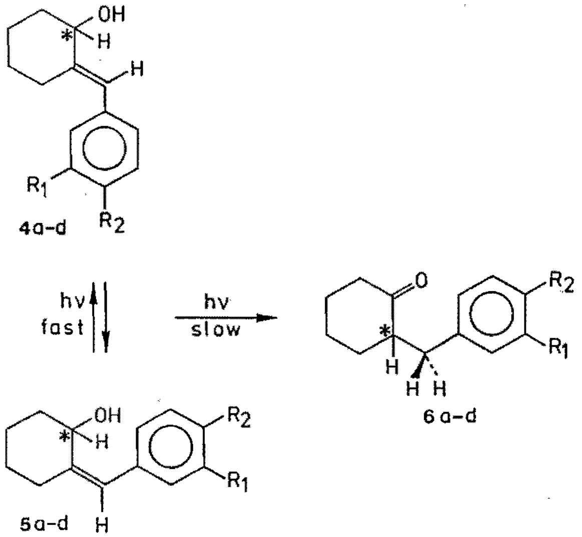
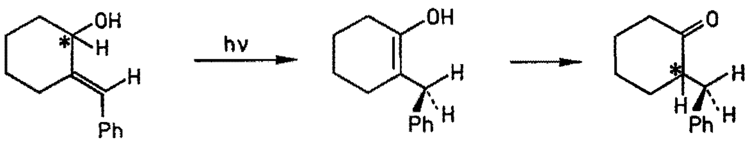


Figure 2. Photochemistry of compounds **4a** (R_1=H, R_2=H), **4b** (R_1=H, R_2=Cl), **4c** (R_1=H, R_2=F) and **4d** (R_1=OMe, R_2=H) upon irradiation in either n-hexane or acetonitrile.

1,2 or 4a,5a will again be followed by a 90° rotation around the exocyclic double bond, leading to the formation of a negatively charged central carbon atom and a positively charged terminal carbon atom[1,2]. In case of a phenyl substituent at this carbon atom, the positive charge will be partially delocalized by resonance over the electron-donating phenyl group. This delocalization decreases the polar character of the terminal carbon atom of the exocyclic double bond, thus lowering the driving force for migration of the partially negatively charged hydroxyl group. Hence, an increase of the activation energy of the [1,3]-OH shift in these compounds is expected (i.e. compared to the case of an alkyl substituent at C_9 as in the compounds described in chapters 3 and 4). As indicated in chapter 2



4a 6a

Figure 3. Formation of photoproducts upon irradiation of **4a**.

the activation energy of the planar [1,3]-OH shift in 2-propenol was calculated to be 17 kcal/mol, whereas comparable calculations on the photochemical [1,3]-H shift in propene revealed an activation energy of 35.5 kcal/mol. Apparently, upon replacing the alkyl substituent at the terminal carbon atom by a phenyl substituent, the activation energy of the [1,3]-OH shift becomes higher than the energy required for the corresponding photochemical [1,3]-H shift. Moreover this latter shift will hardly be affected by the aforementioned delocalization of the positive charge at the terminal carbon atom.

Further evidence in favour of the sudden polarization model was obtained upon irradiation of **4a** in methanol. Irradiation of **4a** in methanol led, apart from fast E-Z isomerization, to formation of the methyl ether **7a**. This product arises from the addition of methanol to the excited double bond of either **4a** or **5a** (see Figure 4).

The first conclusion that can be drawn from this experiment is that apparently the addition of methanol is energetically more feasible than the [1,3]-H shift since formation of **6a** was not observed. Besides this the formation of the methanol addition product clearly supports the supposed polar character of the singlet excited state of **4a** and **5a**.

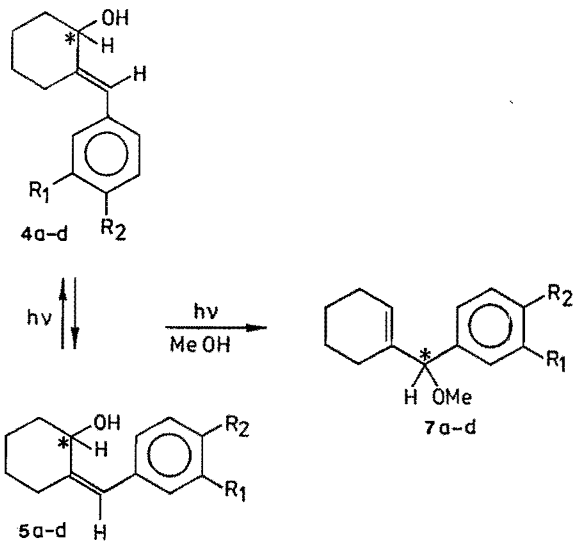


Figure 4. Photochemistry of compounds **4a** (R_1=H, R_2=H), **4b** (R_1=H, R_2=Cl), **4c** (R_1=H, R_2=F) and **4d** (R_1=OMe, R_2=H) upon irradiation in methanol.

