Organic Photochemistry

Additional reading list:

J. Mattay, A. G. Griesbeck: *Photochemical Key Steps in Organic Synthesis*, Wiley-VCH, 1994.

F. A. Carey, R. J. Sundberg, *Advanced Organic Chemistry*, Plenum Publishing Corporation, 2000.

N. J. Turro, *Modern Molecular Photochemistry* 1991, University Science Books, Mill-Valley, California.

A. Gillbert, J. Baggott, *Essentials of Molecular Photochemistry* 1991, Blackwell Scientific Publications, London.

M. Klessinger, J. Michl, *Excited States and Photochemistry of Organic Molecules*, Wiley-VCH, 1994, New York.

B. Valeur, *Molecular Fluorescence*, Wiley-VCH, 2002, Weinheim.

Essential criteria for all photochemical reactions:

> Molecule must absorb light
> Radiation energy must match energy difference of ground and excited state

Typical absorption range of some important classes of organic compounds:

Simple alkene	190 - 200 nm
Acylic diene	220 - 250 nm
Cyclic diene	250 - 270 nm
Styrene	270 - 300 nm
Saturated ketones	270 - 280 nm
α,β-Unsaturated ketones	310 - 330 nm
Aromatic ketones/aldehydes	280 - 300 nm
Aromatic compounds	250 - 280 nm

## Light is absorbed by a molecule – what happens?

The electronic configuration changes. The *Franck-Condon principle* says that the heavy atom nuclei do not change their positions. This leads to an initial geometry of the excited state which is usually not the energy minimum. During excitation the electron spin remains unchanged. Spin inversion during excitation is forbidden by quantum mechanics and therefor unlikely.

Right after the excitation several things may happen. 1) Vibronic relaxation brings the molecule quickly into the new energy minimum structure for the excited state. Energy is released into the solvent. 2) Intersystem crossing leads to triplet states by spin inversion.

Again, the new energy minimum is reached by vibrational relaxation. 3) Emission of light and return to the ground state (luminescence, fluorescence, phosphorescence). 4) Quenching of the exited state: Energy is transferred to another molecule. Usually we observe diffusion controlled dynamic quenching by collision. Investigation of this is possible by the Stern-Vollmer plot (1/quantum yield *vs* concentration of quencher). Gives a strait line for diffusion controlled quenching; large excess of quencher usually needed (1000 times excess).

5) Radiationless deactivation. Molecule goes back to ground state by vibrational (thermal) deactivation (no light emission). The energy goes to the solvent/environment of molecule.

Alternative: A photochemical reaction may occur.
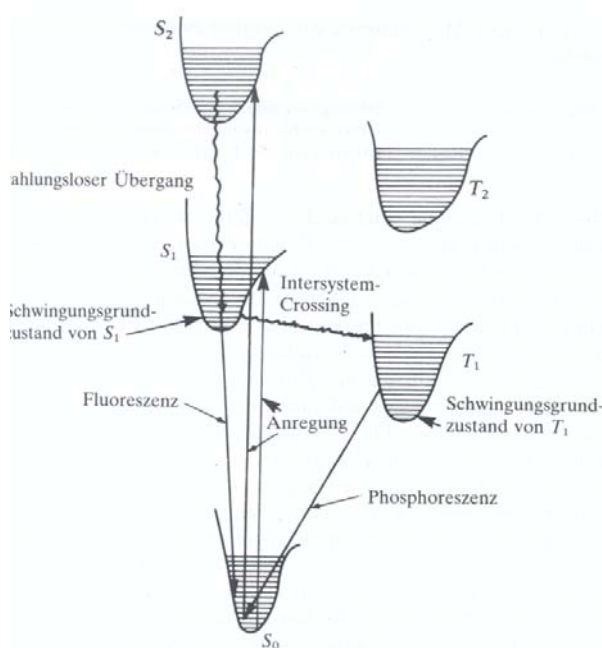
Pathways of photochemical processes

Why are photochemical reactions interesting?

1) The excited states are rich in energy. Therefore reactions may occur that are highly endothermic in the ground state. Using the equation $E = h \times \nu$ we can correlate light of a wavelength of 350 nm with an energy of 343 kJ/mol!

2) In the excited state antibonding orbitals are occupied. This may allow reactions which are not possible for electronic reasons in the ground state.

3) Photochemical reaction can include singlet and triplet states. Thermal reactions usually only show singlet states. In photochemical reaction intermediates may be formed which are not accessible at thermal conditions.

Some practical considerations:

1) Purity of starting materials is of importance!

This prerequisite holds for many techniques in synthesis. While working with organometallic intermediates requires exclusion of air and moisture, photochemistry is very sensitive to colored or light absorbing impurities – either in the starting materials or formed during reaction. Both may interfere with the photo processes and may kill the reaction.

2) UV spectra of substrates: A first hint

Before starting a photochemical reaction a UV/vis spectrum of the "photoactive" compound is recorded. The "photoactive" compound is the molecule which should be electronically excited and undergo or initiate a reaction from its excited singlet or triplet state. From UV spectra recorded with different compound concentrations the extinction coefficients of all bands can be obtained, even for the weak absorptions which may be of importance. UV spectra of all reagents should be recorded to make sure that there is no or little interference in absorption with the "photoactive" compound. If available, a UV spectrum of the product should be recorded.

UV spectra from the reaction mixture may help to identify ground state interactions of compounds or CT complexes, and guide the way to the best reaction conditions.
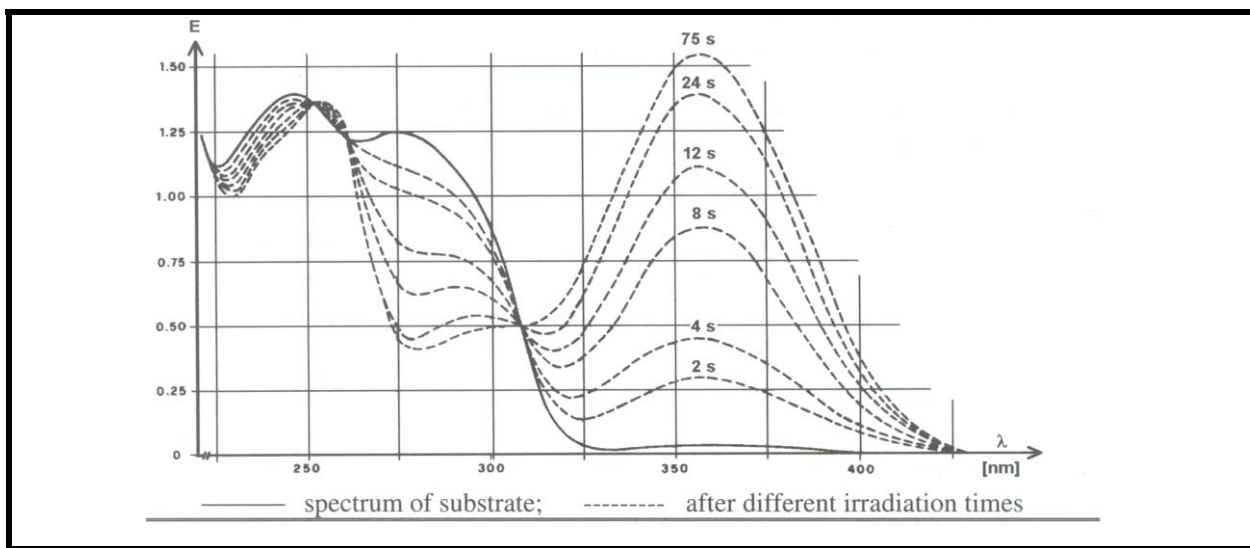
UV spectrum of a photochemical reaction

3) What solvent to use?

Photochemical reactions can be performed – in principle – in the gas phase, in solid state or in solution. For practical reasons most photochemical reactions are done in solution, therefore the choice of the right solvent is critical.

At normal concentrations of a photochemical reaction the concentration of the "photoactive" compound is only 100 – 1000 times larger than the concentration of the solvent. If the extinction coefficient of the "photoactive" compound is only 10 times higher than that of the solvent at the irradiation wavelength, we will observe a significant filter effect of the solvent. The reaction is much slower than it could be.

Key selection criteria:

- Solvent must dissolve reactants (try)
- Solvent should be transparent at the irradiation wavelength (UC spectrum)
- Solvent must be free of impurities (analysis; add EDTA to complex trace metal ion content if necessary)

If a reactive intermediate needs to be stabilized by the solvent, this has to be tried out until a solvent is found which matches all criteria.

Table 1: Solvents used for photoreactions[1]

Solvent	Cut-off wavelength[2]	ε_r[3]	ET(30)[4]
water	185	78.30	63.1
acetonitrile	190	35.94	45.6
n-hexane	195	1.88	31.0
ethanol	204	24.5	51.9
methanol	205	32.66	55.4
cyclohexane	215	2.02	30.9
diethyl ether	215	4.20	34.5
1,4-dioxane	230	2.21	36.0
methylene chloride	230	8.93	40.7
chloroform	245	4.81	39.1
tetrahydrofuran	245	7.58	37.5
ethyl acetate	255	6.02	38.1
acetic acid	250	6.17	51.7
carbon tetrachloride	265	2.23	32.4
dimethylsulfoxide	277	46.45	45.1
benzene	280	2.27	34.3
toluene	285	2.38	33.9
pyridine	305	12.91	40.5
acetone	330	20.56	42.2

[1] taken from C. Reichardt, *Solvents and Solvent Effects in Organic Chemistry* **1988**, VCH, Weinheim.
[2] wavelength (nm) at which E is approximately 1.0 in a 10 mm cell.
[3] dielectric constant.
[4] Dimroth-Reichardt values (kcal/mol) for the longest-wavelength solvatochromic absorption based on a pyridinium-*N*-phenoxide betaine dye no. 30.

Solvents used in photoreactions

4) Direct or sensitized photolysis? You have to find out!

The absorption characteristics do not tell anything about the behavior of a molecule in the excited state. It may rapidly deactivate via fluorescence or radiationless, it may undergo intersystem crossing into the triplet manifold. If available, data on fluorescence, phosphorescence, lifetimes and quantum yield are very helpful to understand the processes. From these data we can learn if it is necessary to sensitize the formation of the triplet state for a reaction or if the triplet is rapidly formed without our help. Sometimes the solvent can be used as a sensitizer. Then it should adsorb at the irradiation wavelength and transfer the energy to the reactant. Acetone is a typical example of such a solvent (adsorbs up to 330 nm).

Sensitizers and quenchers can help to investigate a photochemical reaction:

1) Pure singlet reactivity: No reaction in the presence of appropriate triplet sensitizers.

2) Pure triplet reactivity: enhanced product formation in the presence of appropriate sensitizers; no reaction in the presence of triplet quenchers.

3) Triplet as well as singlet reactivity: combination of methods 1) and 2) gives a product pattern corresponding to the specifically activated states.

Table 2: Sensitizers and quenchers in non-polar solvents[1]

compound	E_T[2]	E_S[3]	Φ_{ISC}[4]
benzene	353	459	0.25
toluene	346	445	0.53
methyl benzoate	326	428[7]	
acetone	332[5]	372[6]	0.90[6]/1.00[5]
acetophenone	310	330	1.00
xanthone	310	324	
benzaldehyde	301	323	1.00
triphenylamine	291[5]	362	0.88[6]
benzophenone	287	316	1.00
fluorene	282	397	0.22
triphenylene	280[5]	349	0.86
biphenyl	274	418	0.84
phenanthrene	260	346	0.73
styrene	258	415	0.40
naphthalene	253	385	0.75
2-acetylnaphthalene	249	325[5]	0.84[5]
biacetyl	236[5]	267[5]	1.00
benzil	223	247	0.92
anthracene	178	318	0.71
eosine	177	209	0.33
rose bengale	164	213	0.61
methylene blue	138	180	0.52

[1] taken from ref. [12] (chapter *General Features*, *a*).
[2] triplet energies in kJ/mol.
[3] first excited singlet state energies in kJ/mol.
[4] quantum yields for singlet-triplet intersystem crossing.
[5] in polar solvents.
[6] taken from H. G. O. Becker, *Einführung in die Photochemie*, **1991**, Deutscher Verlag der Wissenschaften Berlin.
[7] benzoic acid.

Sensitzers and quencher in non-polar solvents

5) Reaction control: Spectroscopy and chromatography

In the course of the reaction more and more product is formed which competes with the starting material for light. If the product is available its UV spectrum gives information about possible competition. The increasing absorption of irradiation by the product may stop the reaction before complete conversion will be reached. Therefor it is important to follow the reaction by UV spectroscopy (see figure above of UV spectra during reaction). The formation of colored byproducts may stop a reaction before complete conversion, too. Chromatographic methods, such as TLC, GC or HPLC should be used to gain information about the course of the reaction. Is there only one (major) product or do we get several? What is the optimal time of the reaction with maximum conversion and minimal side product formation?

6) Side reactions can easily become the major track!

Side reactions of photochemical reactions can in some cases become the major reaction pathway. Examples are photosensitizers, which are use in catalytic or stoichiometric amiunts to mediate the wanted photochemical process, but they may also act as photoinitiator of a radical chain reaction. If solvents or starting materials are present that are susceptible to a radical chain process, this reaction will become dominant. Another origin of severe side reaction may be the presence of oxygen. Photooxygenation may be the desired photoprocess, but if not, it may be a side reaction. Oxygen should be excluded to avoid this. Even if only small amounts of peroxides are formed during the reaction they may become hazardous upon work up. The use of inert gas is not necessary, if the essential excited state is not efficiently quenched by triplet oxygen (which is often the case for short living singlet states).

Free radicals produced during the reaction may cause side reactions. Radical scavengers, such as phenols, are added to trap them.

7) Quantum yield and chemical yield

While reactions of "normal ground state" chemistry are described by the chemical yield of the reaction as one major indicator (there are others, in particular when it comes to describe the technical efficiency of a chemical transformation), for the chemistry of excited molecules another parameter has to be considered: The quantum yield of the reaction. The quantum yield is the number of events (e.g. photochemical induced transformation) divided by the number of absorbed photons in a specific system. Quantum yields can range from 0 to 100 or higher; if smaller than 0.01 conversion is very slow (chemical yield may still be high); for photoinitiated chain reactions the quantum yield can be as high as 100.000.

How much light goes into my reaction? This question must be answered (beside determination of the amount of product formed) to calculate a quantum yield. A standard chemical procedure used since the 1920s is chemical actinometry. A compound that undergoes a defined photochemical transformation with known quantum yield is used to determine the light intensity. The concentration of the actinometric compound and the pathway of the exposure cell must be sufficiently high to make kinetics of the reaction approx. zero order. In this way the rate of the reaction is not concentration dependent. The reaction of 2-nitrobenzaldehyde to 2-nitrosobenzaldehyd is a typical example. The quantum yield of the process is 0.5 for irradiation from 300 – 410 nm.

