Organic Photochemistry – Exercise 1: 24/10/2024, 11.00 am

German group: CH22210 **English group: CH42306**

1. a) For the determination of the singlet and the triplet energy of iminium ion **9** (Figure 1), the absorption (black), fluorescence (red) and phosphorescence (blue) is measured. The singlet energy is determined from the intersection of the absorption spectrum and the fluorescence spectrum at λ = 380 nm. Phosphorescence can be calculated from the inflection point of the most blue shifted shoulder of the phosphorescence emission (λ_{max} = 562 nm). Calculate the singlet and the triplet energy of iminium ion **9**.

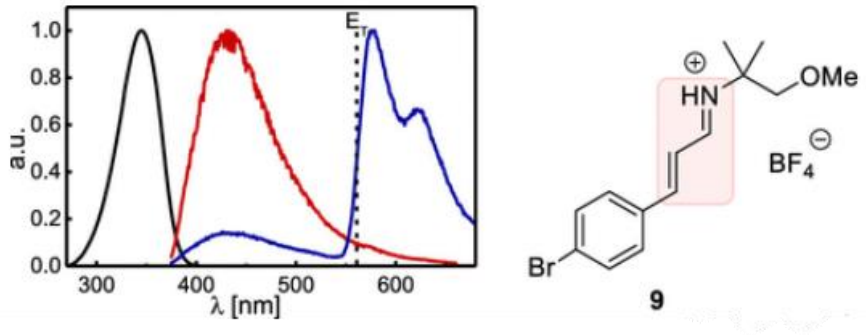


Figure 1. Absorption and luminescence spectra (λ_{exc} = 360 nm) of iminium ion **9** in MeCN. Colors: Absorption, black; fluorescence (rt), red; phosphorescence (77 K), blue. The energy of the (0,0) transition was calculated from the inflection point at λ = 562 nm.

$E=(h\cdot c)/\lambda$

h = Planck's constant = 6.626 x 10^{-34} J·s

c = speed of light = 3 x 10^{8} m/s

λ = 440 nm (given in the question above)

N_A = 6.022 x 10^{23} /mol

Reaction equation can be applied to both Singlet and Triplet Energy!

$E_S(kJ/mol) = (h\cdot c\cdot N_A)/\lambda$ = 314.8 kJ/mol

$E_T(kJ/mol) = (h\cdot c\cdot N_A)/\lambda$ = 212.8 kJ/mol

b) In order to know light of which wavelength to choose for the excitation of a compound into one if its excited states, knowledge about the light absorption of the compound is required. For this, UV/Vis spectroscopy is the method of choice. UV/Vis titration is a way to determine the influence of certain additives on the photophysical properties of a compound. Please calculate the corresponding extinction coefficients for *N,O*-acetal **7a** with and without Brønsted acid. Explain the effects of the presence of Brønsted acid on the light absorption of **7a**. Name the characteristic points of the UV/Vis titration (Figure 2).

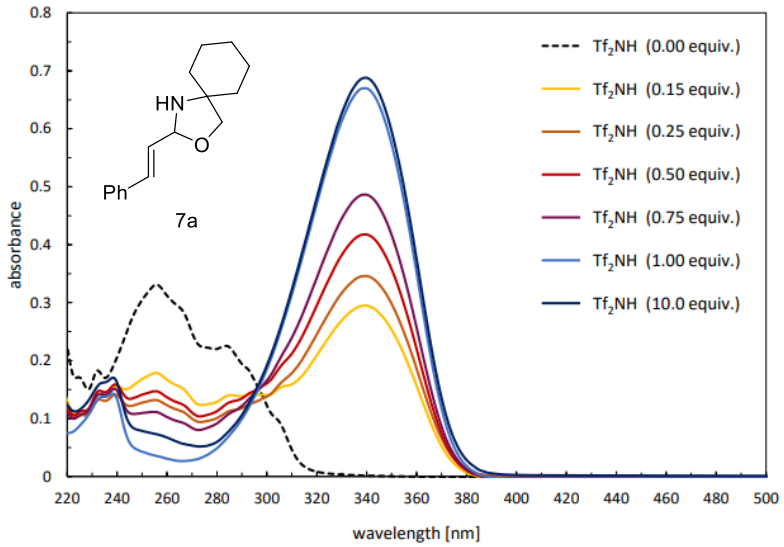


Figure 2. UV-Vis spectrum of *N,O*-acetal **7a** in CH_2Cl_2 as the solvent (c = 0.1 mM) without Brønsted acid (••••) and after addition of various equivalents of Tf_2NH (—). Cuvette d = 1mm.

Lambert Beer law:

$$E_\lambda = \log_{10}\left(\frac{I_0}{I_1}\right) = \varepsilon_\lambda \cdot c \cdot d$$

$$\mathcal{E} = A / (c \times d)$$

$$\mathcal{E}_{256\ nm} = 0.331 / (0.1 \cdot 10^{-3}\ mol/L \times 0.1\ cm) = 33100\ L \cdot mol^{-1} \cdot cm^{-1}$$
$$\mathcal{E}_{340\ nm} = 0.6697 / (0.1 \cdot 10^{-3}\ mol/L \times 0.1\ cm) = 66970\ L \cdot mol^{-1} \cdot cm^{-1}$$

Absorbances can be read from UV/Vis spectra.

bathochromic shift

In spectroscopy, the position shift of a peak or signal to longer wavelength (lower energy). Also called a red shift.