As stated before[1,2] it is the strong electronegative character of the hydroxyl group which invokes the observed charge separation in the excited exocyclic double bond. In case of a phenyl substituent at the terminal carbon atom, the hereby formed positive charge is stabilized by resonance over the phenyl group. It is to be expected that this latter effect will be drastically diminished by the introduction of electron-withdrawing substituents at the phenyl group. Nevertheless, as indicated in Figure 2, irradiation of the compounds having either a p-Cl (**4b**), p-F (**4c**), or a m-OMe (**4c**) substituent as the electron-withdrawing group did not affect their photochemical behaviour compared to the unsubstituted situation (**4a**). Clearly the influence of the strong electronegative hydroxyl group is stronger than the opposite effect of electron-withdrawing substituents at the terminus of the allylic fragment.

Upon application of the strong electron-withdrawing p-CN group (**4e**), the situation changed drastically. Upon irradiation of **4e** in either n-hexane or methanol only fast E-Z isomerization was observed, leading to formation of a 50:50 mixture of **4e** and the corresponding Z-isomer 5e; despite prolonged irradiation no further photoproducts could be detected. From this observation it becomes clear that in this specific case the influence of the phenyl substituent exceeds the influence of the hydroxyl group. Hence a negative charge, partially delocalized by resonance over the electron-withdrawing 4-cyanophenyl group at the allylic terminus is formed. This will preclude both the addition of methanol and the [1,3]-H shift. This latter effect is in accord with ground-state analogy where hydrogen shifts to a cationic centre are common, but those to an anionic centre are rare[3].

Another interesting feature is the observation that in case of a [1,3]-H shift it is always the hydrogen attached to the carbon atom bearing the hydroxy functionality that displays the shift, whereas especially in case of compound 1 a [1,3]-H shift of the C_4-protons is quite feasible since this would lead to formation of a C_3-C_4 double bond conjugated to the endocyclic phenyl group. Apparently the presence of the hydroxyl functionality is a prerequisite for the occurrence of a [1,3]-H shift in 1. To test this hypothesis the tertiary alcohol **8** was synthesized. In this compound the presence of the C_9-phenyl group will preclude a [1,3]-OH shift whereas the alternative [1,3]-Me shift is rather unlikely to occur regarding the high activation energy calculated for this reaction (62.5 kcal/mol)[2].

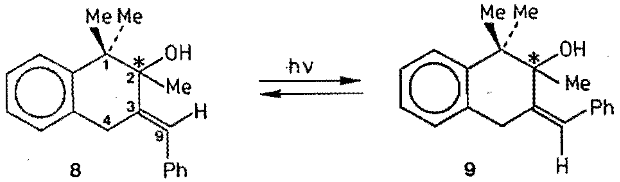


Figure 5. Photochemistry of compound **8** upon irradiation in n-hexane or acetonitrile.

Upon irradiation of **8** in both n-hexane and acetonitrile only fast E-Z isomerization around the exocyclic double bond was observable; no products derived from a migration of the C_4-hydrogens could be detected (see Figure 5).

The results depicted in this chapter once again demonstrate the unique properties of the compounds studied. The presence of a subtile interplay between the various factors govering the course of the photochemical reactions of the compounds studied is clearly shown. First of all a chromophoric group is needed in order to initiate the photochemical reactions. Thereupon in the case of acyclic alkenes a 90° twist of the excited double bond will take place, accompanied by a charge separation in the orthogonal situation. At this point both the solvent applied and the substituents at the excited double bond will have a profound and directive influence on the subsequently occuring [1,3] sigmatropic shift.

5.3 Experimental Section

5.3.1 Synthesis of Reactants of Interest

3,4-Dihydro-1,1-dimethyl-(E)-3-(phenylmethylene)-2(1H)-naphthalenol 1 was synthesized starting from 3,4-dihydro-2(1H)-naphthalenone. Methylation of this compound, using a twofold excess of methyliodide, was followed by a base catalyzed aldol condensation with benzaldehyde. This reaction is known to yield an E-configuration around the exocyclic double bond of the thus formed α,β-unsaturated ketone[4]. Addition of the Grignard reagent MeMgI to this ketone yielded the tertiary alcohol **8** whereas upon $LiAlH_4$-reduction 1 was obtained in almost quantitative yield. All 2-(phenylmethylene)-cyclohexanol derivatives were prepared by either $LiAlH_4$- or $NaBH_4$-reduction of the α,β-unsaturated ketones obtained by base catalyzed aldol condensation of cyclohexanone with the corresponding benzaldehyde derivatives. As mentioned before this reaction is known to yield an E-configuration around the exocyclic double bond.

5.3.2 Structural Assignment of Photoproducts

The structure elucidation of the various photoproducts was accomplished by comparison of the relative positions and multiplicities of the ^1H- and ^{13}C-NMR resonances. This enabled an unambiguous structural assignment of all products formed upon E-Z-isomerization and methanol-addition. Comparison of the relative positions and multiplicities of the ^1H- and ^{13}C-NMR resonances of the products derived from a photochemical [1,3]-H shift in compounds **4a–d** and subsequent keto-enol tautomerism left two possibilities regarding the location of the carbonyl group i.e. based upon these data either the presence of a cyclohexyl-phenyl-ketone or a 2-benzyl-cyclohexanone derivative could be deduced. Upon comparison of the ^{1}H- and ^{13}C-NMR spectra of the photoproducts with the spectra of authentic samples of the corresponding cyclohexyl-ketones, the photoproducts could unambiguously be identified as 2-benzyl-cyclohexanone derivatives. Similarly, the structure of the product derived from a photochemical [1,3]-H shift upon irradiation of 1 could unambiguously be assigned.