I_0 = light intensity
ϕ = quantum yield
f = fraction of absorbed light

$$-\frac{d[Act]}{dt} = I_o \, \phi \, f$$
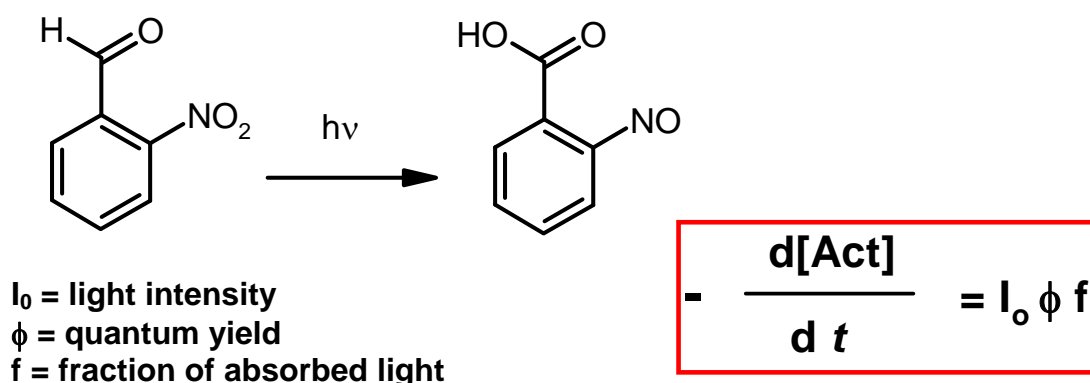
Reference: K. L. Willett, R. A. Hites, *J. Chem. Edu.* **2000**, *77*, 900 - 902.

8) Lamps, vessels and filters

Typical light sources for preparative photochemistry:

- the sun (300 – 1400 nm),
- low-pressure mercury (Hg approx. 10^{-5} atm) lamp: 185 nm (5%); 254 (95%) (see a in figure),
- Rayonet lamps (specific emission wavelength from secondary fluorescence emission, coated; see c in figure for an example),
- medium pressure Hg (Hg vapor pressure 5 atm) lamps (distinct lines between 250 and 600 nm),
- high pressure Hg lamps (Hg vapor pressure approx. 100 atm; expensive, easily damaged) (emission 360 – 600 nm, broad),
- low- and high pressure sodium lamps (emission around 600 nm)
- High power light emitting diodes (available at low cost for 650 to 400 nm; very narrow and intensive emission, long lifetime; UV-LED are currently still expensive.

Many types of reactors for photochemical reactions are known. The most typical are:

1) Apparatus for external irradiation (simplest case is an irradiated flask)
2) Immersion-well reactor in which the lamp is surrounded by the reaction solution
3) Falling film apparatus
4) Photo microreactor (similar to falling film, but easier to handle)

In all cases the lamp usually needs cooling to avoid its overheating and heating of the reaction solution.

The material of the reactor depends on the irradiation wavelength necessary.

For irradiation at 254 nm quartz glass (expensive apparatus) is needed. for irradiation at 300 nm pyrex glass is needed, and for irradiation > 350 nm normal lab glass (window glass) is sufficient. The glass acts as a solid filter. Additional solid or liquid optical filters may be used to restrict the irradiation wavelength.
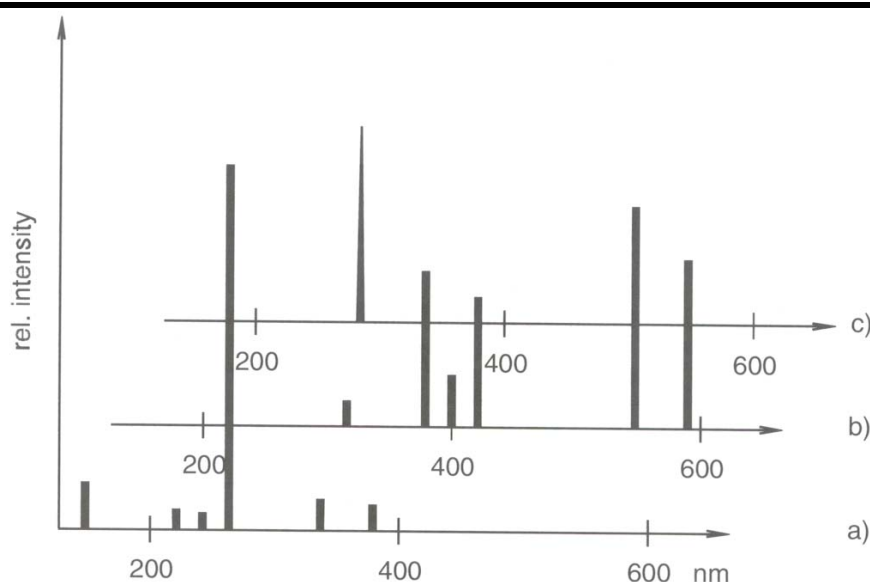
Figure 2: Emission properties of a) mercury low-pressure lamp (strong 254 line), b) mercury high-pressure lamp and c) RPR-3000Å lamp for Rayonet photoreactors (300 nm line).

Left: High power LED; right: Photo microreactor

9) Hazards

Like in all chemical operations there are risks in photochemistry.

Irradiation. Low-pressure mercury lamps have their main output at 254 nm. This light severely damages cells, eyes and skin. Shield reactors; turn lamps off before checking the reaction. Never look into the beam of a high power LED; the lights very high intensity damage your eyes.

Ozone generation: Short wavelength light may generate ozone from oxygen. Perform reactions always in a well ventilated fume hood.

Lamps: Most lamps operate at high temperature and at high vapor pressure. Never move or touch lamps during operation. Never switch of the cooling right after switching of the lamp!

Photochemical reactions

1) Carbonyl compounds

The absorption properties of ketones and aldehyds are convenient for irradiation around 300 nm (nπ* 330 - 280 nm). Triplet-singlet energy gap is small (20-70 kJ/mol); intersystem crossing rates are high. Lifetime of first excited singlet state is in the nanosecond region for aliphatic aldehydes and ketones; in the subnanosecond region for aromatic aldehydes and ketones. Singlet photochemistry can be detected with aliphatic aldehydes or ketones, while aromatic substrates, such as benzophenone or acetophenone, react exclusively from their corresponding triplet states and are excellent triplet sensitizers.

Norrish Type I cleavage reaction (α-cleavage reaction)

This reaction type dominates gas phase photochemistry of many aldehydes and ketones. Less common in solution chemistry; only if no suitable C-H bonds are present to allow hydrogen atom abstraction.

Examples:
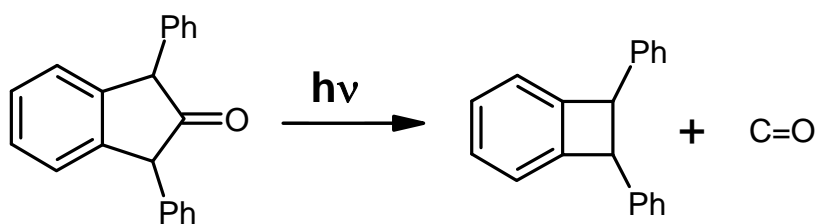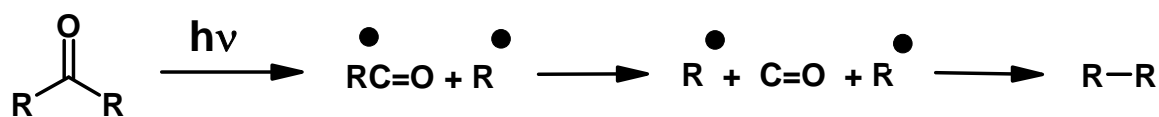
Special topic:[1] C-C Bond formation in Organic Crystals

Photochemical irradiation of crystalline (2*R*,4*S*)-2-carbomethoxy-4-cyano-2,4-diphenyl-3-butanone **1** led to highly efficient decarbonylation reactions. Experiments with optically pure and racemic crystals show that the intermediate radical pairs undergo a highly diastereo- and enantiospecific radical-radical combination that leads to the formation of two adjacent stereogenic centers in good chemical yield and with high chemical control. Reactions with chiral crystals occurred with quantitative enantiomeric yields and >95% diastereomeric yields.

(+)-(2R,4S)-1 ⟶ [ca. 100 % ee / ca. >95 % de] ⟶ (+)-(2R, 3R)-2

(±)-(2RS,4SR)-1   (±)-(2RS, 3RS)-2
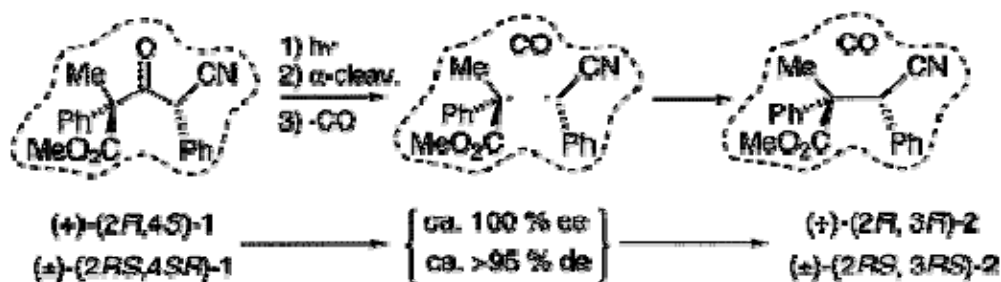
Compound **1** was obtained in enantiomerically pure and racemic forms from 2-methyl-2-phenyl malonic acid monomethyl ester **3b**. Samples of (+)-(R)-**3b** were prepared from the *meso* diester **3a** by enzymatic desymmetrization with pig liver esterase (90% ee) or by resolution of acid (±)-**3b** with (-)-1-(1-naphthyl)ethylamine. Acid (+)-**3b** was converted into the corresponding acyl chloride, which was reacted with the anion of benzyl cyanide to give ketone (2R,4S)-**1** and its diastereomer (2R,4R)-**1a** (not shown) in 85% isolated yield in a 4:1 ratio.
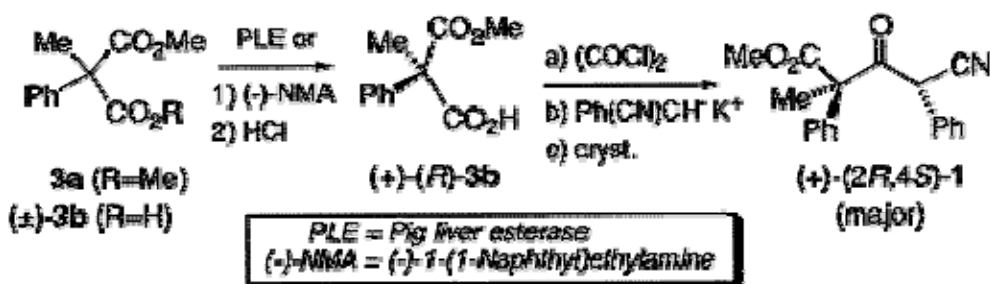
Photochemical experiments with oxygen-free 0.1 M **benzene solutions** of (+)-(2R,4S)-**1** and (±)-(2RS,4SR)-**1** using a Hanovia lamp with a Pyrex filter (> 300 nm) at 298 K led to complex product mixtures (Figure, bottom). In contrast, crystals of (+)-(2R,4S)-**1** and (±)-(2RS,4SR)-**1** (ca. 50 mg) irradiated under similar conditions resulted in a very clean reaction with formation of a major photoproduct in 40-60% conversion and >95% selectivity (Figure, top). The product was later shown to be (+)-(2R,3R)-**2** and (±)-(2RS,3RS)-**2** from the optically pure and racemic crystals, respectively.

[1] M. E. Ellison, D. Ng, H. Dang, M. A. Garcia-Garibay, *Org. Lett.* **2003**, *5*, 2531.
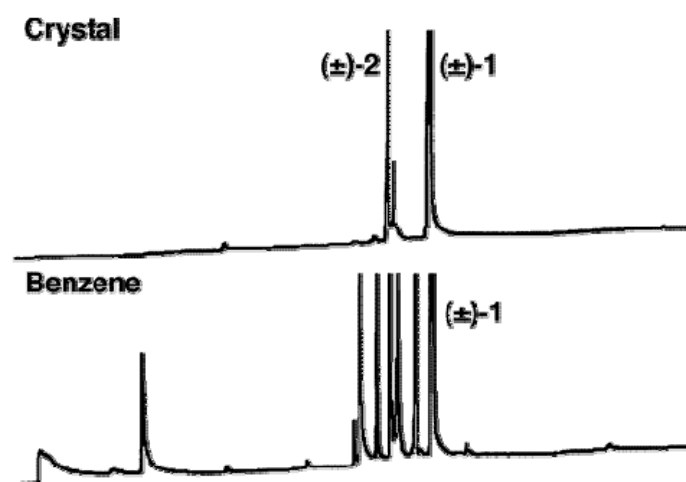
Norrish Type II photoelimination reaction

Beside carbon monoxide extrusion acyl radicals formed in a α-cleavage can be stabilized by subsequent hydrogen migration.

Examples:
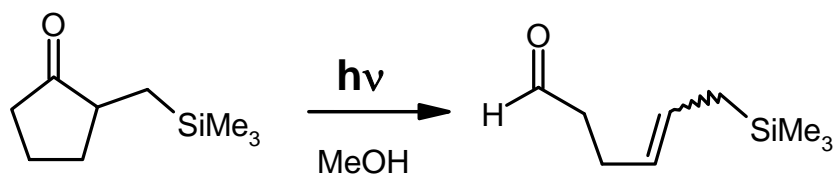
L. F. Tietze, J. R. Wünsch, *Synthesis*, **1990**, 985 – 990, 1204.
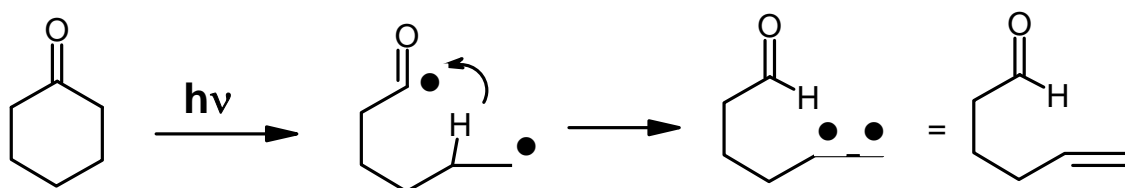
Cyclobutanol formation (Yang reaction)

With an appropriate alignment of C=O and C-H groups and no secondary transformation prevents cyclization of the 1,4-diradical leads to cyclobutanols.