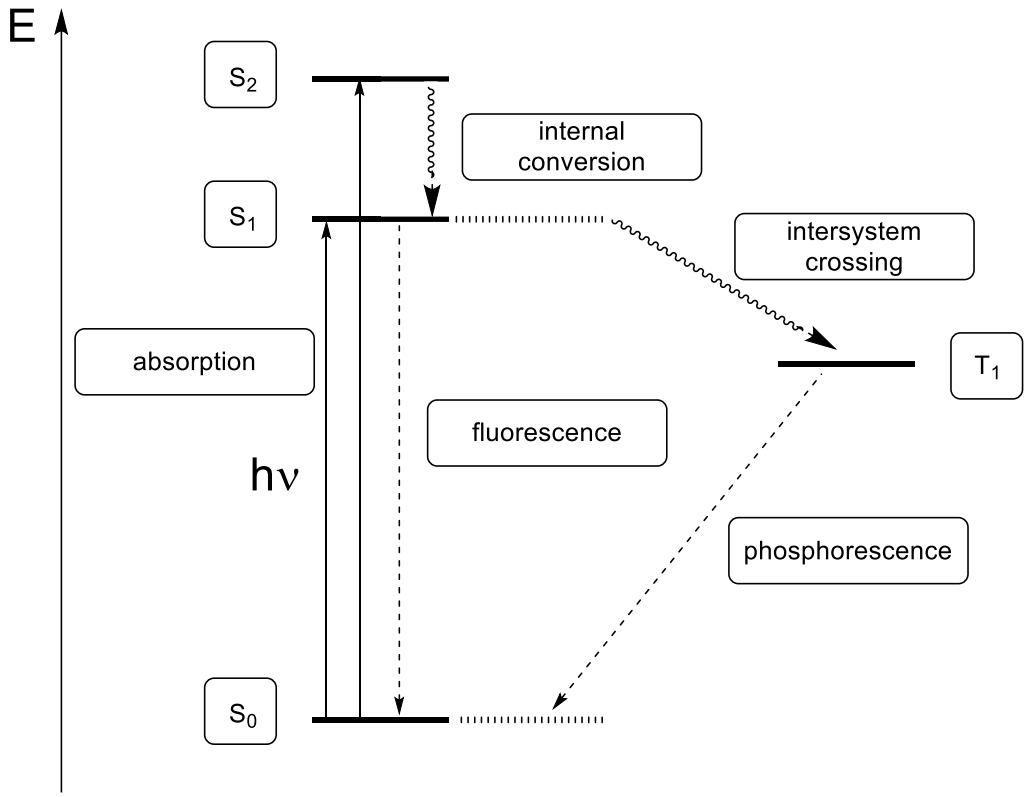
Isobestic point

When an isosbestic plot is constructed by the superposition of the absorption spectra of two species (whether by using molar absorptivity for the representation, or by using absorbance

and keeping the same molar concentration for both species), the isosbestic point corresponds to a wavelength at which these spectra cross each other.

J. Am. Chem. Soc. 2021, 143, 9350−9354

2. a) Complete the following *Jablonski* diagram. Define every energy transfer noted on the diagram.



Absorption: The absorption of electromagnetic radiation is how matter (typically electrons bound in atoms) takes up a photon's energy — and thus transforms electromagnetic energy into internal energy of the absorbing compound (for example, thermal energy).

Internal conversion (IC): IC denotes the isoenergetic and therefore radiationless transition from the vibrational ground state of an electronically excited state (e.g. S1) to a highly excited vibrational state of the next lower electronic state (e.g. the electronic ground state S0). Occurs without changing the multiplicity of the spin.

Fluorescence: It is the spontaneous emission of radiation by an excited molecule, typically in the first excited singlet state (S1), with retention of spin multiplicity.

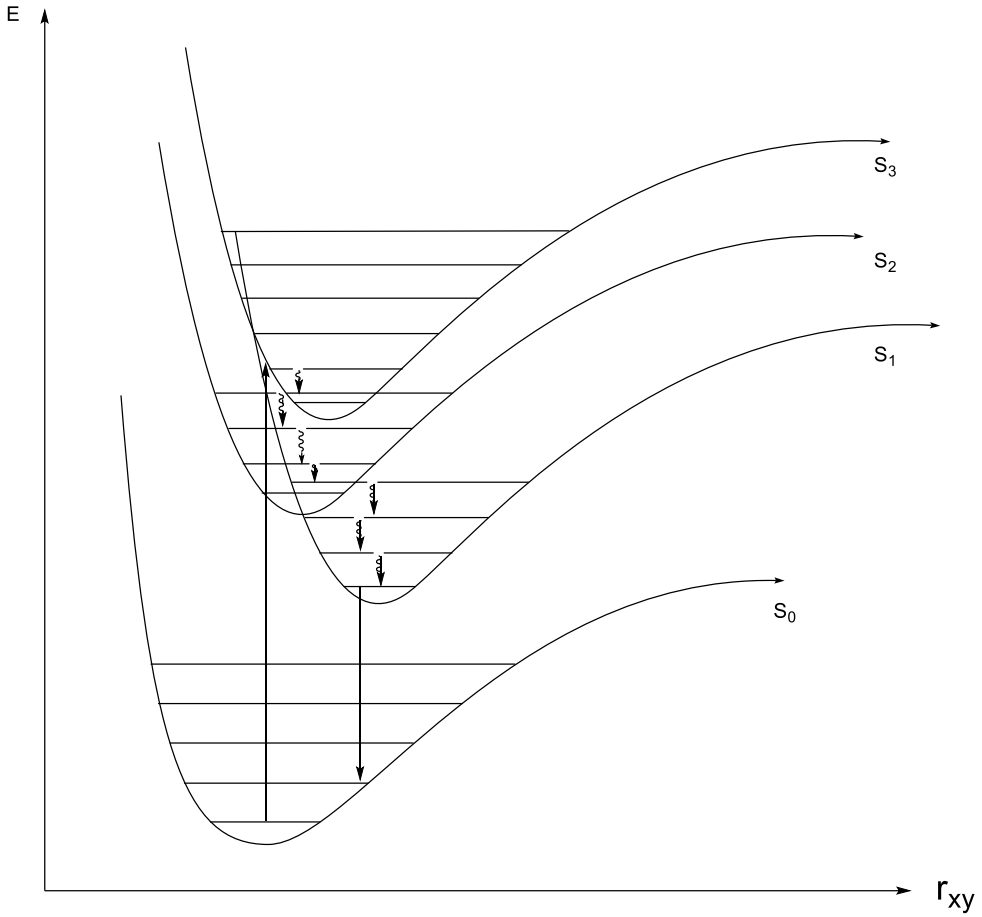
Intersystem crossing (ISC): Isoenergetic radiationless process involving a transition between the two electronic states with different states spin multiplicity.