5.3.3 Materials and Methods. Preparation of compounds

^{1}H and ^{13}C NMR spectra were recorded at 200 respectively 50 MHz on a Bruker AC 200 NMR spectrometer, interfaced with an ASPECT 3000 computer. An internal field-frequency lock was used. Chemical shifts were referenced against tetramethylsilane (δ = 0 ppm), which was added as a small trace. Gas chromatograms were recorded using a Kipp Analytica 8200 equipped with a flame-ionization detector. Columns used were Chrompack fused silica wall, open tubular columns with CP Wax 51 as liquid phase (25 m x 0.23 mm). The UV measurements were performed on a Perkin-Elmer 124 spectrofotometer.

5.3.4 Irradiation Procedure

Irradiations were carried out according to the general irradiation procedure described in chapter 3. Products were separated by column chromatography (silica gel, type 60 Merck, or silica Woelm as stationary phase), generally using n-hexane-ether 9:1 (v/v) as eluent.

3,4-Dihydro-1,1-dimethyl-(E)-3-(phenylmethylene)-2(1H)-naphthalenone.

A solution of 2.5 g of sodium hydroxide in 60 mL of water was added with stirring to a mixture of 11 g (0.10 mol) of benzaldehyde and 12 g (0.07 mol) of 3,4-dihydro-1,1-dimethyl-2(1H)-naphthalenone (prepared by alkylation of 3,4-dihydro-2(1H)-naphthalenone[5]) in 200 mL of water at room temperature. The mixture was stirred overnight at room temperature, and extracted with two 300-mL portions of ether. After removal of the solvent the crude 3,4-dihydro-1,1-dimethyl-3-(hydroxyphenylmethyl)-2(1H)-naphthalenone was dissolved in 150 mL of 96% ethanol, acidified with 20 mL of concentrated hydrochloric acid and heated at 50 °C for 15 minutes. The aqueous layer was washed with four 200-mL portions of ether. The combined organic layers were washed with a saturated $NaHCO_3$-solution, dried over $MgSO_4$ and concentrated in vacuo. Chromatography (silica 60, n-hexane-ether 3:1 (v/v)) afforded 11.4 g (63%) of 3,4-dihydro-1,1-dimethyl-(E)-3-(phenylmethylene)-2(1H)-naphthalenone.

^1H NMR ($CDCl_3$) δ 1.48 (s,6H), 4.13 (m,2H), 6.83-7.56 (m,10H); ^{13}C NMR ($CDCl_3$) δ 202.62 (s), 142.43 (s), 137.37 (s), 136.23 (s), 134.54 (s), 131.51 (d), 131.10 (d), 129.56 (d,2x), 129.28 (d), 129.01 (d, 2x), 128.07 (d), 127.60 (d), 125.64 (d), 48.03 (s), 33.80 (t), 25.47 (q,2x).

3,4-Dihydro-1,1-dimethyl-(E)-3-(phenylmethylene)-2(1H)-naphthalenol (1).

To a stirred suspension of 2.5 g (66 mmol) of $LiAlH_4$ in 150 mL of anhydrous ether was added dropwise, at 0 °C, a solution of 11.4 g (42.5 mmol) of 3,4-dihydro-1,1-dimethyl-(E)-3-(phenylmethylene)-

2(1H)-naphthalenone in 100 mL ether. After 45 min. additional stirring the reaction mixture was allowed to warm to room temperature. After addition of respectively 5 mL of water, 5 mL of a 5 N NaOH solution and 30 mL of water, filtration, separation of the organic layer and removal of the solvent afforded 11.1 g (97%) of **1**.

^{1}H NMR ($CDCl_3$) δ 1.23 (s,3H), 1.40 (s,3H), 3.86 (m,2H), 4.08 (s,1H), 6.53 (s,1H), 6.98-7.39 (m,9H); ^{13}C NMR ($CDCl_3$) δ 143.81 (s), 138.46 (s), 137.50 (s), 133.65 (s), 129.96 (d), 129.48 (d), 129.14 (d), 128.66 (d,2x), 127.34 (d), 126.68 (d), 126.41 (d,2x), 125.53 (d), 82.32 (d), 41.50 (s), 32.66 (t), 30.41 (q), 25.91 (q).

UV (EtOH) λ_{max} 275 nm.

(E)-2-(Phenylmethylene)-cyclohexanol (4a)[6].

A solution of 2 g of sodium hydroxide in 50 mL of water was added with stirring to a mixture of 5 g (0.05 mol) of benzaldehyde and 14 g (0.14 mol) of cyclohexanone in 200 mL of water at room temperature. The mixture was stirred overnight at room temperature. The resulting precipitate was filtered with suction and washed thoroughly with water. The crude 2-(hydroxyphenylmethyl)-cyclohexanone was dissolved in 150 mL of 96% ethanol, acidified with 20 mL of concentrated hydrochloric acid and heated at 50 °C for 15 minutes. Cooling in ice gave 7.5 g of crude crystalline material which was recrystallized from ethanol to yield 6.5 g (74%) of (E)-2-(Phenylmethylene)-cyclohexanone.