Examples:
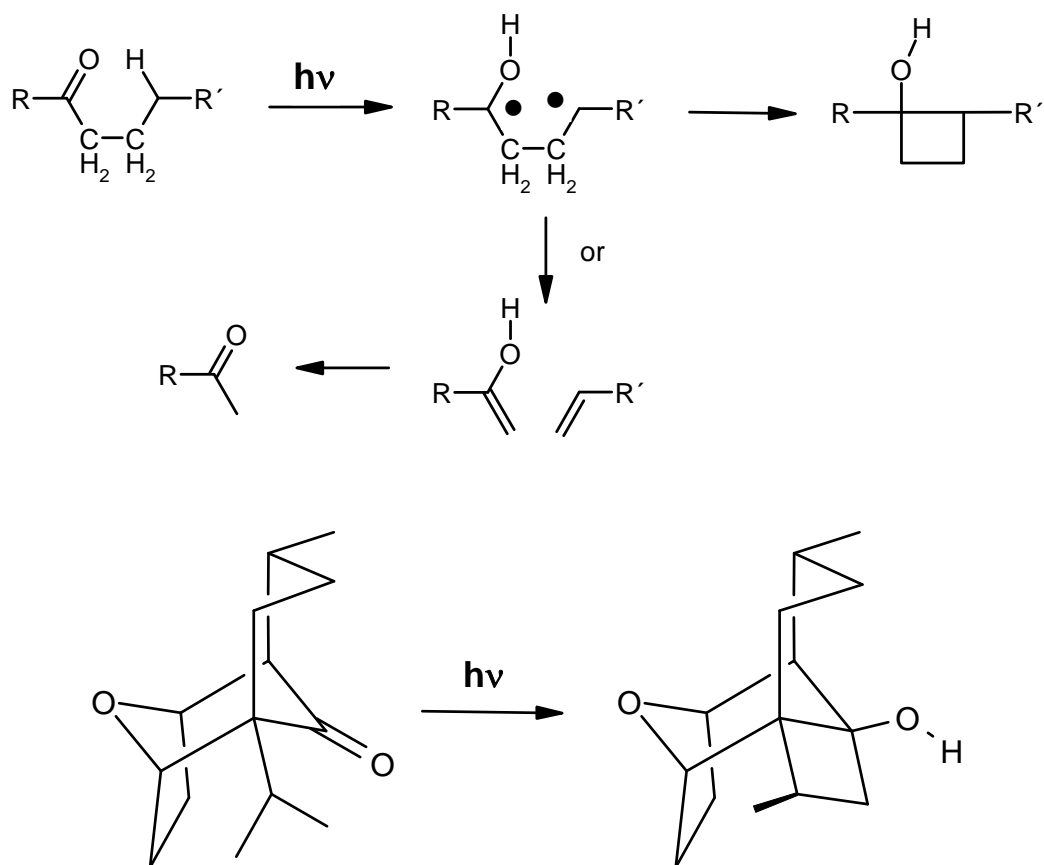
Paternó Büchi reaction

The photochemical [2+2] cycloaddition of an alkene and a carbonyl group is called Paternó Büchi reaction. Inter- and intramolecular examples are known. High diastereoselectivities can be observed in many examples.

Examples:
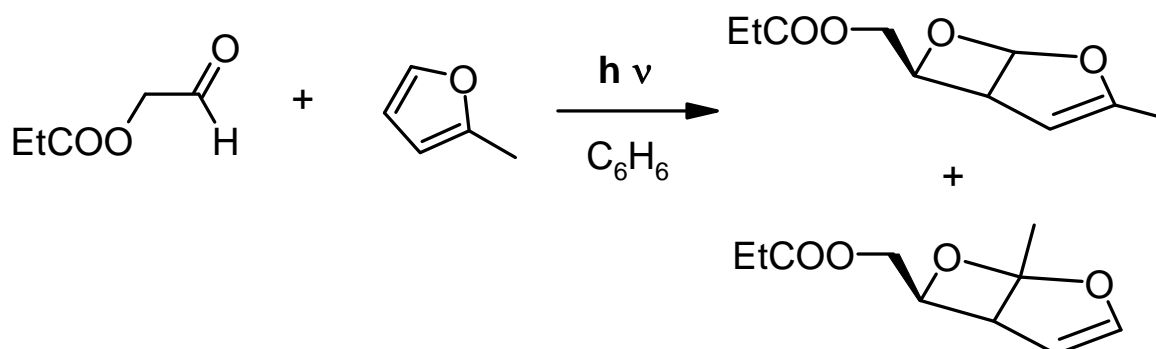
R. Hambalek, G. Just, *Tetrahedron Lett*. **1990**, *31*, 5444 – 5448.
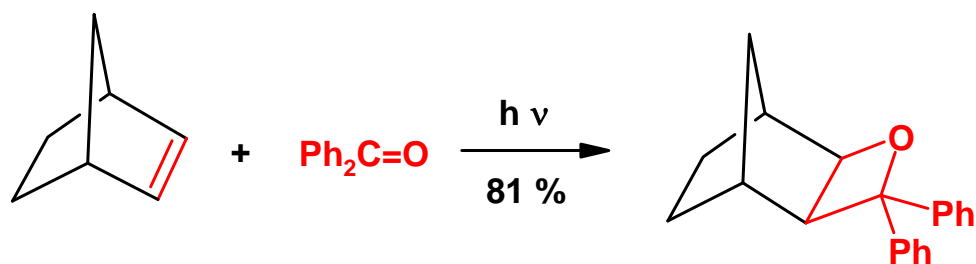
Diastereoselective reaction:

major diastereomer
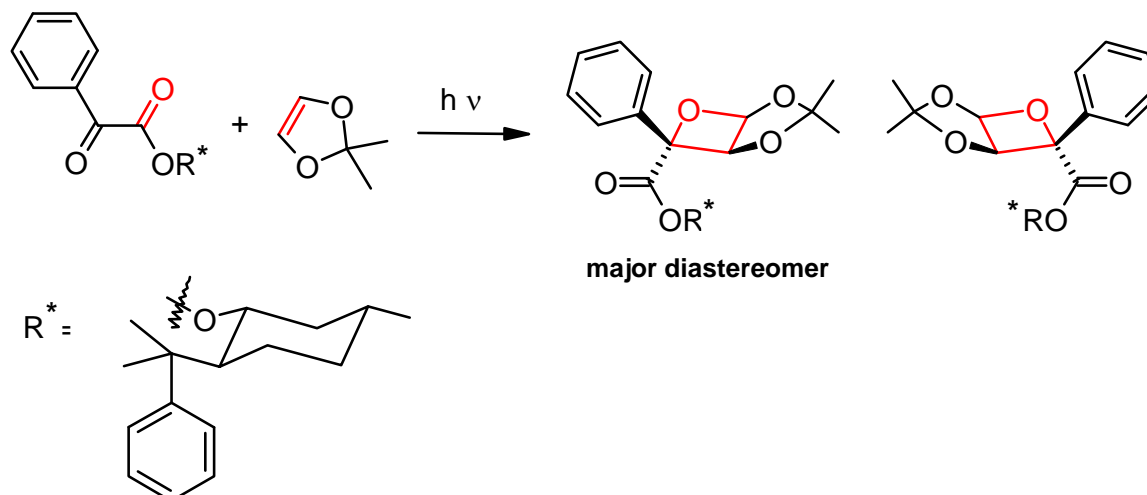
Photoisomerizations and photoreductions

Photoisomerisations and photoreductions are observed. Some examples:

In this reaction the first event is an abstraction of hydrogen from the γ position. Neither Norrish type II nor Yang reaction follow. Instead another hydrogen is stereoselectively transferred, now from the δ position.
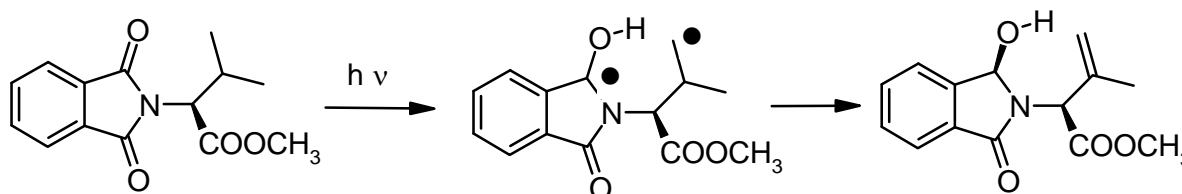
A. G. Griesbeck, M. Mauder, *Angew. Chem.* **1992**, *104*, 97 - 99.

The second example is a photoreduction of an α,β-epoxy ketone derived from carbohydrates. Triethylamine acts as the sacrificial electron and hydrogen donor. The configuration of one of the epoxy stereocenters remains intact.
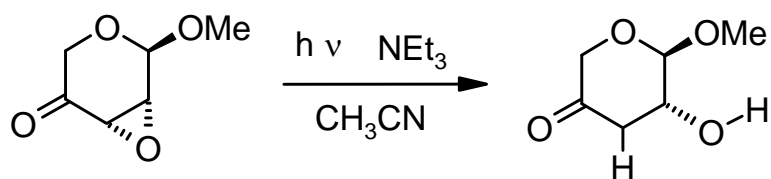
2) Alkenes

The formation of the lowest excited singlet state of simple alkenes arises from the allowed π-π* transition. This generally requires short wavelength irradiation extending to about 200 – 210 nm. Absorption of solvents and lack of suitable light sources make the use of simple alkenes in preparative photochemistry difficult. Substituted or conjugated derivatives are mainly used. Another possibility to circumvent the problem of absorption at short wavelengths is the use of sensitizers.

E,Z-Isomerizations

E,Z-Isomerizations of 1,2-disubstituted alkenes are well documented. A typical example is the photoisomerization of stilbene, where because of different absorption spectra the Z-isomere can be enriched in the photostationary state.

A more complex example is the sensitized preparation of enantiomerically enriched trans-cyclooctene.

ee up to 53%
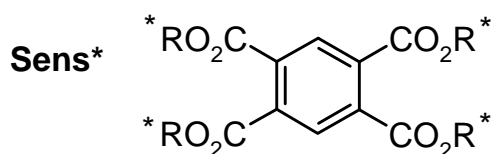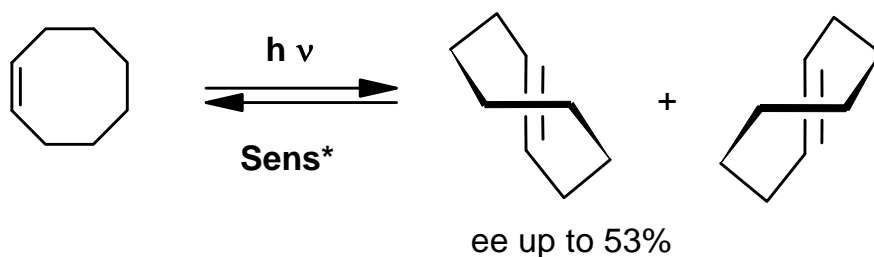
Y. Inoue et al., *J. Am. Chem. Soc.*, **1989**, *111*, 6480 - 6482; *J.Org. Chem.* **1992**, *57*, 1332 - 1345.

Sigmatropic shifts

These rearrangements involve a migration of a σ-bond across an adjacent π-system. The type of activation (thermal or photochemical) and the stereochemistry can often be predicted by the

Woodward-Hoffmann rules. Processes involving stepwise biradical intermediates may be present in photochemical reactions.

Examples:
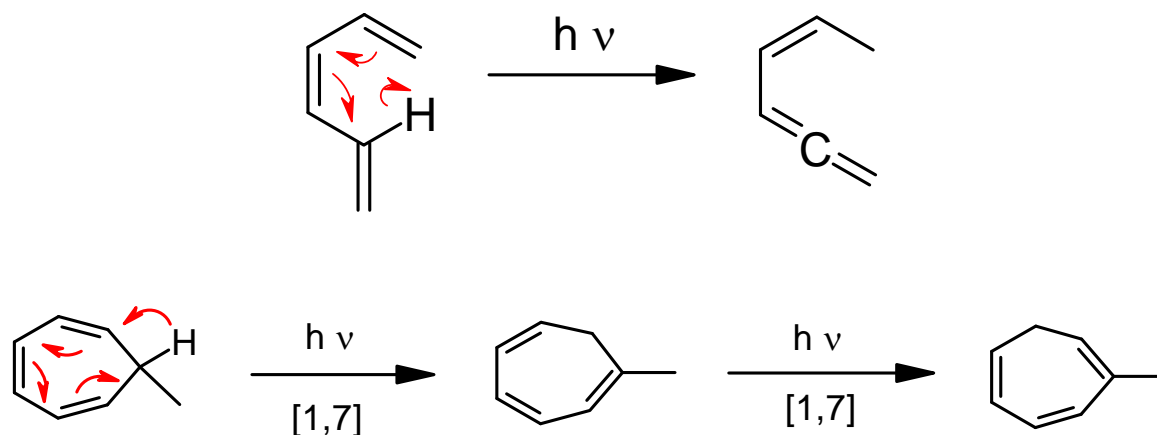
Di-π-methane rearrangement

This unique rearrangement was discovered by H. Zimmermann in the late sixties and belongs to the sigmatropic rearrangements of type [1,2]. The rearrangement is stereospecific and has been used in organic synthesis.

Examples:
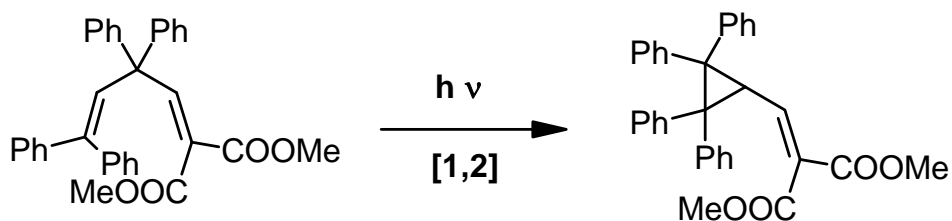
H. E. Zimmermann, R. E. Factor, *Tetrahedron* **1981**, *37*, Supplement 1, 125 - 141.
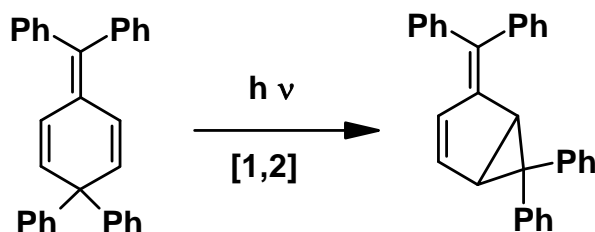
H. E. Zimmermann, D. R. Diehl, *J. Am. Chem. Soc*. **1979**, *101*, 1841 - 1857.

[2+2] Cycloaddition reactions

These transformations belong to the classic reactions that generally can be rationalized by the Woodward-Hoffmann rules. The [2+2] cycloaddition is photochemically allowed and a practical way to cyclobutane derivatives. Cyclobutene ring opening and hexatriene ring closure belong to the most frequently investigated electrocyclic reactions.