The dominant mechanism for the ISC in organic molecules is the interaction between the magnetic moment of the spin and that of the associated orbital (spin-orbit coupling). In the case of diradicals, direct interaction between two spins is also possible (spin-spin coupling). The spin-orbit coupling

depends to the fourth power on the atomic numbers of the atoms involved. The ISC is thus significantly accelerated in the presence of heavy elements.

Phosphorescence: It is the spontaneous emission of radiation by an excited molecule, typically in the first excited triplet state (T_1), involving a change in spin multiplicity.

b) Draw an energy diagram to explain the Franck Condon principle and Kasha's rule.



E: potential energy; r_{xy}: bond distance (diatomic molecule)

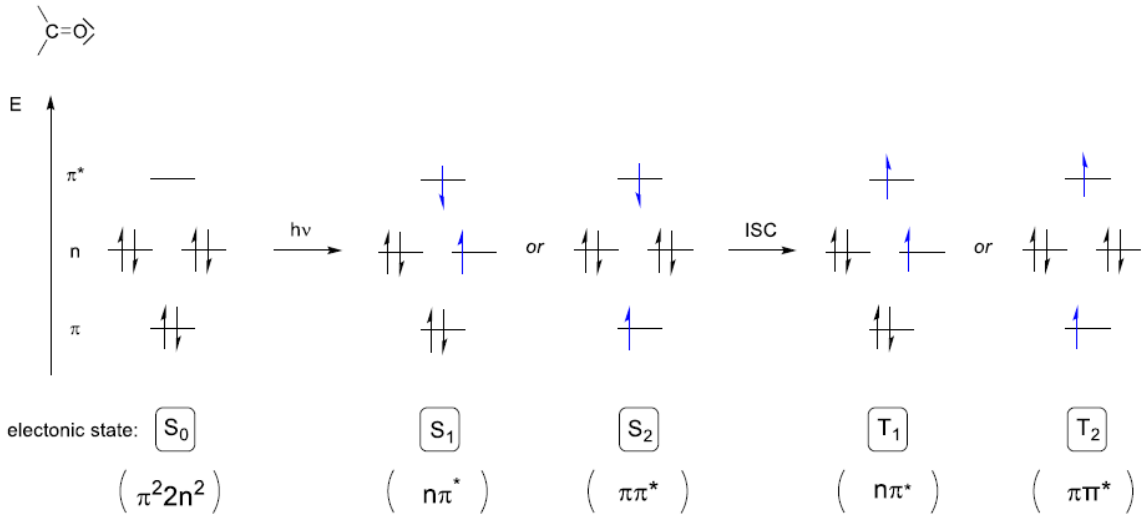
Kasha's rule: The rule states that photon emission (fluorescence or phosphorescence) occurs in appreciable yield only from the lowest excited state of a given multiplicity. This is due to fast relaxation of excited vibrational states.

Franck Condon principle: The principle states that during an electronic transition, a change from one vibrational energy level to another will be more likely to happen if the two vibrational wave functions overlap more significantly.

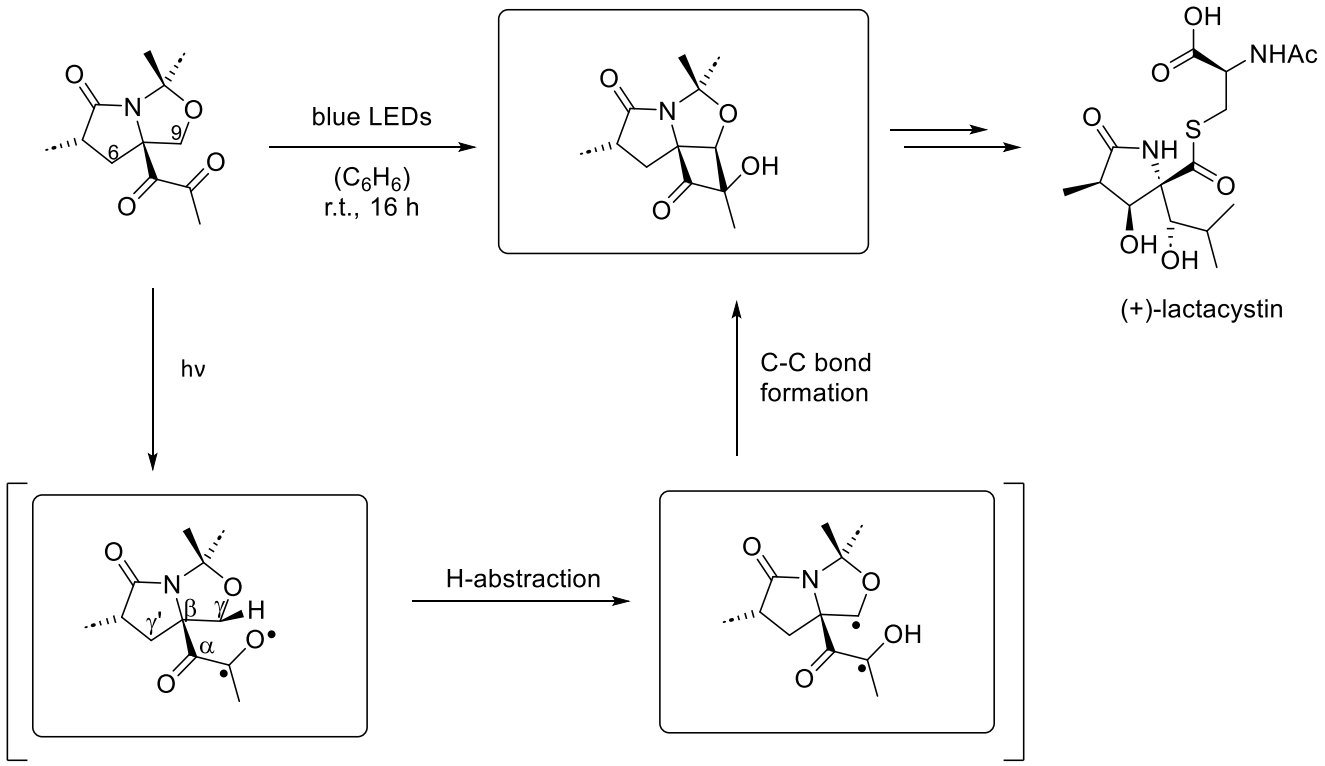
→ Electronic transitions are orthogonal!