Reduction was achieved by adding dropwise, at 0 °C, a solution of 6.5 g (34.9 mmol) of this ketone in 35 mL of anhydrous ether to a stirred solution of 1.35 g (35.64 mmol) of $LiAlH_4$ in 100 mL of anhydrous ether. After 30 min. additional stirring the reaction mixture was allowed to warm to room temperature. Addition of respectively 3 mL of water, 3 mL of a 5N NaOH solution and 20 mL of water, filtration, separation of the organic layer and removal of the solvent afforded 6.5 g (99%) of **4a**.

^{1}H NMR ($CDCl_3$) δ 1.25-2.92 (m,8H), 4.14 (m,1H), 6.47 (s,1H), 6.97-7.26 (m,5H); ^{13}C NMR ($CDCl_3$) δ 144.95 (s), 138.42 (s), 129.52 (d, 2x), 128.64 (d,2x), 126.69 (d), 121.36 (d), 74.04 (d), 37.17 (t), 28.00 (t), 27.66 (t), 23.95 (t).

UV (EtOH) λ_{max} 260 nm.

(E)-2-[(4-Chlorophenyl)methylene]-cyclohexanol (4b).

The same procedure was used as for the synthesis of **4a** except for the fact that $NaBH_4$ was used as the reducing agent: to a stirred solution of 5 g (22.7 mmol) of (E)-2-[(4-chlorophenyl)methylene]-cyclohexanone in 50 mL of 96% ethanol and 3 mL of 0.5 N sodium hydroxide, was added in small portions, whilst stirring, 0.4 g (10.7 mmol) of $NaBH_4$ at such a rate that the temperature of the solution was maintained at 18-25 °C. After completion of the addition stirring was continued for one hour. Removal of the ethanol, extraction with ether, drying over magnesium sulphate and removal of solvent left 4.5 g (89%) of **4b**.

^{1}H NMR ($CDCl_3$) δ 1.15-2.92 (m,8H), 4.20 (m,1H), 6.49 (s,1H), 6.85-7.27 (m,4H); ^{13}C NMR ($CDCl_3$) δ 145.87 (s), 136.97 (s), 132.51 (s), 130.83 (d,2x), 128.88 (d,2x), 120.18 (d), 74.08 (d), 37.34 (t), 28.04 (t), 27.83 (t), 24.13 (t).

UV (EtOH) λ_{max} 270 nm.

(E)-2-[(4-Fluorophenyl)methylene]-cyclohexanol (4c).

The same procedure was used as for the preparation of **4b**. With an overall yield of 68%, 6.3 g of **4c** was obtained.

^{1}H NMR ($CDCl_3$) δ 1.18-2.91 (m,8H), 4.17 (m,1H), 6.57 (s,1H), 6.83-7.40 (m,4H); ^{13}C NMR ($CDCl_3$) δ 162.06 (d,J_{C-F}=234 Hz), 145.22 (s), 134.64 (s), 131.25 (d,2x), 120.34 (d), 115.58 (dd,2x,J_{C-F}=21 Hz), 74.12 (d), 37.39 (t), 28.12 (t), 27.85 (t), 24.25 (t).

UV (EtOH) λ_{max} 275 nm.

(E)-2-[(3-Methoxyphenyl)methylene]-cyclohexanol (4d).

Exactly the same procedure was followed as for the synthesis of **7a**. Starting from 20 g (0.20 mol) of cyclohexanone and 9.9 g (0.07 mol) of 3-methoxy-benzaldehyde, 8.8 g (55%) of **4d** was obtained.

^{1}H NMR ($CDCl_3$) δ 1.16-2.93 (m,8H), 3.63 (s,3H), 4.09 (m,1H), 6.42 (s,1H), 6.59-7.14 (m,4H); ^{13}C NMR ($CDCl_3$) δ 160.26 (s), 145.57 (s), 140.16 (s), 129.87 (d), 122.36 (d), 121.33 (d), 115.43 (d), 112.50 (d), 74.31 (d), 55.87 (q), 37.43 (t), 28.27 (t), 28.08 (t), 24.23 (t).

UV (EtOH) λ_{max} 265 nm.

(E)-2-[(4-Cyanophenyl)methylene]-cyclohexanol (4e).

The same procedure was used as for the synthesis of **4b**. Thus 5.2 g (overall yield 45%) of **4e** was obtained.

^{1}H NMR ($CDCl_3$) δ 1.01-2.80 (m,8H), 4.22 (m,1H), 6.53 (s,1H), 7.26-7.63 (m,4H); ^{13}C NMR ($CDCl_3$) δ 148.35 (s), 143.59 (s), 132.26 (d, 2x), 129.19 (d,2x), 119.50 (s), 119.18 (d), 109.42 (s), 73.38 (d), 37.26 (t), 27.94 (t), 27.82 (t), 24.12 (t).

UV (EtOH) λ_{max} 275 nm.

3,4-Dihydro-1,1,2-trimethyl-(E)-3-(phenylmethylene)-2(1H)-naphthalenol (8).