Examples:

Intramolecular [2+2] photocycloaddition
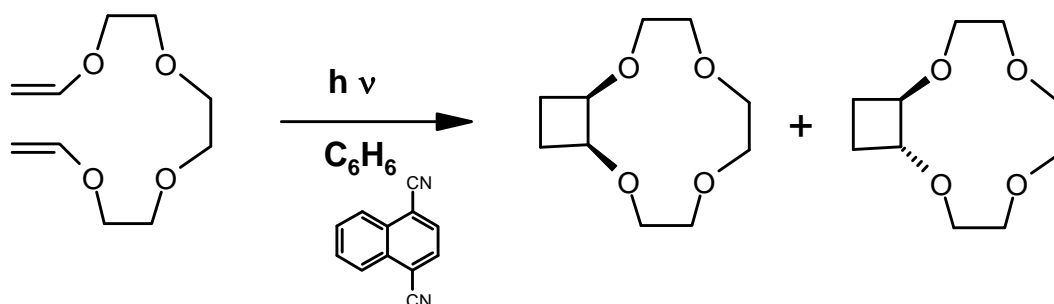
K. Mitzuno, Y. Otsuji, *Chem. Lett.* **1986**, 683 – 686.
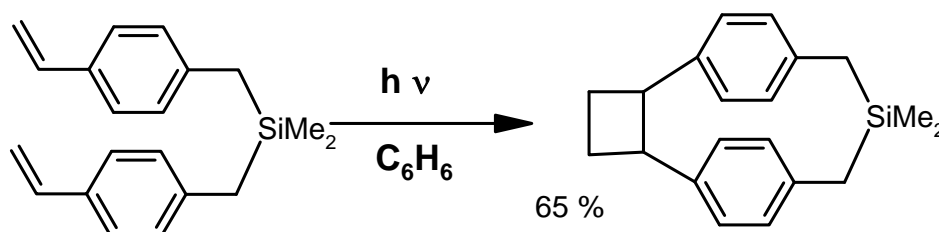
K. Nakanishi, K. Mizuno, Y. Otsuji, *J. Chem. Soc., Perkin Trans. 1* **1990**, 3362 – 3363.

Intermolecular [2+2] photocycloaddition
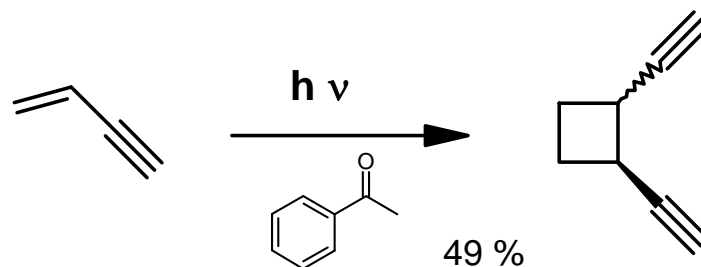
Reaction in falling-film reactor
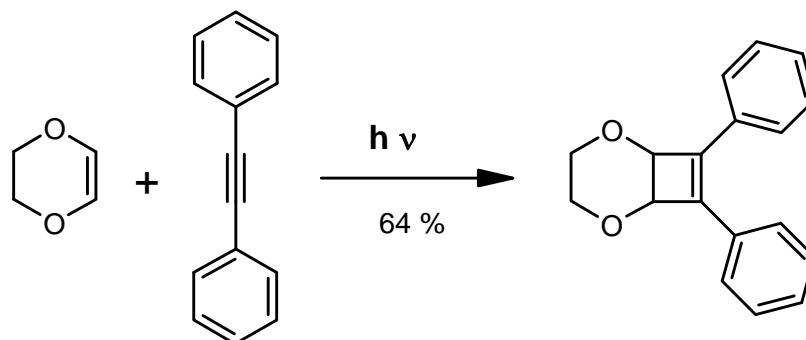
Irradiation with low pressure Hg lamp

The length of the side chain leads to a complete control of the regioselectivity of the [2+2] photocycloaddition:
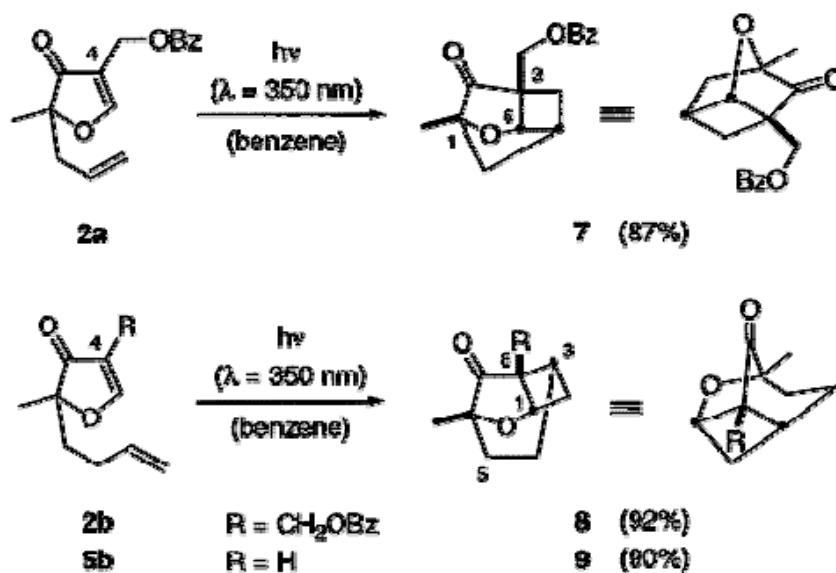
T. Bach, M. Kemmler, E. Herdtweck, *J. Org. Chem* **2003**, *68*, 1994 – 1997.
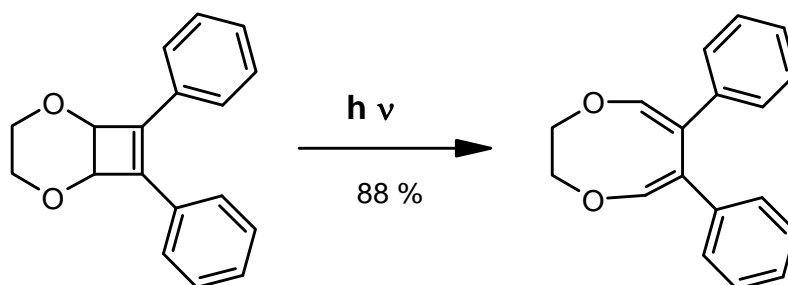
Irradiation with high pressure Hg Lamp through pyrex filter.

G. Kaupp, M. Stark, *Chem. Ber.* **1978**, *111*, 3608 – 3623.

Photoinitiation of radical reactions

Photoinduced electron transfer reactions can be used to initiate radical reactions of alkenes. Both pathways, oxidative leading to a radical cation, and reductive, leading to a radical anion, are possible. The majority of reported examples involve oxidative pathways.
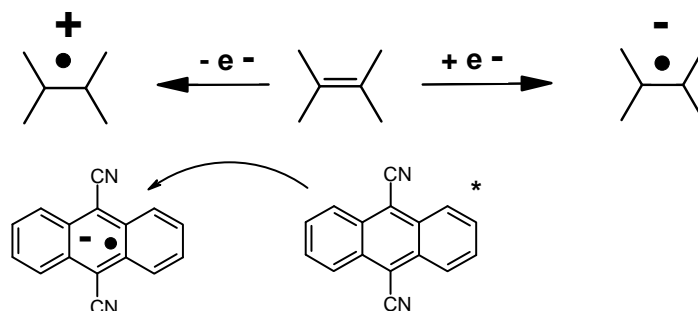
Examples:

Photooxidation of an enol silyl ether
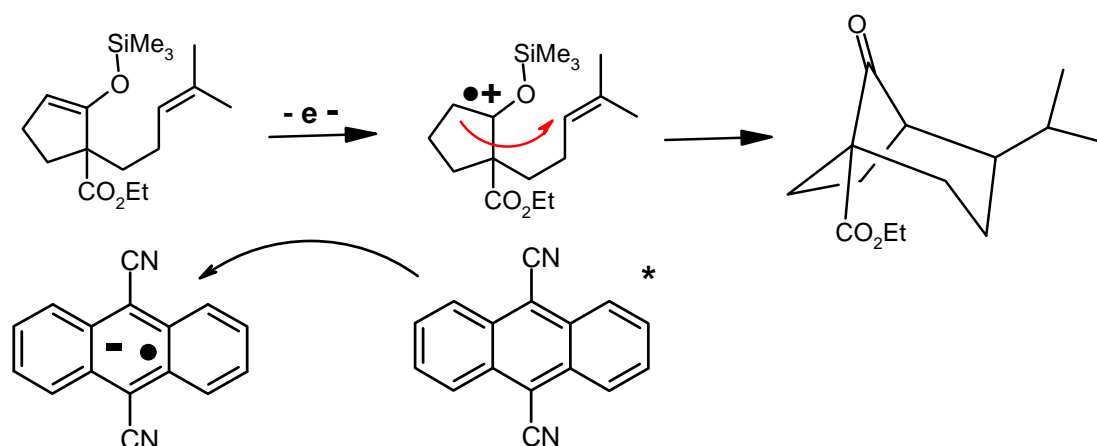
A. Heidbreder, J. Mattay, *Tetrahedron Lett*. **1992**, *33*, 1973 – 1976.

Photoinduced cyclobutane ring opening. This reaction occurs in light dependent enzymatic DNA repair in bacteria. The enzymatic redox cofactor flavin is excited in its reduced form, transfers an electron onto the thymine cyclobutane dimer, which undergoes stepwise ring opening as radical anion. The electron is transferred back to the flavin and a new cycle can begin.
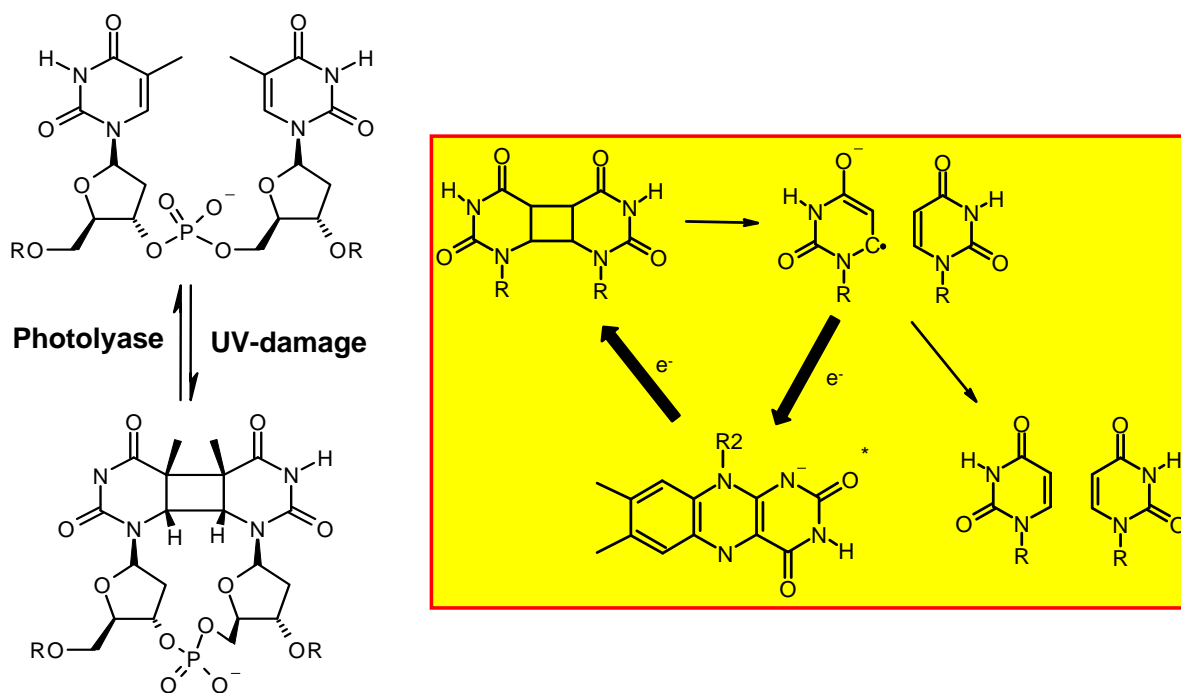
Exkurs: Alkene photocycloadditions as key steps in organic synthesis – a recent example

Photochemical synthesis of a complex skeleton found in natural products[2]

In contrast to simple homoallyl vinyl ethers, which have been shown to undergo Cu-catalyzed [2+2] photocycloadditions, the more highly substituted substrates of type **B** do not react as desired, but decompose in the presence of the copper salts. As an alternative to enol ethers derivatives of tetronic acid (**1**, R=H) were tested in direct [2+2] photocycloaddition reactions. These building blocks deliver excellent results under irradiation conditions.
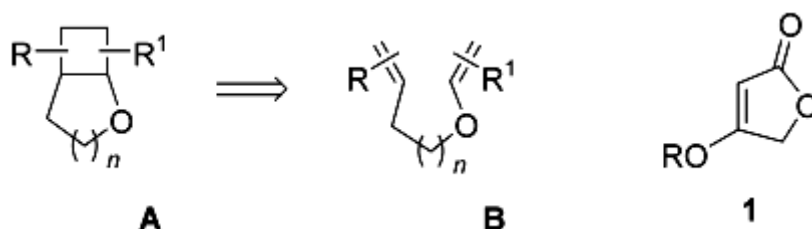
Synthesis of 2-oxabicyclo[3.2.0]heptanes by intramolecular [2+2] photocycloaddition

[2] M. Kemmler, T. Bach, *Angew. Chem.* **2003**, *115*, 4973.

Tetronates of the general formula **2** are available from tetronic acid or its derivatives and -alkenols by nucleophilic substitution. The intramolecular [2+2] photocycloaddition of the O-bridged dienes **2** proceedes smoothly yielding tetrahydrofuran **3a** and tetrahydropyran **3b** with excellent diastereoselectivity. In each case a single product is observed in diastereomerically pure form. The relative configuration was assigned by NOESY experiments and X-ray crystallographic analysis. The light source in the irradiation experiments was either a TNN 15/32 (Original Hanau, Heraeus Nobelight) low-pressure mercury arc or lamps of the type RPR-2437 Å (Rayonet).