Maybe we can also explain Born Oppenheimer in this regard. (→ For calculation of electronic movements, the movement of the nuclei does not have to be taken into account since it is much slower.)

3. Draw the MO diagram for benzophenone (C=O, π-n-π*) in the ground state, after excitation with light and intersystem crossing processes (ISC).



4. An important photo-induced transformation was used in the total synthesis of (+)-lactacystin. Describe the mechanism and analyze the regioselectivity (C6 *vs.* C9) and the diastereoselectivity of the reaction. What is the name of this reaction? Explain why the usage of visible light (instead of higher energy UV light) is crucial for the success of this transformation.



Name of reaction: Norrish-Yang-Cyclization

Regioselectivity:

Ethereal C(sp3)-H at C9 is more electron-rich in comparison to the aliphatic C-H bond (C6) and can hence stabilize the radical better.

Diastereoselectivity:
No strained 4-membered cyclic systems.

Light source:
UV light (<360 nm) can lead to undesired reaction pathways associated with concomitant photoexcitation of the monoketone photoproduct. A blue LED (≈ 460 nm) excites 1,2-diketone (λ_{max}=433 nm) selectively.

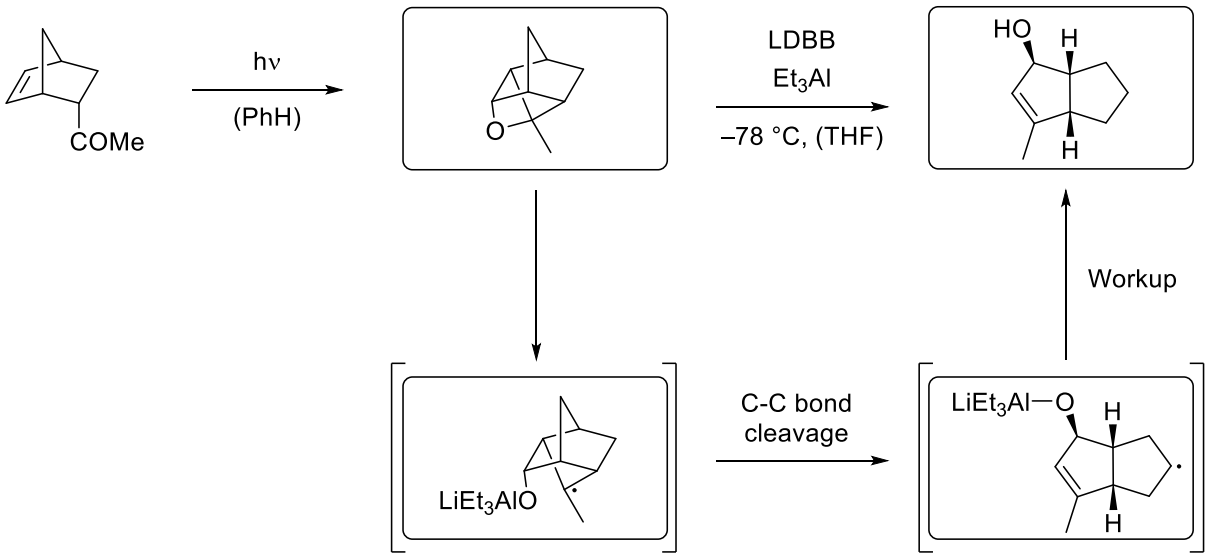
Org. Lett. **2015**, *17*, 90.

Organic Photochemistry – Exercise 2: 07/11/2024, 11.00 am

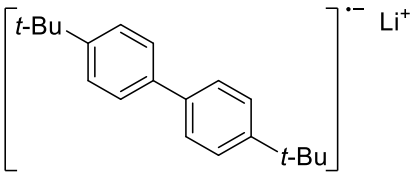
German group: CH22210 **English group: CH42306**

1. Oxetanes present a class of a valuable synthetic targets not only due to their occurrence in a plethora of natural products and biologically active compounds, but also due to their diverse follow up reaction profile. In the following synthesis, the authors utilized an elegant cleavage reaction after the photoreaction, enabling access to substituted diquinanes from norbornene derivatives. Fill in the missing products and intermediates.

Hint: *In the second step, the Lewis acid coordinates to the oxygen atom, followed by a one-electron reduction mediated radical cleavage of a C-O bond.*

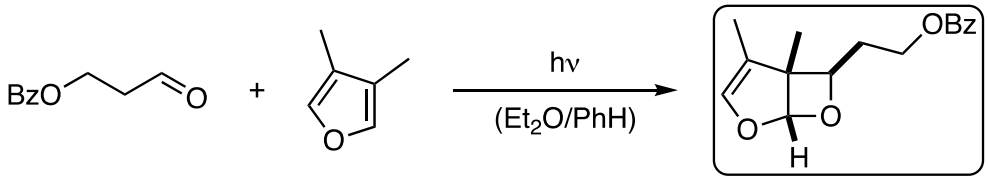


LDBB:



J. Org. Chem. **1998**, *63*, 5302–5303.

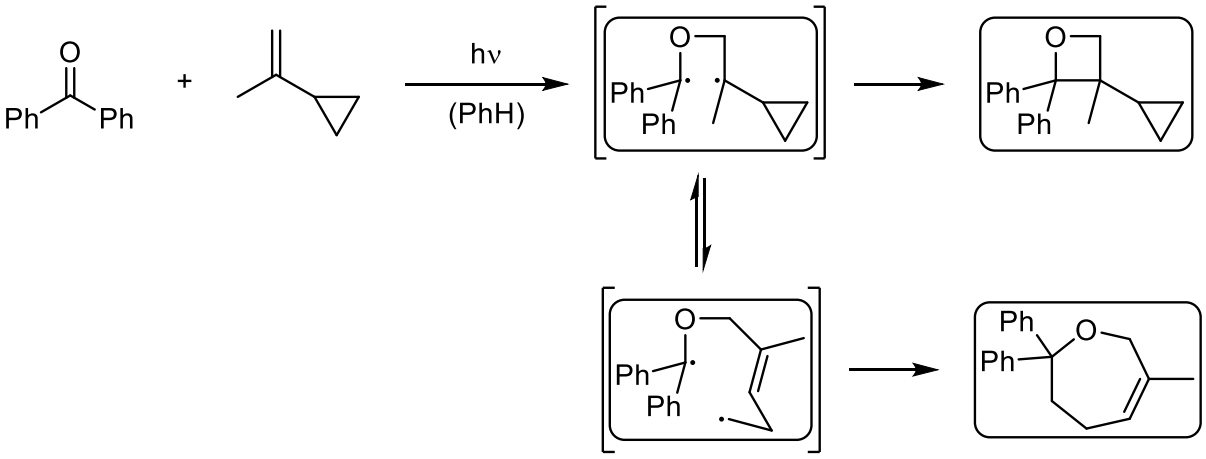
2. Give the structures of the products and intermediates in the following two reactions. In the first case, please also explain the regio- and diastereoselectivity of the reaction.



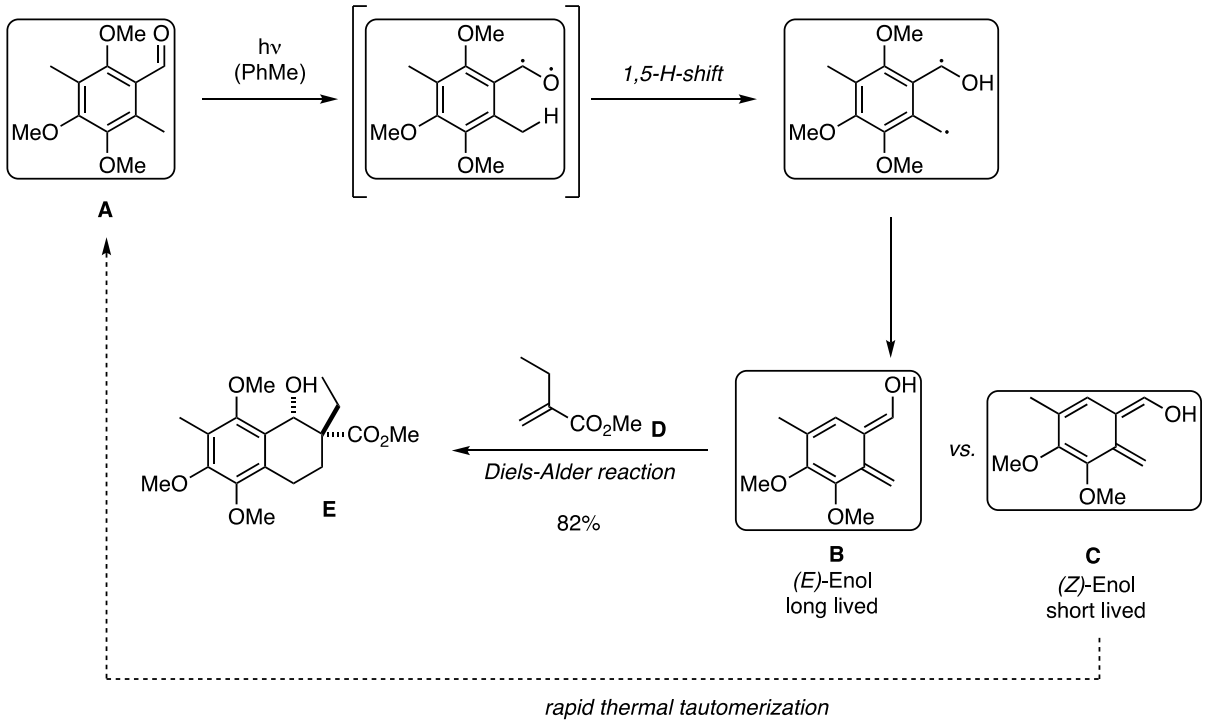
explanation for regio- and diastereselectivity:

- stability of 1,4-diradical

-large substituents will be trans to each other

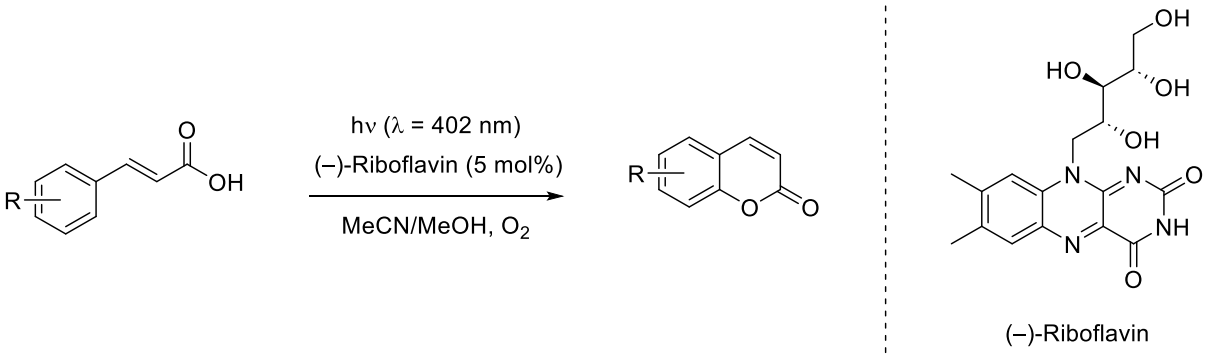


3. Another interesting total synthesis using a photochemical key step was described by the group of Nicolaou. Upon excitation of starting material **A** and subsequent intersystem crossing, two highly reactive intermediates are generated. Only one of the intermediates (**B** or **C**?) can be trapped in an intermolecular reaction with compound **D** to give the product **E** in high yield. Complete the scheme given below (including intermediates and electron arrows) and explain the diastereoselectivity of the final reaction step.