To a stirred suspension of 103.1 g (0.62 mol) of MeMgI in 450 mL of anhydrous ether was added dropwise, at 0 °C, a solution of 9.5 g (36.3 mmol) of 3,4-dihydro-1,1-dimethyl-(E)-3-(phenylmethylene)-2(1H)-naphthalenone in 50 mL ether. After 1h of additional stirring at 30 °C the reaction mixture was poured very slowly into a mixture of 8.25 g (0.16 mol) of NH_4Cl and 500 g of ice. An extra amount of ether was added, the organic layer was separated and the solvent removed. Column chromatography (silica 60, chloroform-ether 3:1 (v/v)) afforded 2.3 g (21%) of 8.

^{1}H NMR ($CDCl_3$) δ 1.14 (s,3H), 1.26 (s,3H), 1.40 (s,3H), 3.87 (AB-q, A 3.72, B 4.02, J_{AB}=18.0 Hz,2H), 6.80 (s,1H), 6.85-7.51 (m,9H); ^{13}C NMR ($CDCl_3$) δ 146.04 (s), 143.37 (s), 138.78 (s), 134.01 (s), 129.91 (d,2x), 129.17 (d), 129.04 (d,2x), 128.46 (d), 127.12 (d), 126.73 (d), 126.39 (d), 122.28 (d), 77.50 (s), 43.97 (s), 33.55 (t), 28.19 (q), 24.93 (q), 22.84 (q).

UV (EtOH) λ_{max} 270 nm.

5.3.5 Spectral Data for the Photoproducts

2; ^{1}H NMR ($CDCl_3$) δ .99 (s,3H), 1.43 (s,3H), 3.80 (m,2H), 4.46 (s,1H), 6.62 (s,1H), 6.93-7.42 (m,9H); ^{13}C NMR ($CDCl_3$) δ 143.05 (s), 137.92 (s), 137.22 (s), 134.39 (s), 129.87 (d), 129.68 (d), 129.03 (d,2x), 128.86 (d), 128.36 (d,2x), 128.13 (d), 127.94 (d), 126.56 (d), 75.51 (d), 41.72 (s), 35.84 (t), 31.16 (q), 26.08 (q).

3; ^{1}H NMR (CDCl$_3$) δ 1.28 (s,3H), 1.31 (s,3H), 2.43-3.63 (m,5H), 6.75-7.43 (m,9H); ^{13}C NMR (CDCl$_3$) δ 214.69 (s), 144.32 (s), 140.41 (s), 135.01 (s), 129.79 (d), 129.08 (d,2x), 128.85 (d,2x), 127.73 (d), 127.33 (d), 126.99 (d), 126.75 (d), 48.46 (s), 48.06 (t), 36.26 (t), 34.71 (d), 28.91 (q), 27.43 (q).

5a; ^{1}H NMR (CDCl$_3$) δ 1.20-2.94 (m,8H), 4.78 (m,1H), 6.26 (s,1H), 6.93-7.24 (m,5H); ^{13}C NMR (CDCl$_3$) δ 143.91 (s), 138.05 (s), 129.37 (d,2x), 128.03 (d,2x), 125.64 (d), 121.60 (d), 66.39 (d), 35.11 (t), 33.29 (t), 28.91 (t), 21.03 (t).

6a; ^{1}H NMR (CDCl$_3$) δ 1.20-3.31 (m,11H), 6.85-7.15 (m,5H); ^{13}C NMR (CDCl$_3$) δ 211.98 (s), 140.81 (s), 129.69 (d,2x), 129.32 (d,2x), 126.72 (d), 53.20 (d), 42.96 (t), 36.37 (t), 34.30 (t), 29.08 (t), 26.03 (t).

7a; ^{1}H NMR (CDCl$_3$) δ 1.19-2.65 (m,8H), 3.18 (s,3H), 4.32 (s,1H), 5.81 (m,1H), 6.90-7.16 (m,5H); ^{13}C NMR (CDCl$_3$) δ 141.73 (s), 137.80 (s), 129.23 (d,2x), 128.45 (d,2x), 127.34 (d), 124.66 (d), 83.37 (d), 55.93 (q), 28.38 (t), 27.87 (t), 26.19 (t), 22.29 (t).

5b; ^{1}H NMR (CDCl$_3$) δ 1.22-3.00 (m,8H), 4.73 (m,1H), 6.33 (s,1H), 6.90-7.25 (m,4H); ^{13}C NMR (CDCl$_3$) δ 144.46 (s), 136.08 (s), 133.62 (s), 130.91 (d,2x), 129.43 (d,2x), 124.51 (d), 66.48 (d), 35.62 (t), 33.68 (t), 29.13 (t), 21.53 (t).

6b; ^{1}H NMR (CDCl$_3$) δ 1.18-3.20 (m,11H), 6.84-7.24 (m,4H); ^{13}C NMR (CDCl$_3$) δ 212.29 (s), 138.99 (s), 134.76 (s), 130.78 (d,2x), 128.48 (d,2x), 53.16 (d), 42.91 (t), 35.75 (t), 34.34 (t), 28.91 (t), 26.03 (t).

7b; ^{1}H NMR (CDCl$_3$) δ 1.11-2.96 (m,8H), 3.29 (s,3H), 4.55 (s,1H), 5.93 (m,1H), 6.79-7.30 (m,4H); ^{13}C NMR (CDCl$_3$) δ 143.16 (s), 138.69 (s), 131.96 (s), 130.23 (d,2x), 128.55 (d,2x), 123.28 (d), 81.06 (d), 56.02 (q), 27.78 (t), 26.39 (t), 24.21 (t), 23.64 (t).