2a	*n* = 1	74%	**3a**
2b	*n* = 2	71%	**3b**
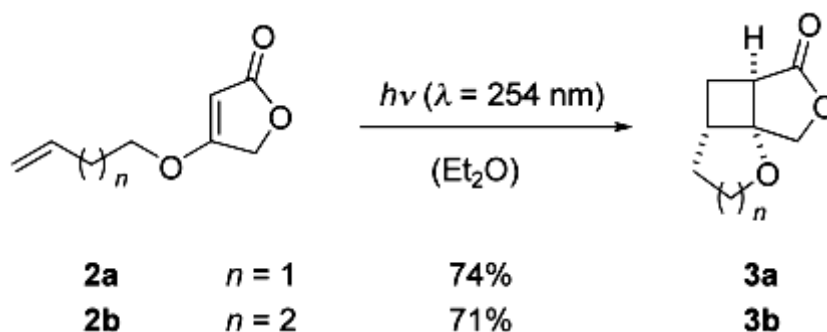
Intramolecular [2+2] photocycloaddition of -alkenyl tetronates **2**

Analogous experiments in acetone as the solvent or with a triplet sensitizer (benzophenone, acetophenone) in diethyl ether or acetonitrile were less successful and led to the formation of side products. The intramolecular photocycloaddition is not restricted by the position of the alkenyl side chain. In compound **4** the -alkenyl chain is attached at C3, in compound **6** at C5. The cyclization of these substrates gives tricyclic products **5** and **7** with high chemo-, regio-, and stereoselectivity. In all cases (**3, 5, 7**), a single product was formed in which the cyclobutane ring and the annelated five- or six-membered rings are connected in a *cis* fashion. The facial diastereoselectivity in the reaction **6** to **7** can be understood as the attack of the terminal alkene to the face of the tetronate to which the alkyl chain is directed by the stereogenic center at C5.
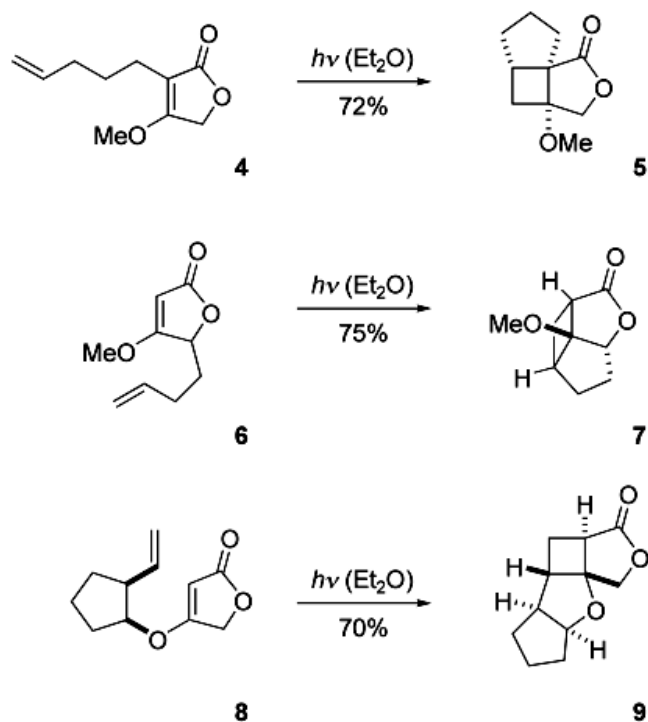
Intramolecular [2+2] photocycloaddition of further substituted tetronates
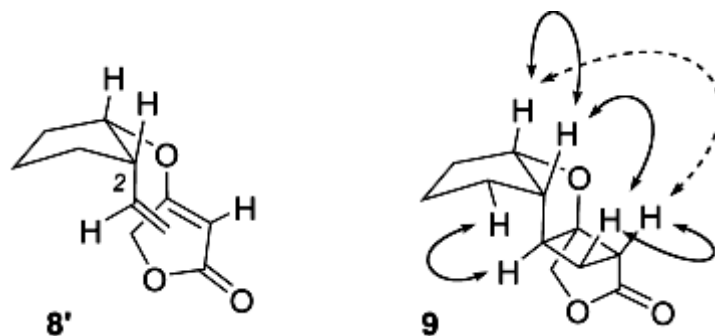
Preferred conformation of compound **8** in the reaction to form **9** and NOESY contacts in the tetracyclic compound **9** (- - - - medium, - strong).

The methodology was expanded to use the cyclobutane ring in the products for subsequent fragmentation reactions. A retroaldol reaction converts **10** into the ketolactone **11** upon treatment with a base.
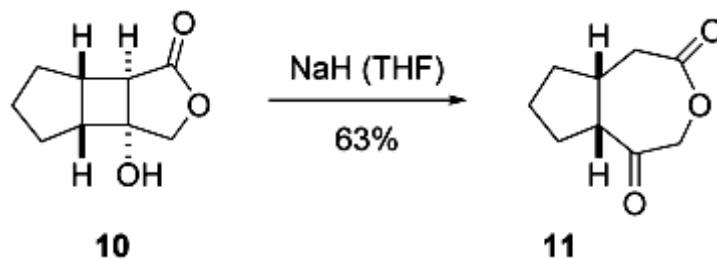
Retroaldol reaction of the photocycloaddition product **10**

3) Nitrogen-containing compounds

The presence of a nitrogen atom often alters the photophysical and photochemical properties of a given chromophore. Many nitrogen containing compounds are much easier to oxidized than the corresponding nitrogen-free analogous.

Aza-di-π-methane rearrangements

Acetophenone is used as triplet sensitizer.
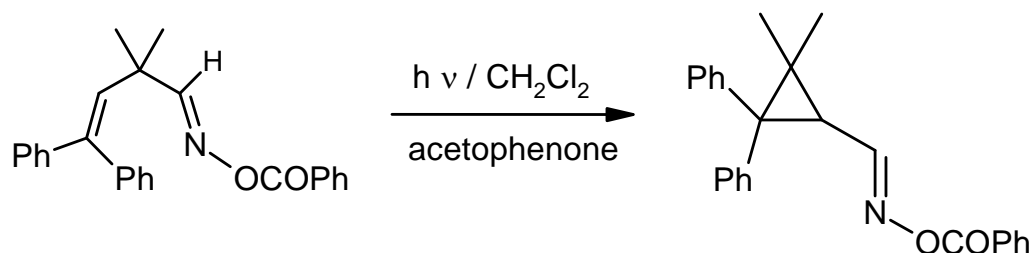
D. Armesto et al., *J. Chem. Soc., Perkin Trans. 1* **1992**, 2325 – 2329.
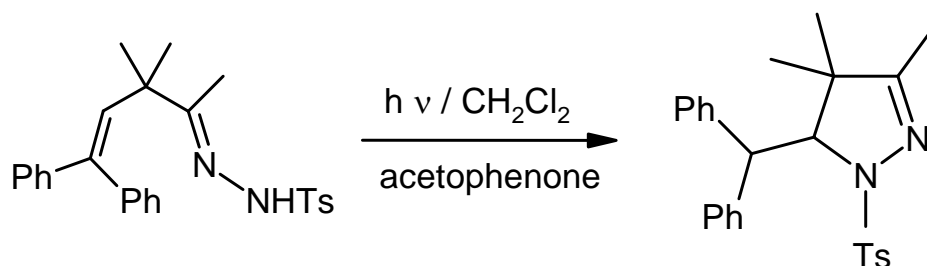
D. Armesto et al., *J. Chem. Soc., Chem. Commun.* **1993**, 721 – 722.

Decomposition of azo-compounds

As an alternative to heat or transition metal ions light can be used to generate carbenes from azo-compounds.
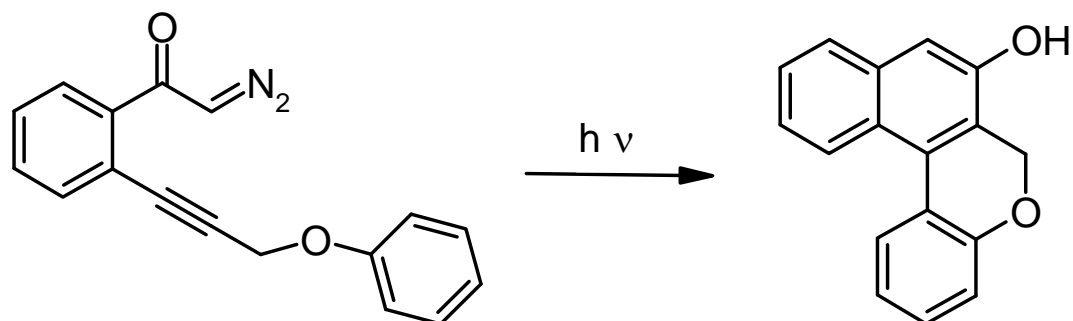
A. Padwa et al., *Tetrahedron Lett.* **1991**, 5923.
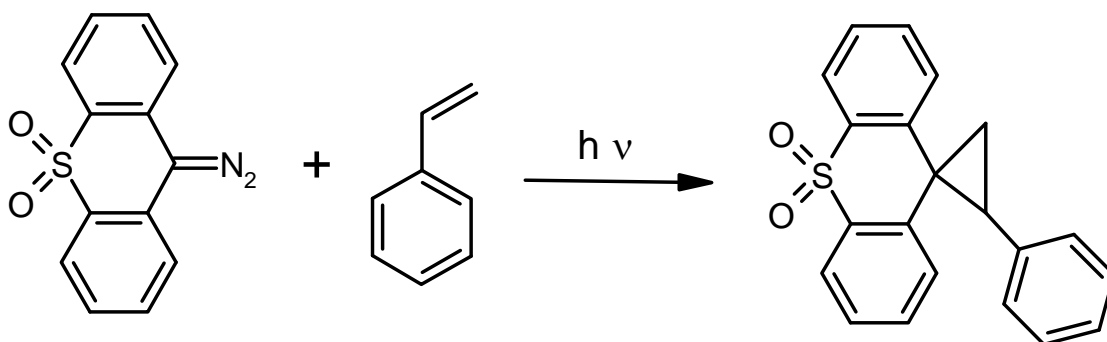
H. Dürr, N. J. Turro et al., *J. Org. Chem.* **1987**, *52*, 429 – 434.

4) Aromatic compounds

The origin of reactivity of arenes (which are usually not very reactive) in the electronically excited state results from changes in the electron distribution. If benzene is irradiated with light of 254 nm small amounts for benzvalene and fulvene are formed. Upon irradiation with light of 203 nm formation of Dewar benzene is observed. Such isomerisations may be the initial steps of arene photoreactions.
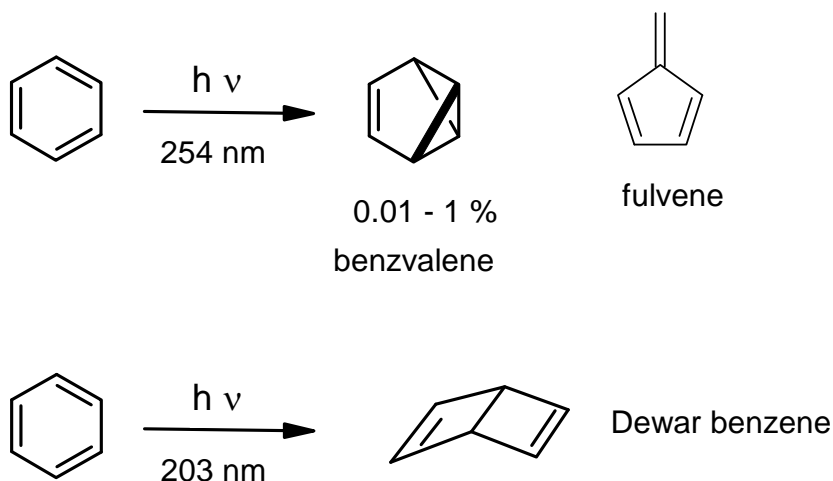
Ortho-cycloaddition to benzene
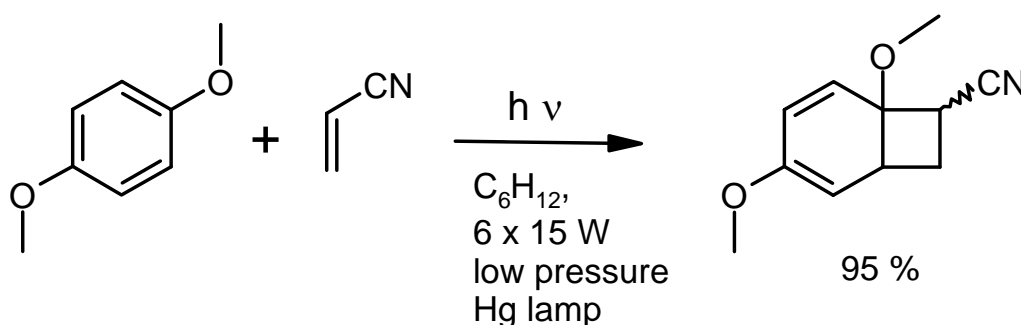
T. Kametani, Y. Kato, T. Honda, K. Fukumoto, *J. Am. Chem.* Soc. **1976**, *98*, 8185 – 8190.
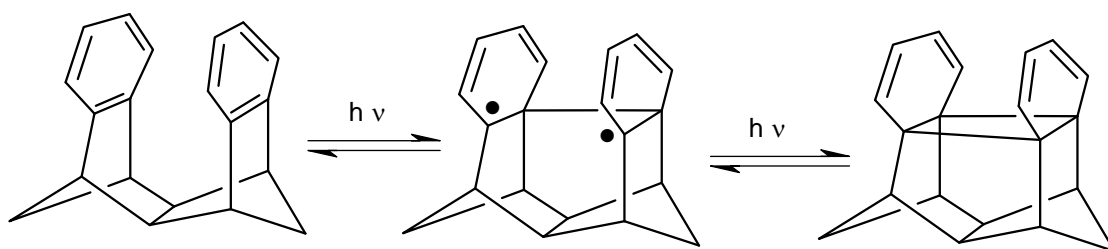
This is the photochemical key step of the synthesis of Pagodan. The photoreaction gives a mixture with about 30% of the cyclization product. Laborious purification is necessary.

W.-D. Fessner, H. Prinzbach et al. *J. Am. Chem. Soc*. **1987**, *109*, 4626 - 4642.

Photoaddition by photoxidation: Synthesis of 6,7-dimethoxycoumarin
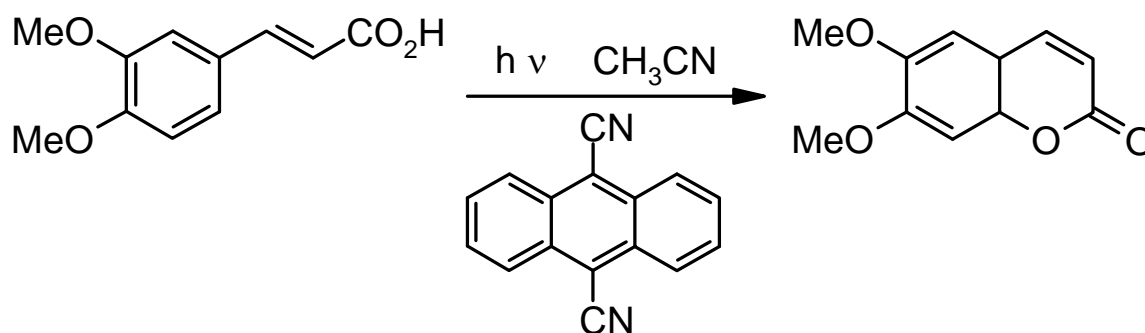
G. Pandey et al. *Tetrahedron Lett*. **1986**, *27*, 4075 - 4076.

5) Photooxigenation and photoreduction

Singlet oxygen is an easily available reagent. It can be generated from triplet oxygen in many solvents by a broad variety of sensitizers. The reaction of organic compounds with singlet oxygen can lead to reactive molecules, such as hydroperoxides, 1, 2-dioxetanes and endoperoxides. These compounds are useful for subsequent transformations.