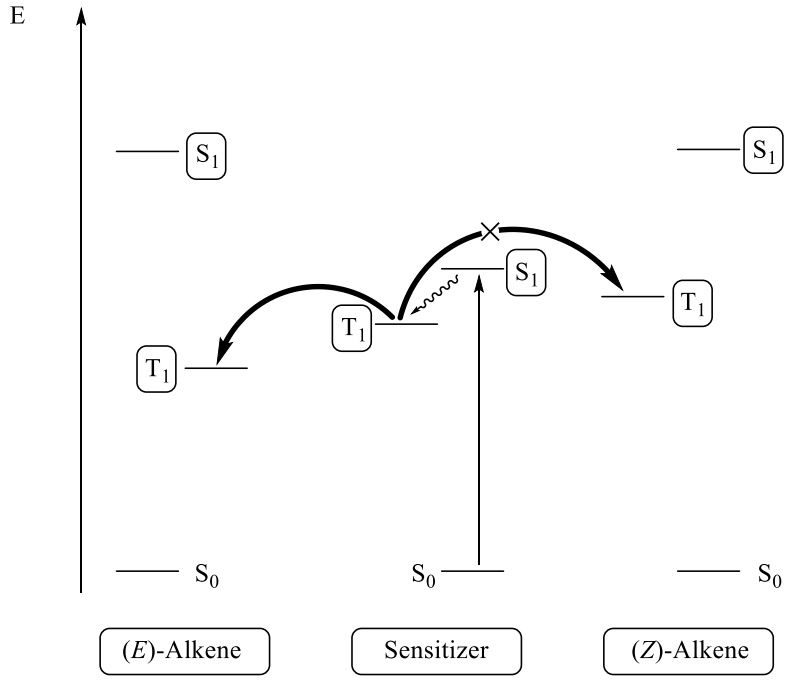


J. Am. Chem. Soc. **2004**, *126*, 607-612.

4. One way for the synthesis of complex molecular structures is to use a single catalyst that performs several sequential transformations. A prerequisite for this type of cascade reactivity is that each transformation must follow a different activation mode, by which all preceding and following intermediates remain untouched. In the following reaction, cinnamic acids undergo cyclization to form coumarins.



The depicted catalyst serves a dual purpose, as direct cyclization from the (*E*)-alkene to the coumarin is unfavorable. Explain how the photocatalyst can transform the (E)-alkene into an isomer that is more amenable to cyclization. Elaborate on the reactivity concerning the relative energy levels of the involved electronic states and the relevant energetic transitions.



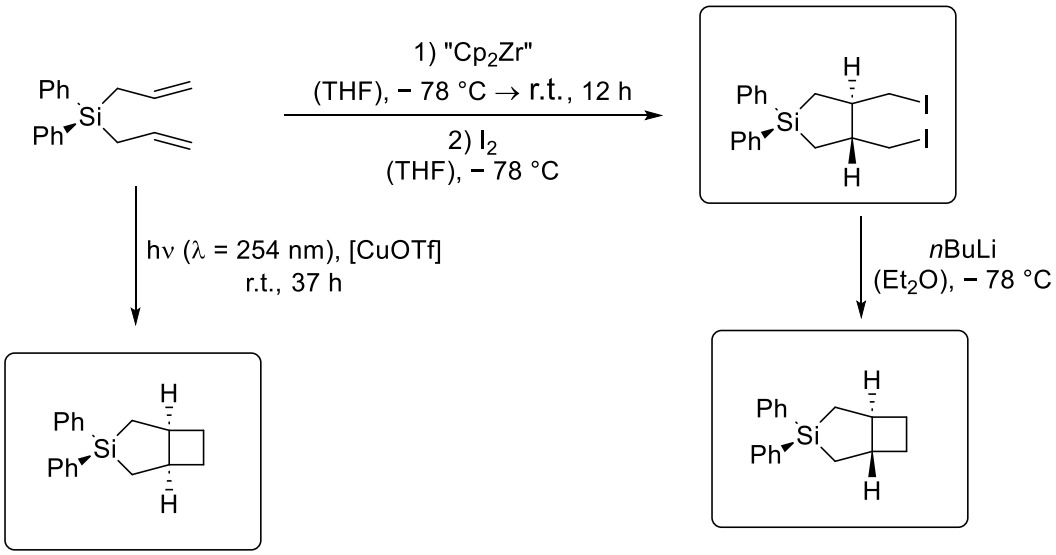
J. Am. Chem. Soc. **2016**, *138*, 1040–1045.