5c; ^{1}H NMR (CDCl$_3$) δ 1.20-2.93 (m,8H), 4.68 (m,1H), 6.40 (s,1H), 6.91-7.39 (m,4H); ^{13}C NMR (CDCl$_3$) δ 162.66 (d,J_{C-F}=246 Hz), 143.91 (s), 134.14 (s), 131.55 (d,2x), 125.16 (d), 115.72 (dd,2x,J_{C-F}=20 Hz), 66.78 (d), 35.33 (t), 33.43 (t), 28.97 (t), 21.23 (t).

6c; ^{1}H NMR (CDCl$_3$) δ 1.21-3.33 (m,11H), 6.89-7.42 (m,4H); ^{13}C NMR (CDCl$_3$) δ 213.58 (s), 163.15 (d,J_{C-F}=240 Hz), 139.68 (s), 131.01 (d,2x), 116.13 (dd,2x,J_{C-F}=22 Hz), 54.56 (d), 42.44 (t), 35.82 (t), 33.62 (t), 29.35 (t), 26.37 (t).

7c; ^{1}H NMR (CDCl$_3$) δ 1.23-2.95 (m,8H), 3.31 (s,3H), 4.38 (s,1H), 6.01 (m,1H), 6.89-7.45 (m,4H); ^{13}C NMR (CDCl$_3$) δ 162.86 (d,J_{C-F}=243 Hz), 137.68 (s), 132.05 (s), 131.36 (d,2x), 120.17 (d), 116.56 (dd,2x,J_{C-F}=20 Hz), 86.18 (d), 55.85 (q), 31.27 (t), 27.16 (t), 23.73 (t), 22.86 (t).

5d; ^{1}H NMR (CDCl$_3$) δ 1.23-2.89 (m,8H), 3.59 (s, 3H), 4.77 (m,1H), 6.20 (s,1H), 6.68-7.16 (m,4H); ^{13}C NMR (CDCl$_3$) δ 160.20 (s), 144.14 (s), 139.47 (s), 129.98 (d), 125.63 (d), 122.15 (d), 115.24 (d), 112.86 (d), 66.50 (d), 55.96 (q), 35.11 (t), 33.29 (t), 28.92 (t), 21.04 (t).

6d; ^{1}H NMR (CDCl$_3$) δ 1.22-3.29 (m,11H), 3.65 (s,3H), 6.54-7.36 (m,4H); ^{13}C NMR (CDCl$_3$) δ 214.21 (s), 160.68 (s), 143.08 (s), 130.27 (d), 122.58 (d), 116.04 (d), 112.24 (d), 58.38 (q), 53.42 (d), 43.18 (t), 36.58 (t), 34.49 (t), 29.06 (t) 26.57 (t).

7d; ^{1}H NMR (CDCl$_3$) δ 1.20-2.24 (m,8H), 3.26 (s,3H), 3.68 (s,3H), 4.40 (s,1H), 5.72 (m,1H), 6.54-7.50 (m,4H); ^{13}C NMR (CDCl$_3$) δ 160.42 (s), 143.63 (s), 138.59 (s), 129.71 (d), 125.94 (d), 119.78 (d), 113.20 (d), 112.93 (d), 88.29 (d), 56.97 (q), 55.77 (q), 26.45 (t), 24.30 (t), 23.42 (t), 23.36 (t).

5e; ^{1}H NMR (CDCl$_3$) δ 1.13-2.75 (m,8H), 4.63 (m,1H), 6.33 (s,1H), 7.22-7.69 (m,4H); ^{13}C NMR (CDCl$_3$) δ 147.06 (s), 142.95 (s), 132.86 (d,2x), 130.27 (d,2x), 124.06 (d), 119.89 (s), 110.03 (s), 66.14 (d), 36.28 (t), 35.21 (t), 28.67 (t), 20.76 (t).

9; ^{1}H NMR (CDCl$_3$) δ 1.17 (s,3H), 1.30 (s,3H), 1.37 (s,3H), 3.76 (AB-q, A 3.63, B 3.89, J_{AB}=19.0 Hz,2H), 6.61 (s,1H), 6.91-7.47 (m,9H); ^{13}C NMR (CDCl$_3$) δ 146.65 (s), 143.19 (s), 139.46 (s), 134.57 (s), 129.92 (d,2x), 129.76 (d,2x), 129.12

(d), 128.97 (d), 128.13 (d), 127.22 (d), 126.88 (d), 124.31 (d), 80.02 (s), 45.25 (s), 40.47 (t), 29.62 (q), 25.62 (q), 21.67 (q).

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Summary

This thesis deals with the results of an experimental and quantum-chemical study on the mechanism and stereochemistry of photochemically induced [1,3] sigmatropic shifts. Classicaly, the mechanism of this type of reaction is described by the rules of Woodward and Hoffmann, which are based on the symmetry of the highest occupied molecular orbital. In this thesis the first experimental evidence for the occurrence of an alternative mechanism is presented. This mechanism starts with the energetically favourable rotation of an excited double bond towards a 90° twisted structure. In unsymmetrically substituted alkenes this twist will be accompanied by a complete charge separation in the orthogonal situation (sudden polarization). From this twisted geometry a sigmatropic [1,3] shift then takes place *in* the plane of the carbon skeleton (planar shift).