Examples:

Synthesis of 3-hydroperoxy-4-methyl-3-penten-2-ol
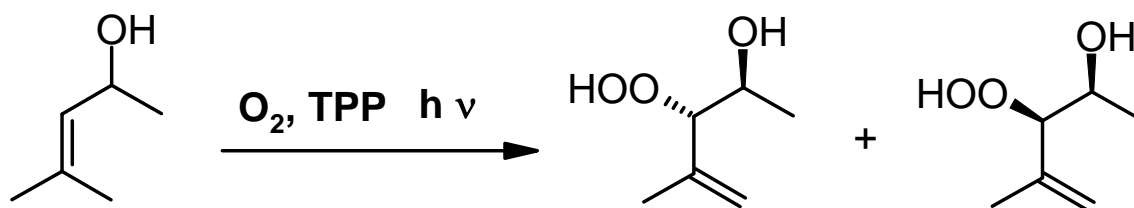
TPP means tetraphenylporphyrin. The mechanism can be described as an ene-type reaction. In general the reactivity of an alkene in this reaction increases with alkyl substitution, because an electrophilic reagent is attacking. Terminal alkenes usually do not react. If there is competion of several allyl positions for hydrogen abstraction, a general rule says that hydrogen abstraction occurs from the side of the double bond that is more substituted (see given example, two alkyl substituents *vs* one hydrogen and one alkyl substituent).
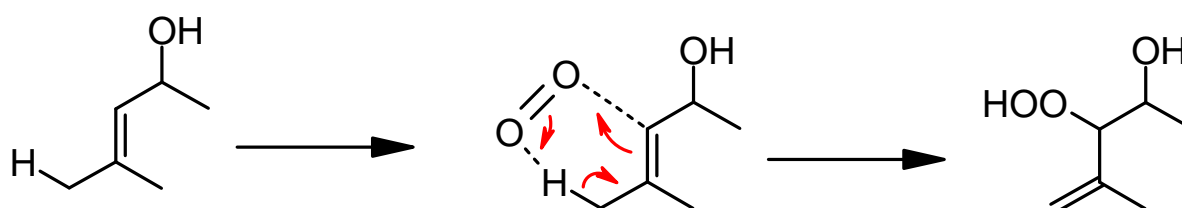
W. Adam, B. Nestler, *J. Am. Chem. Soc*. **1992**, *114*, 6549 - 6550.

[4+2] Cycloaddition

O$_2$ hν
sensitizer
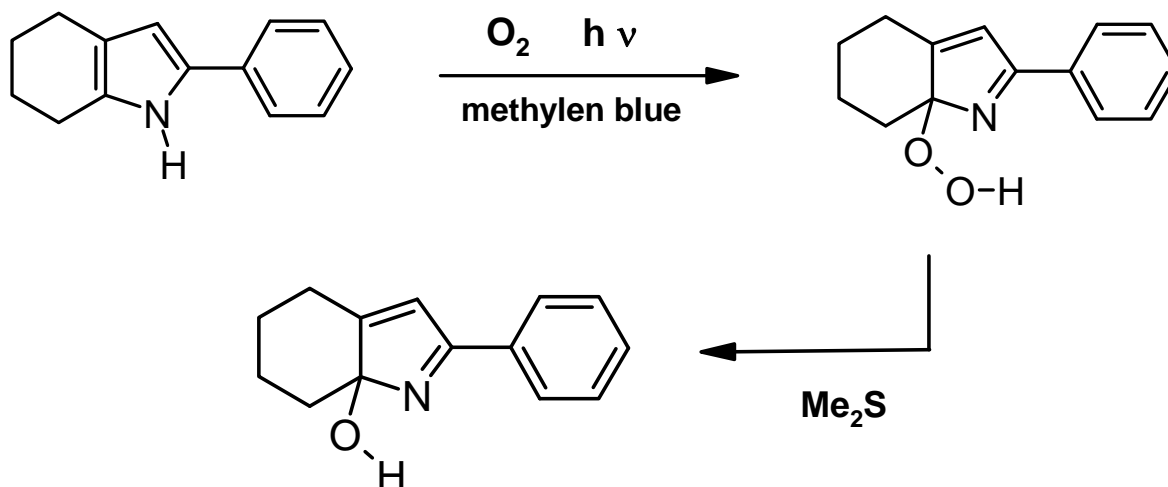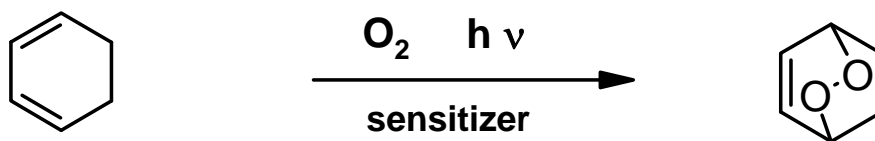
Photochemical sulfoxide formation

O$_2$ hν
1-cyanonaphthalene   80 %
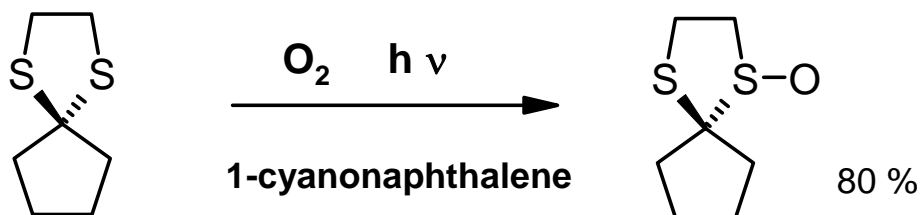
B. Pandey, S. Y. Bal, U. R. Khire, *Tetrahedron Lett.* **1989**, *30*, 4007 – 4008.

Photoinduced electron transfer can lead to reduction processes, e.g. irradiation of the compound to be reduced in the presence of a sacrificial amine as electron donor. An example is the reduction of a strained bond in a tricyclic molecule.

hν
NEt$_3$ / EtOH 8:2   79 %
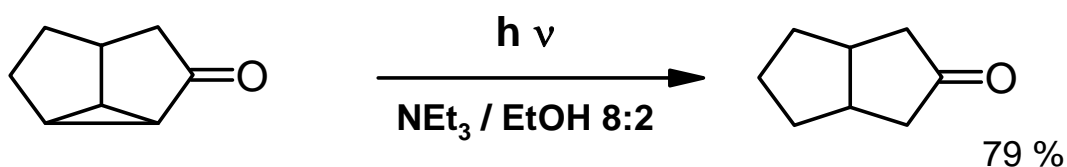
Irradiation in a Rayonet photoreactor at 300 nm; B. Pandley et al. *Tetrahedron* **1994**, *50,* 3843 – 3848.

An alternative reducing agent is tributyl tin hydride. The reductive expoide opening is photochemically initiated and proceeds by a radical chain mechanism.

Bu$_3$SnH   hν
C$_6$H$_6$ 75 %
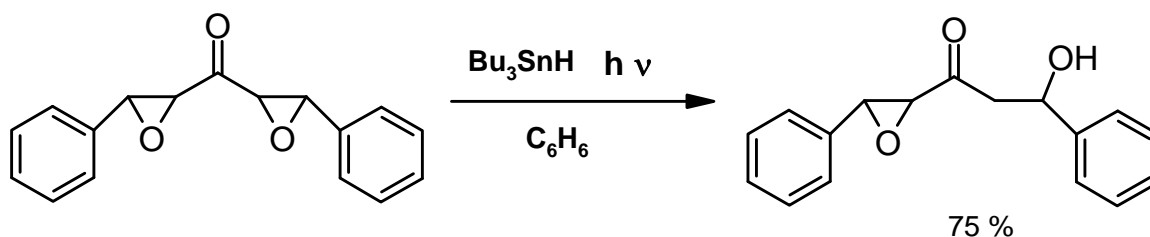
Photo initiation
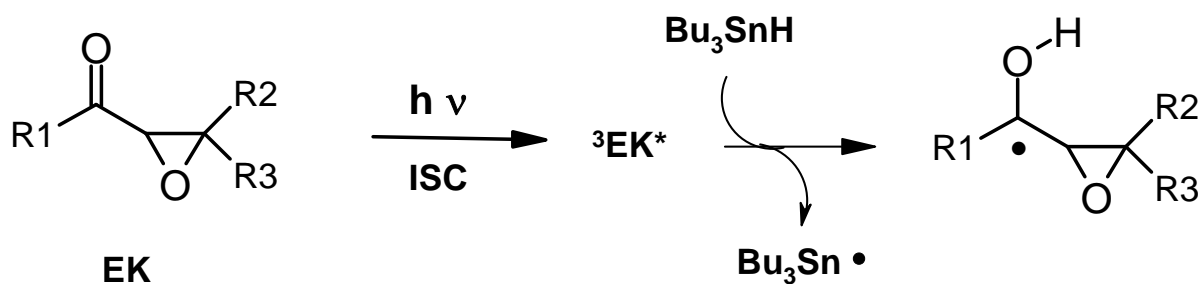
Radical chain propagation
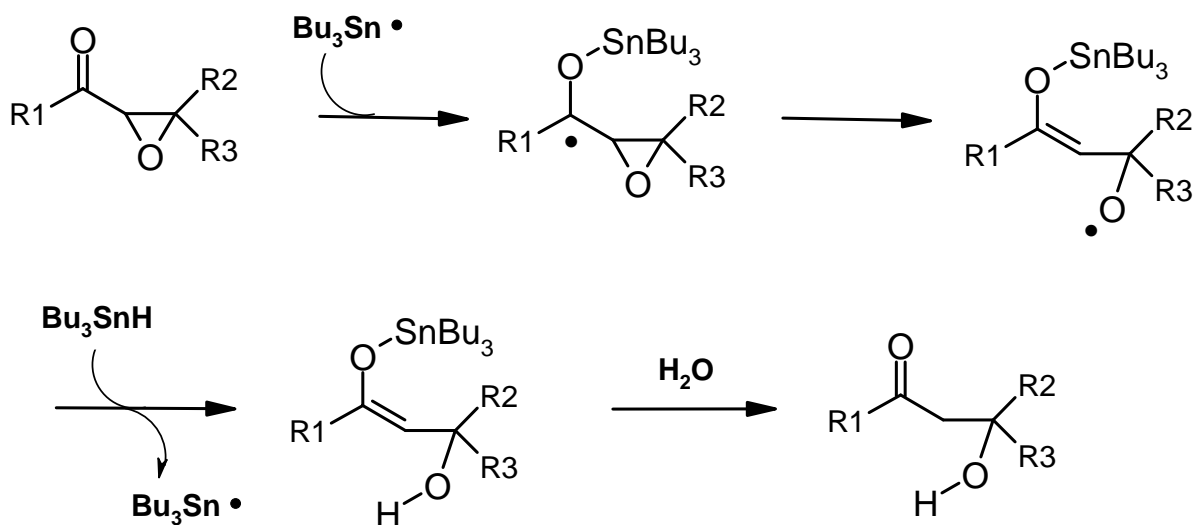
E. Hasegawa et al., *J. Org. Chem.* **1992**, *57*, 5352 – 5359.

6) Photochemistry in organized systems

The selectivity of photochemical reactions can increase if the environment in which the reaction occurs has a specific geometry. This can either be the case in the solid state. The best known example is the [2+2] photocycloaddition of cinamic acid, which gives many isomers in solution, while irradiation of a crystal leads to fewer products. However, photochemistry in the solid state is difficult to predict in many cases. Therefore modern approaches focus on topological reaction control in solution using templates to which the reactands are covalently or non-covalently bound.

Examples:

Topochemical reaction control of [2+2] cycloadditions in solution
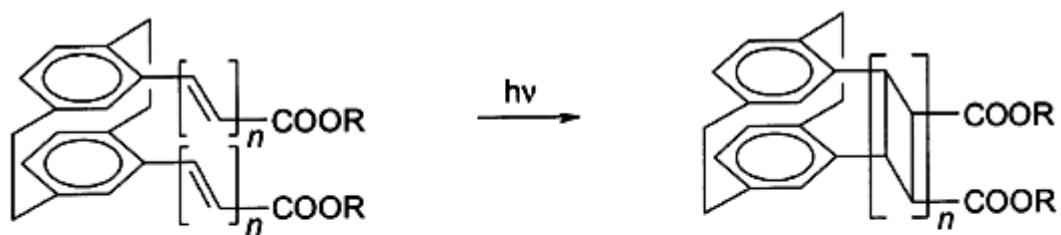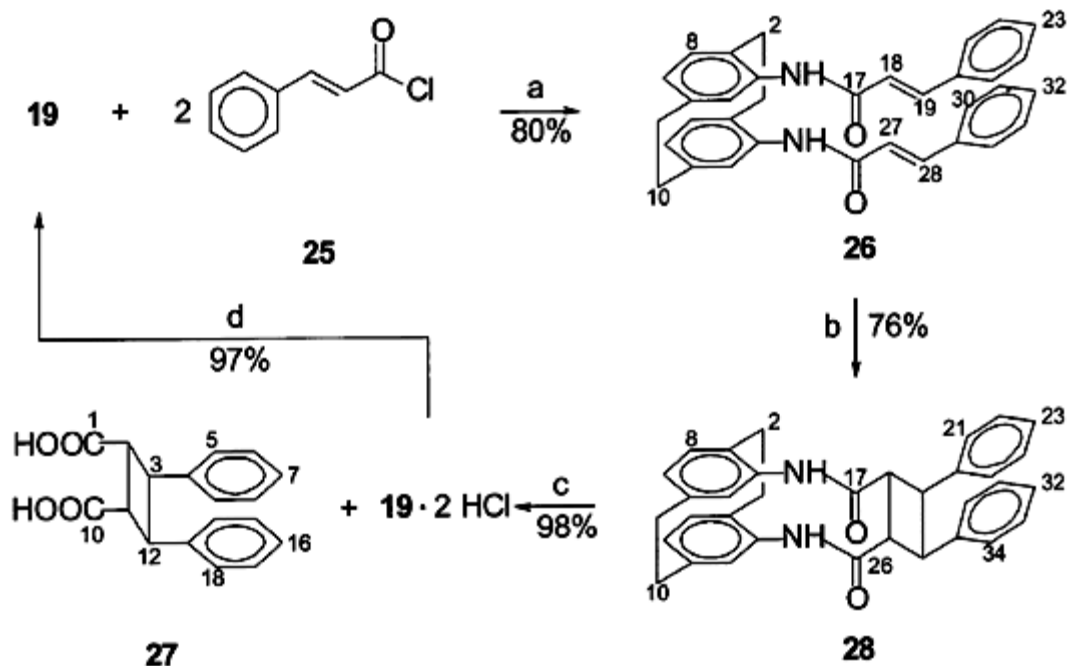
Compound **19** is a [2.2] paracyclophane-diamine