Organic Photochemistry – Exercise 3: 21/11/2024, 11.00 am

German group: CH22210 **English group: CH42306**

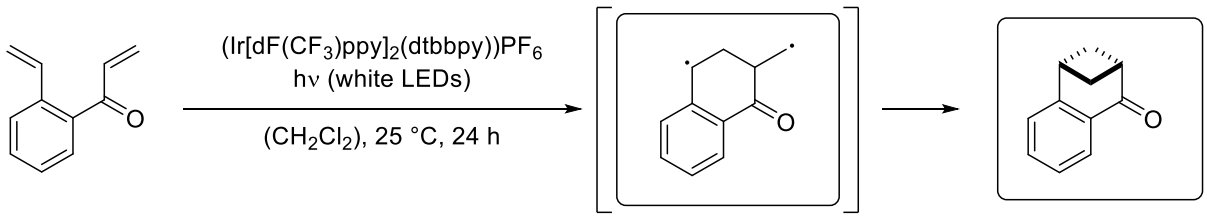
1. Complete the following reactions. Pay attention to the stereoinformation

a)



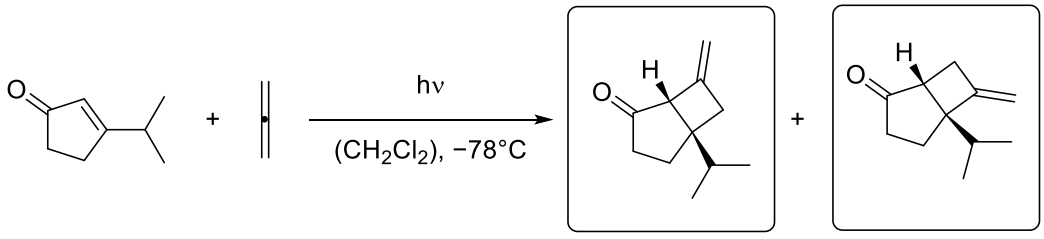
J. Organomet. Chem. **2002**, 643−644, 324−330.

b)



J. Am. Chem. Soc. **2017**, *139*, 9807−9810.

c)

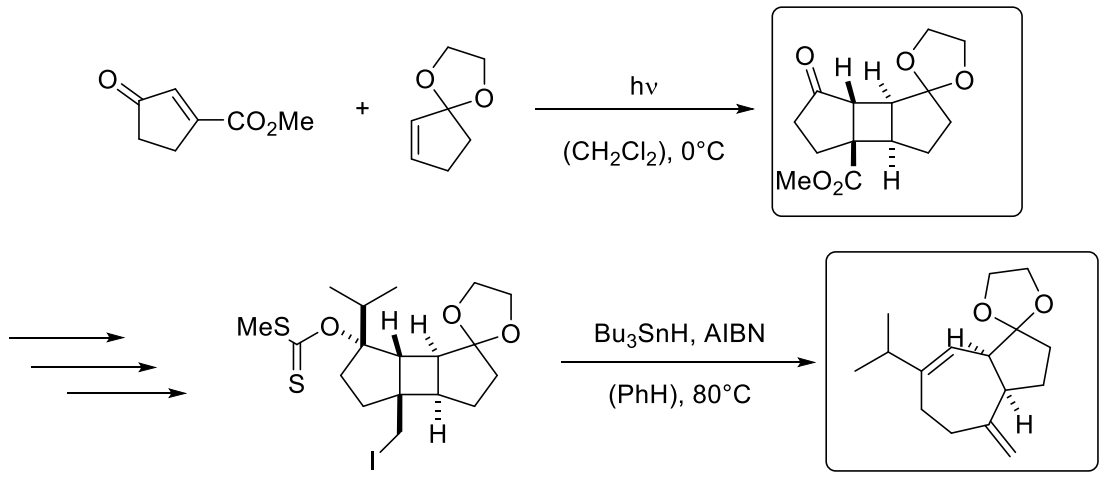


Tetrahedron Lett. **2003**, *44*, 1401-1403.

84%
head to head
product

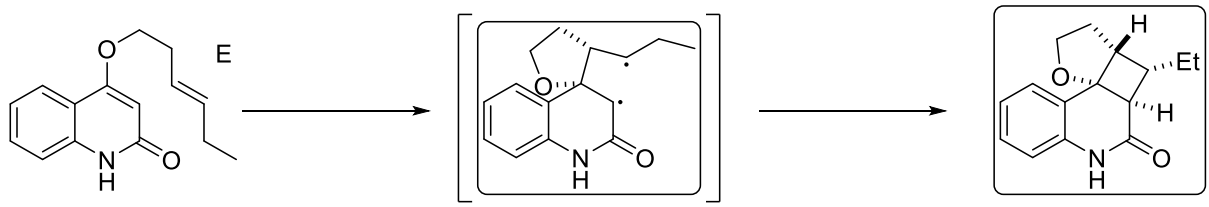
12%
head to tail
product

d)



Tetrahedron Lett. **1994**, *35*, 8513−8516.

2. The molecule below can undergo a intramolecular [2+2] photocycloaddition.
a) Draw the intermediate 1,4-biradical(s) and the product(s) and try to predict the regio- and diastereomeric outcome.

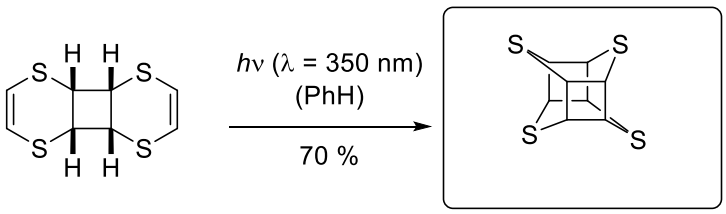


b) If we wanted to prove that this is a triplet reaction, a stereoconvergent reaction outcome is necessary: which similar starting substrate is needed for this? Why are triplet reactions generally stereoconvergent?