In chapter 2 the results of semi-empirical calculations of the exocyclic double bond isomerization in both germacrol and germacrene are presented. The different photochemistry of these compounds (a photochemical [1,3]-OH shift versus reactions of the endocyclic 1,5-diene moiety) could be well explained assuming an initial isomerization of the exocyclic double bond. It is shown that in case of germacrol the exocyclic double bond can reach a twisted conformation in which the lowest excited state has a polarization favourable for a planar [1,3]-OH shift i.e. a negative charge at the central carbon atom and a positive charge at the terminal carbon atom. For germacrene however this state is strongly coupled to two diradicalar states and therefore the corresponding [1,3]-H shift will not take place.

In chapter 3 the photochemical behaviour of some 4-methyl, 4-ethyl disubstituted 3-alkylidene-2-naphthalenol derivatives is investigated. Irradiation of these diastereoisomeric compounds leads, because of the large steric interaction between the allylic ethyl group and the vinylic alkyl group, to a preferential twisting of the exocyclic double bond into *one* direction. The stereochemical outcome of the subsequent [1,3]-OH shift is in full agreement with the one expected in case of a planar mechanism. Besides this it is shown that occurrence of a [1,3]-OH shift depends only on the ground-state conformation of the substrate. Thus additional experimental evidence regarding the occurrence of a non-Woodward and Hoffmann reaction path was obtained.

In chapter 4 it is shown that the yield of formation of the products derived from a photochemical [1,3]-OH shift is influenced by the polarity of the solvent employed. This observation could be well explained in terms of a stabilization of the, polarized, 90° twisted intermediate, by reorientation polarization of the dipole solvent molecules.

Finally in chapter 5 it is shown that, dependent on the nature of the substituents at the exocyclic double bond, either a photochemical [1,3]-OH or [1,3]-H shift takes place. This result could be well accounted for using the concept of sudden polarization. In case of a phenyl substituent at the terminal carbon atom of the excited exocyclic double bond, the positive charge formed at this carbon atom will be partially delocalized by resonance over the electron-donating phenyl group. This delocalization decreases the polar character of the terminal carbon atom, thus decreasing the driving force for migration of the partially negatively charged hydroxyl group. Hence upon replacing the alkyl substituent at the terminal carbon atom by a phenyl group, the activation energy of the photochemical [1,3]-OH shift becomes higher than the energy required for the corresponding [1,3]-H shift.

Samenvatting

In dit proefschrift worden de resultaten beschreven van een experimentele en kwantumchemische studie naar het mechanisme en de stereochemie van fotochemische [1,3] sigmatrope shifts. Klassiek gezien wordt het mechanisme van dit type reaktie beschreven door de regels van Woodward en Hoffmann, die gebaseerd zijn op de symmetrie van de hoogst bezette molecular orbital. In dit proefschrift wordt het eerste experimentele bewijs gegeven voor het optreden van een alternatief mechanisme. Dit mechanisme begint met een energetisch gunstige draaiing van een aangeslagen dubbele binding naar een 90° gedraaide structuur. In asymmetrische alkenen zal deze draaiing gepaard gaan met een scheiding van lading in de orthogonale situatie (sudden polarization). Vanuit deze getwiste toestand vindt dan de sigmatrope [1,3] shift plaats *in* het vlak van het koolstofskelet (planaire shift).

In hoofdstuk 2 worden de resultaten weergegeven van semi-empirische berekeningen betreffende de draaiing rond de exocyclische dubbele binding in zowel germacrol als germacreen. Het verschillend fotochemisch gedrag van deze verbindingen (een fotochemische [1,3]-OH shift versus reakties van het endocyclische 1,5-dieen fragment) kon goed verklaard worden uitgaande van een isomerisatie rond de exocyclische dubbele binding. In het geval van germacrol ontstaat hierbij in de eerste aangeslagen toestand een 90° gedraaid intermediair met een polarisatie die gunstig is voor een planaire [1,3]-OH shift, dat wil zeggen een negatieve lading op het centrale koolstofatoom en een positieve lading op het eindstandige koolstofatoom. Voor germacreen is deze toestand sterk gekoppeld met twee diradicalaire toestanden waardoor de overeenkomstige [1,3]-H shift niet zal optreden.

In hoofdstuk 3 wordt het fotochemisch gedrag van enkele 4-methyl, 4-ethyl digesubstitueerde 3-alkylideen-2-naftalenol derivaten beschreven. Bestraling van deze diastereoisomere verbindingen leidt, vanwege de grote sterische interactie tussen de allylische ethylgroep en de vinylische alkylgroep, tot een preferente draaiing van de exocyclische dubbele binding in *een* richting. De stereochemie van de vervolgens optredende [1,3]-OH shift komt volledig overeen met hetgeen verwacht in het geval van een planair reactiemechanisme. Daarnaast is gebleken dat het optreden van een [1,3]-OH shift afhankelijk is van de conformatie van het substraat in de grondtoestand. Hierdoor werd een verdere bevestiging verkregen betreffende het optreden van een niet-Woodward en Hoffmann reaktiemechanisme.