H. Zitt, I. Dix, H. Hopf, P.G. Jones, *Eur. J. Org. Chem.* **2002**, 2298 – 2307.

Photochemical reaction within a hydrogen-bonded aggregate

1) Intra-assembly:
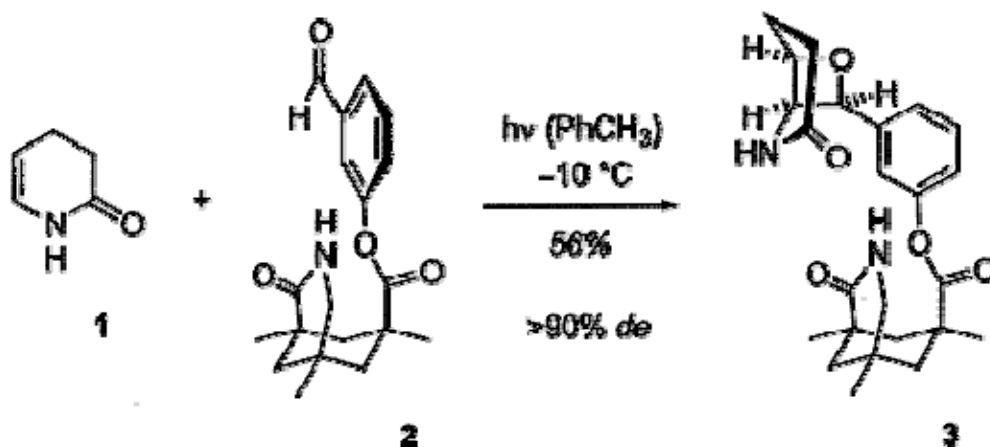
2) Catalytic with template molecule:
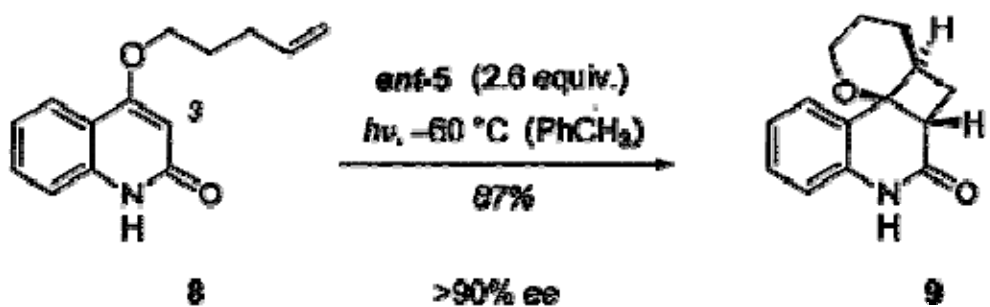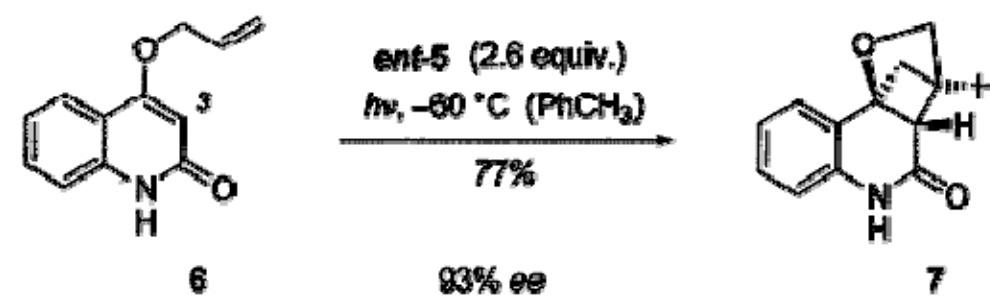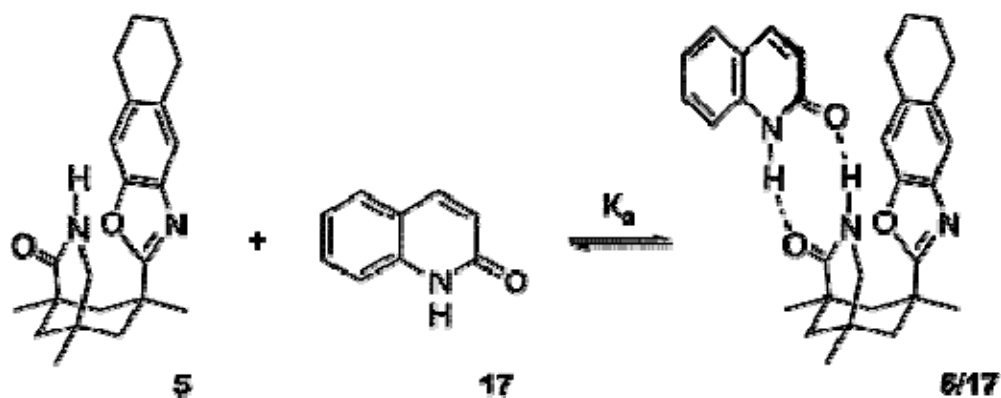
Enantioselective Norrish-Yang cyclization on a chiral template

From all possible stereoisomers of the reaction compound **12a** was formed preferentially if the reaction was performed in the presence of the chiral template.
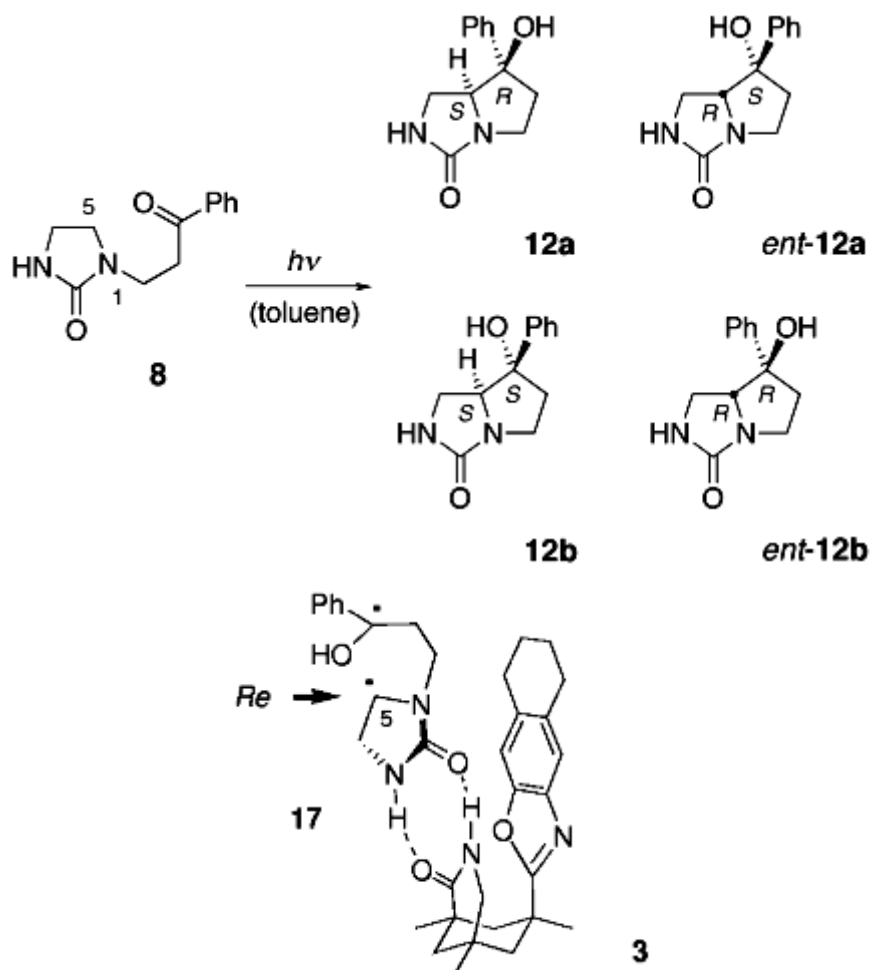
T. Bach, T. Aechtner, B. Neumüller, *Chem. Eur. J.* **2002**, *8*, 2464 – 2475.

Enantioselective catalytic PET-induced cyclization reaction
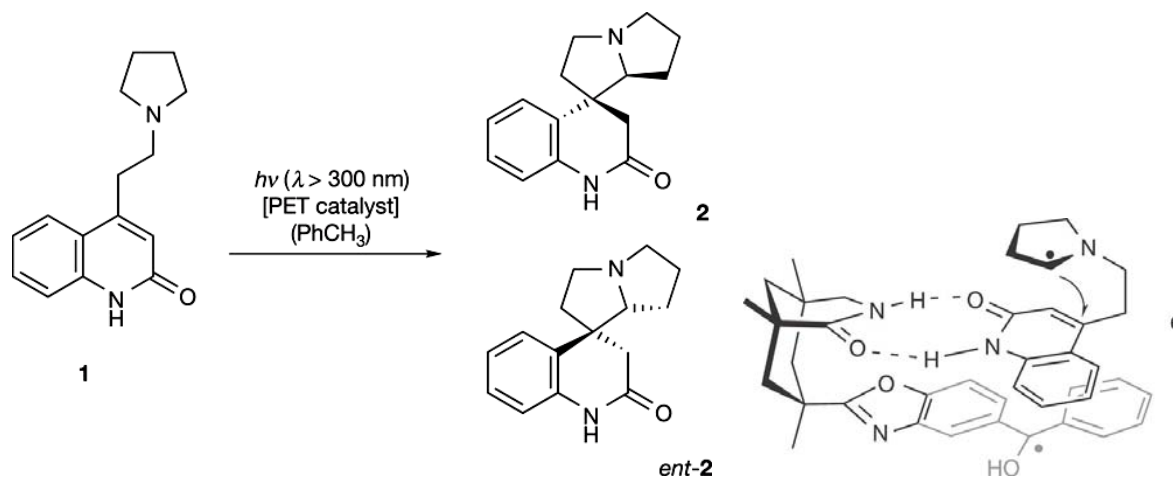
Nature, **2005**, *436*, 1139

7) Photochromic compounds

Photochromism characterizes reversible reactions in which one or both directions of the process can be triggered photochemically. The absorption spectra of starting material and product differ with respect to absorption wavelength and extinction; therefore each process can be addressed more or less selectively. Photochromic switches can be regarded as a simple way of information storage. Many examples involve charge separation that leads to a different electronic structure with different absorption properties. The spiropyran – merocyanine dye system is one of the classics.
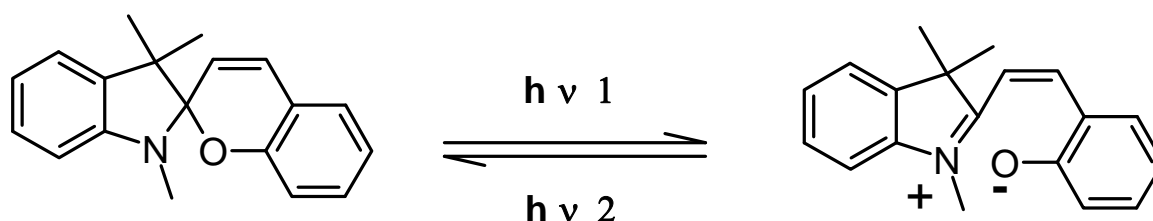
The photodimerization of tethered anthracene has found to be thermally reversible by simple heating in diethyl ether.
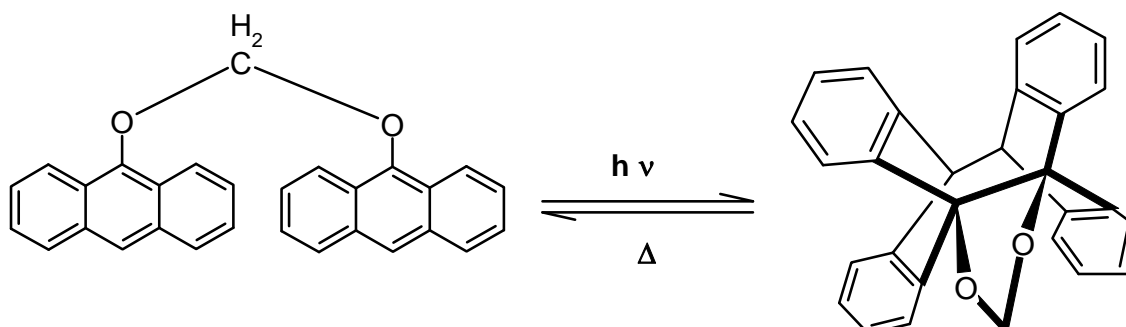
Close: high-pressure Hg lamp in pyrex
Open: heat diethyl ether solution with hairdryer for 15 min

J.-P. Desvergne, H. Bouas-Laurent, F. Lahmani, J. Sepiol *J. Phys. Chem.* **1992**, *96*, 10616 – 10622.

Spiro compound – betaine switch
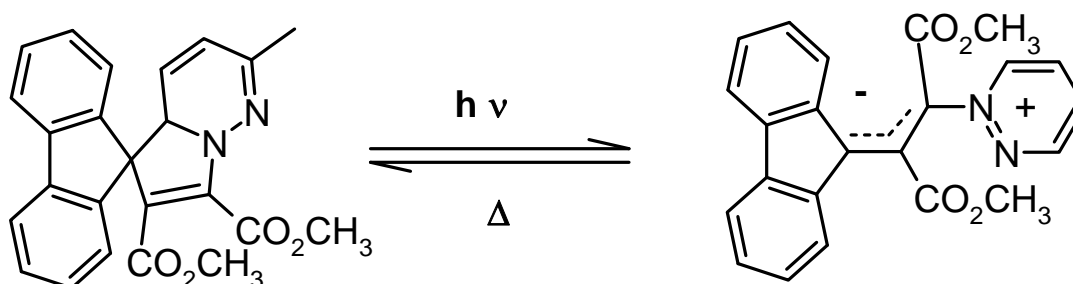
Irradiation with visible light; half-life of the betaine at 20°C: 14.4 min

open form
(generally colorless)

closed form
(generally colored)
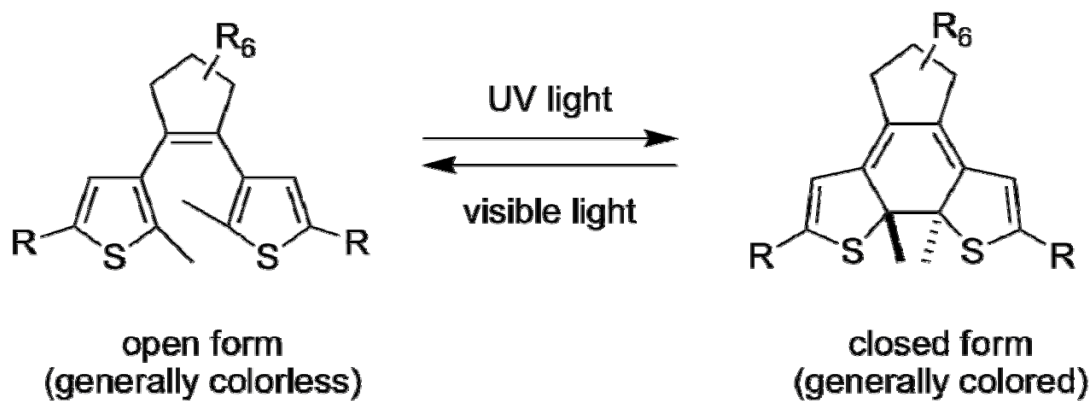
The dithienylethylene allows reversible switching with UV and visible light. These switches can show (depending on R) perfect reversibility and complete switching.