In hoofdstuk 4 wordt aangetoond dat het rendement van een fotochemische [1,3]-OH shift afhankelijk is van de polariteit van het gebruikte oplosmiddel. Deze waarneming kon verklaard worden door een stabilisatie van het na bestraling gevormde, gepolariseerde, 90° gedraaide intermediair, door dipolaire oplosmiddel moleculen.

Tenslotte wordt in hoofdstuk 5 aangetoond dat het optreden van een fotochemische [1,3]-OH dan wel [1,3]-H shift afhankelijk is van de aard van de substituenten aan de exocyclische dubbele binding. Ook deze waarneming kon verklaard worden gebruik makend van het sudden polarization model. In het geval van een fenylsubstituent op het eindstandige koolstofatoom van de aangeslagen exocyclische dubbele binding zal de positieve lading die op dit koolstofatoom gevormd wordt, gedeeltelijk door resonantie worden gedelocaliseerd over de in dit geval electron-donerende fenylgroep. Deze delocalisatie vermindert het polaire karakter van het eindstandige koolstofatoom met als gevolg dat de drijvende kracht voor migratie van de partieel negatief geladen hydroxylgroep afneemt. Aldus zorgt de vervanging van de alkylsubstituent op het eindstandige koolstofatoom door een fenylgroep er voor dat de aktiveringsenergie van de [1,3]-OH shift hoger wordt dan de energie benodigd voor de overeenkomstige [1,3]-H shift.

Curriculum Vitae

De schrijver van dit proefschrift werd op 22 september 1959 te Boxtel geboren. Na het behalen van het diploma Atheneum-B aan het Jacob Roelands Lyceum te Boxtel in 1977, werd in datzelfde jaar begonnen met de studie Chemische Technologie aan de Faculteit der Scheikundige Technologie van de Technische Universiteit Eindhoven. Het afstudeerwerk werd verricht in de vakgroep Organische Chemie onder leiding van prof. dr. H.M. Buck, dr. ir. H.R. Fransen en dr. ir. G.J.M. Dormans. In februari 1984 werd het ingenieursexamen afgelegd. Vanaf 1 maart 1984 tot 1 maart 1988 was hij als wetenschappelijk assistent in dienst van de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO). In deze periode werd het onderzoek, beschreven in dit proefschrift, uitgevoerd onder leiding van prof. dr. H.M. Buck. Per 1 mei 1988 is hij werkzaam op het laboratorium voor ecotoxicologie, milieuchemie en drinkwater van het Rijksinstituut voor Volksgezondheid en Milieuhygiene te Bilthoven.

Dankwoord

Aan het tot stand komen van dit proefschrift hebben velen een bijdrage geleverd. Voor alle adviezen en assistentie op theoretisch, synthetisch en technisch gebied ben ik zeer erkentelijk.
Mijn promotor prof. dr. H.M. Buck dank ik hartelijk voor de waardevolle suggesties, die de loop van het onderzoek mede hebben bepaald. In het bijzonder wil ik tevens dr. ir. Do Dormans, dr. ir. Rob Hermans, dr. ir. René Janssen, ir. Gerrit Groenenboom en ir. Olav Aagaard bedanken voor de prettige samenwerking en belangstelling voor mijn promotieonderzoek. Verder ben ik ir. Jos Hagelaars zeer erkentelijk voor het werk dat hij tijdens zijn afstudeerperiode heeft verricht.
Voor de vormgeving van het proefschrift ben ik veel dank verschuldigd aan dhr. Henk Eding voor de voortvarende wijze waarop hij de vele tekeningen en de lay-out verzorgd heeft.
Een bijzonder woord van dank gaat tenslotte uit naar mijn ouders voor hun voortdurende steun en belangstelling.

The work described in this thesis was supported by the Netherlands Foundation for Chemical Research (SON) with financial aid from the Netherlands Organization for Scientific Research (NWO).

1. De waarneming van Suoranta et al. dat de substraatspecificiteit van het enzym fosfodiesterase afhankelijk is van de aard van het bij de hydrolyse van cAMP noodzakelijk metaalion bevestigt het optreden van een cAMP-intermediair met een equatoriaal-axiaal gesitueerde fosfaatring.

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J.L. Sussman, E.N. Trifonov, Proc. Natl. Acad. Sci. USA, **75**, 103 (1978).
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8. Het optreden van "sudden polarization" in de aangeslagen toestand van gesubstitueerde cycloheptatrienen vormt een goede verklaring voor het waargenomen fotochemische gedrag van deze verbindingen.

T. Tezuka, O. Kikuchi, K.N. Houk, M.N. Paddon-Row, C.M. Santiago, N.G. Rondan, J.C. Williams, Jr., R.W. Gandour, J. Am. Chem. Soc., **103**, 1367 (1981).

9. Gezien de over het algemeen geringe spelregelkennis van zowel spelers als toeschouwers kan het toenemend aantal gevallen van molestaties van voetbalscheidsrechters niet gezien worden als een te letterlijke interpretatie van de spelregels waarin de scheidsrechter als 'dood' object omschreven wordt.

W.J.G.M. Peijnenburg Eindhoven, 21 juni 1988