8) Photocleavable protecting groups and linkers

Protecting groups

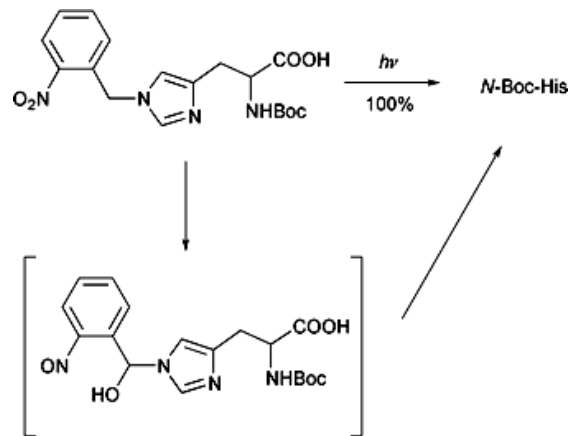Good review: C. G. Bochet, *J. Chem. Soc.*, *Perkin Trans. 1* **2002**, 125 - 142.
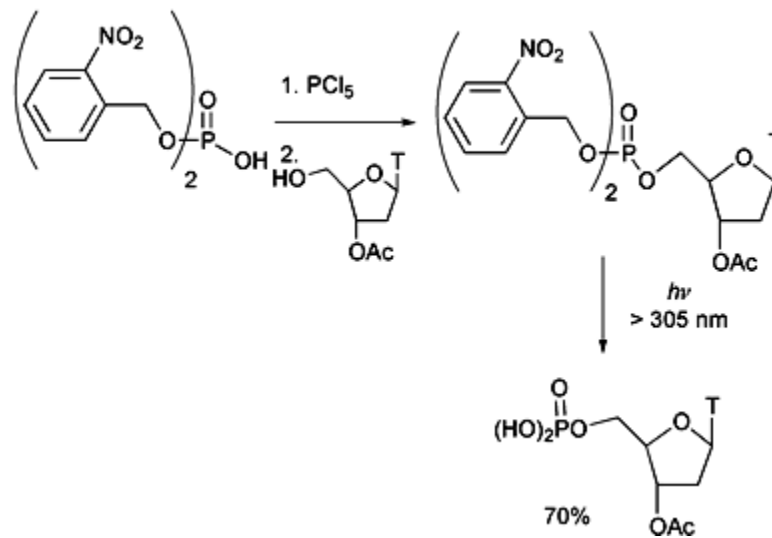
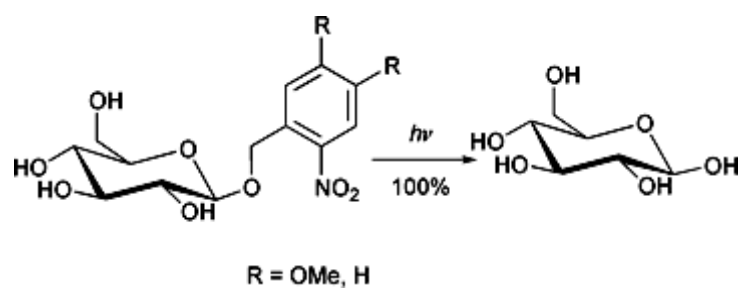*Norrish-type II: ortho-nitrobenzyl alcohols*
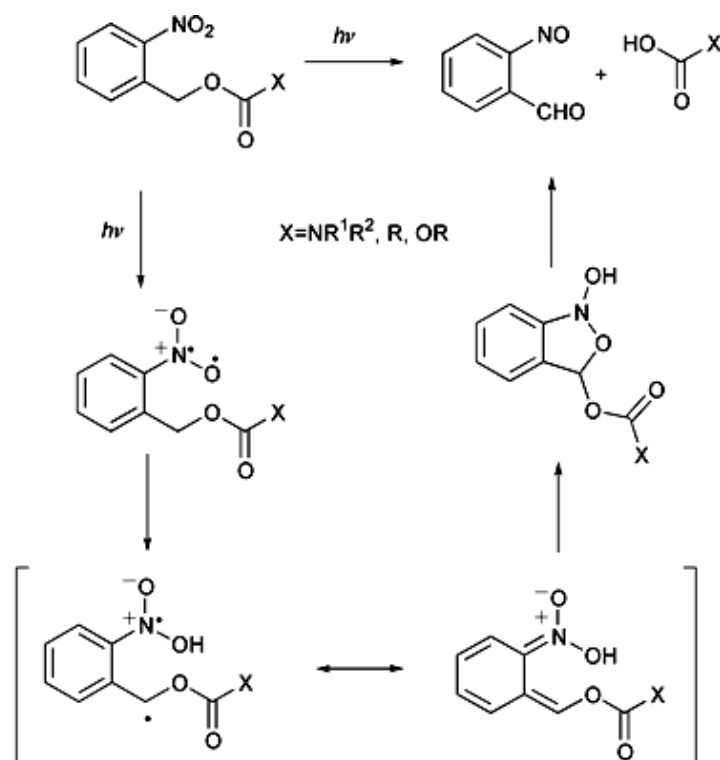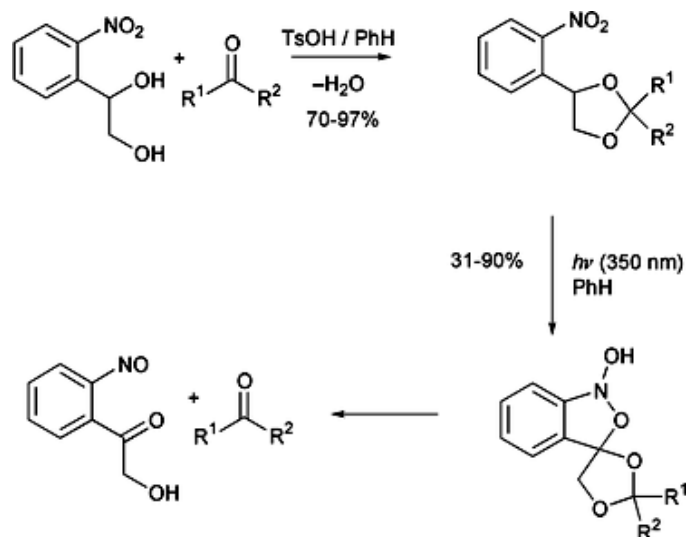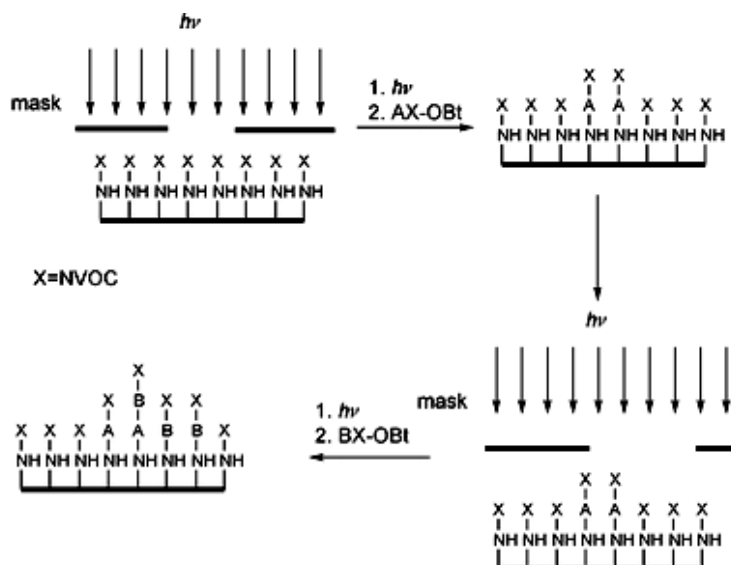
For amino acids:
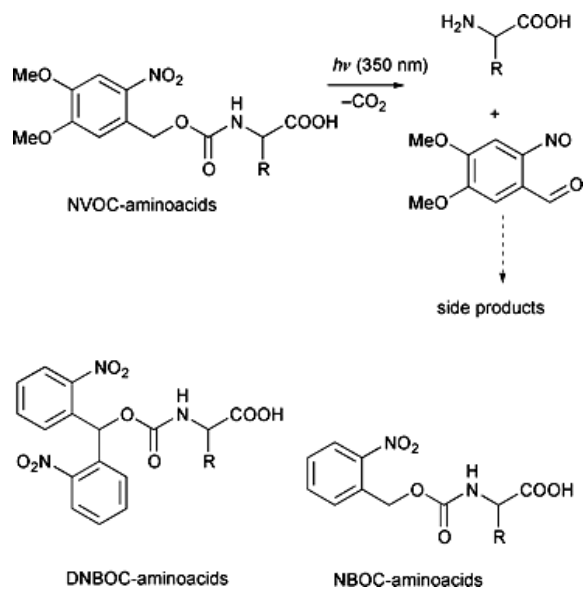
For heterocycles:

For nucleic acids:

For sugars:

Different reaction pathway if functional group to be protected is linked in β-position:
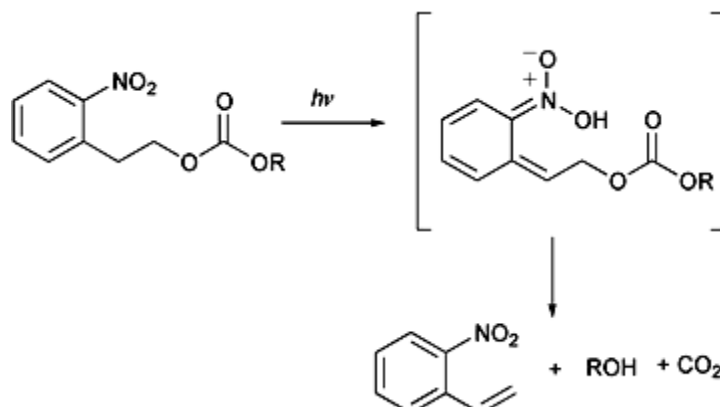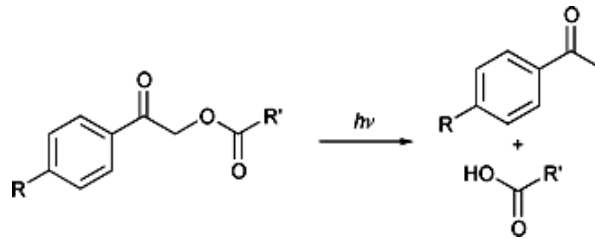

Protecting group for ketones:

Protecting groups in array synthesis:
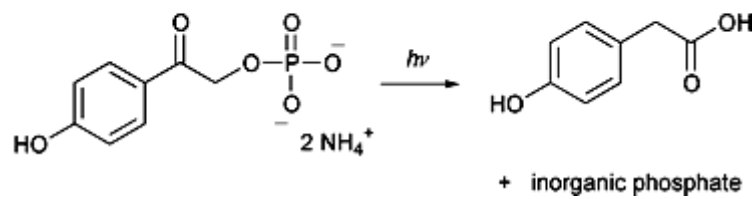

X=NVOC

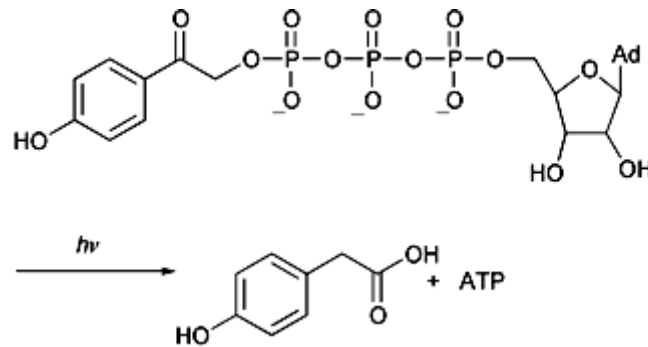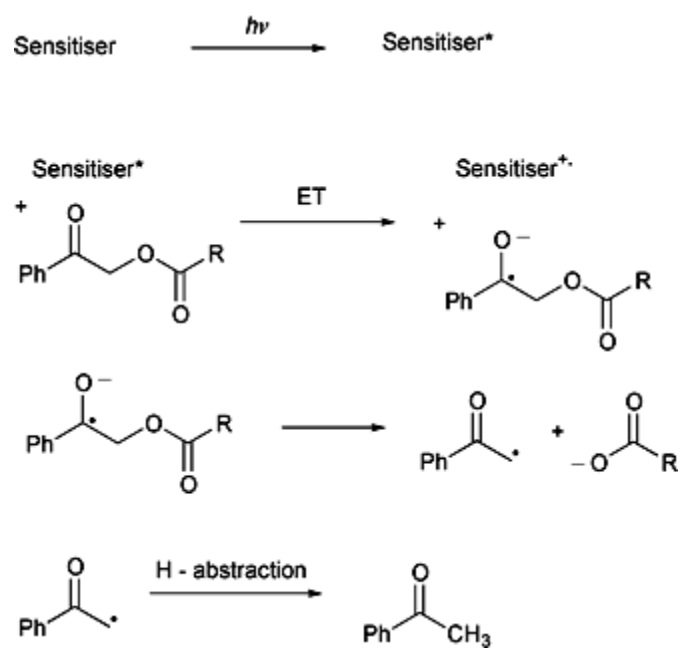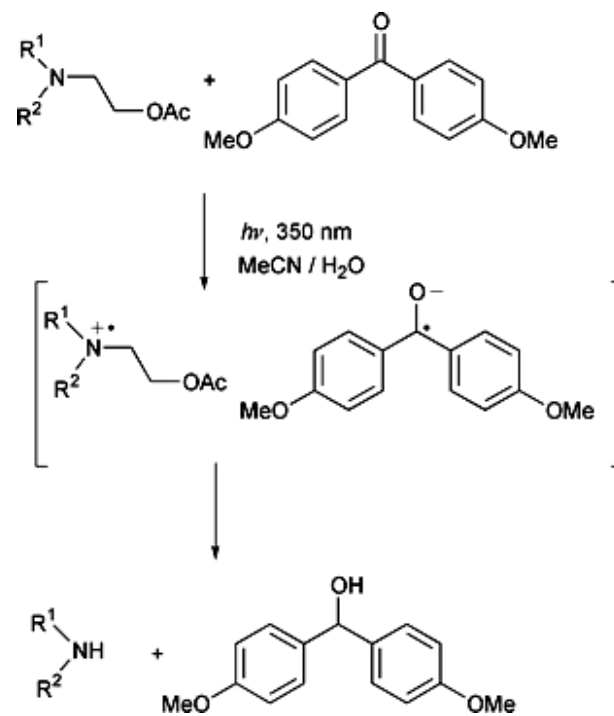Phenacyl esters:

Caged ATP:

Photo-induced electron transfer: Benzophenone as oxidant

Photodeprotection of an amine:

Photoisomerization: cis-trans