Use the Z alkene substrate. Stereoconvergence occurs due to loss of stereochemical information in the 1,4-biradical (biradical lives long enough for rotation around C-C bond to thermodynamically most stable conformer)

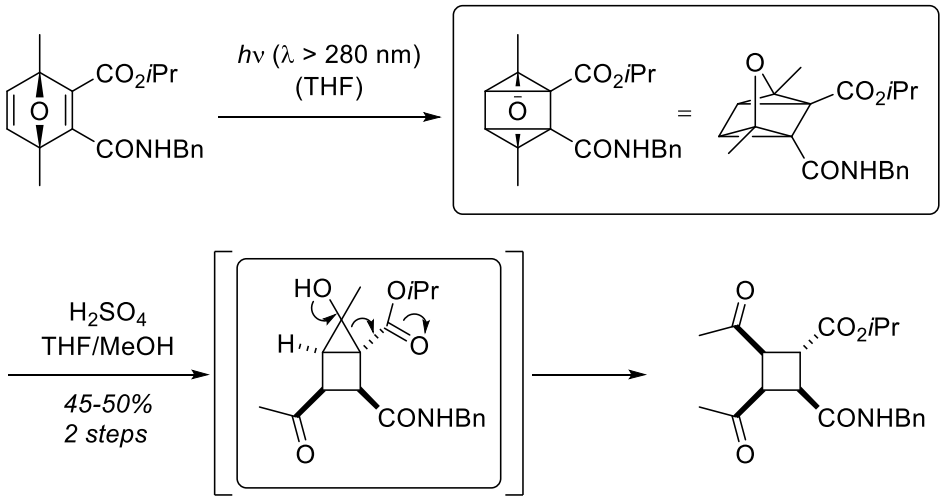
3. Fill in the products and intermediates of the following examples.

a)



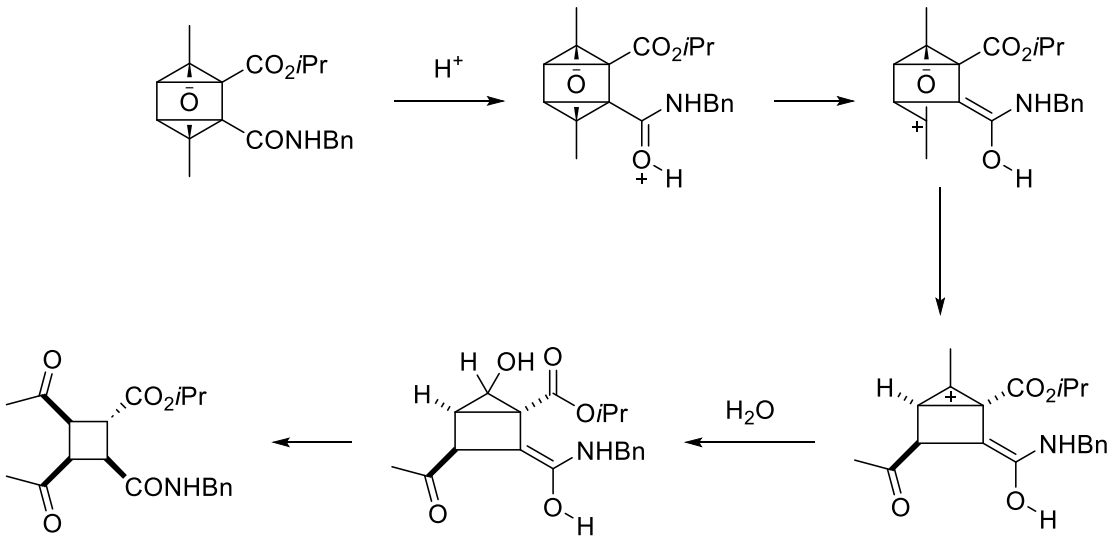
Tetrahedron Lett. **1998**, *39*, 9125– 9126.

b)



Angew. Chem. Int. Ed. **2006**, *45*, 249-252.

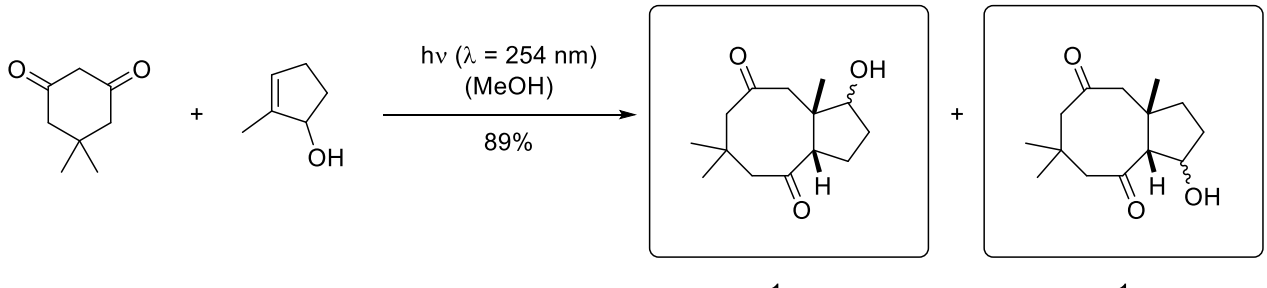
via

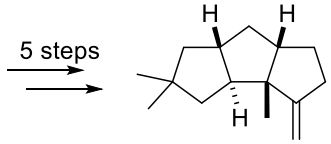


Organic Photochemistry – Exercise 4: 03/12/2024, 09.00 am

German group: CH27402 **English group: CH42306**

1. In their total synthesis of racemic hirsutene, the Weedon group utilized a named photochemical reaction as a key step where two regioisomeric products are obtained in a 1:1 mixture. What are these products and what is the name of the reaction? How does it work mechanistically?



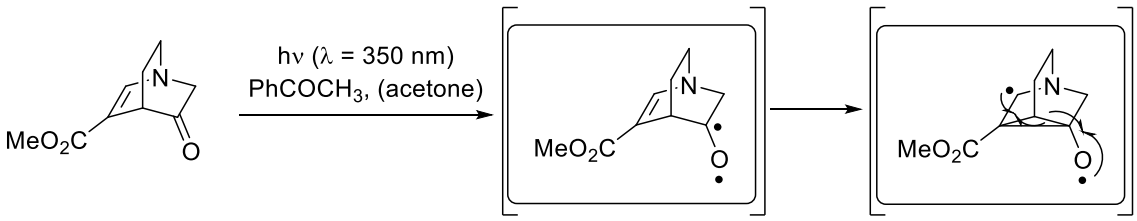


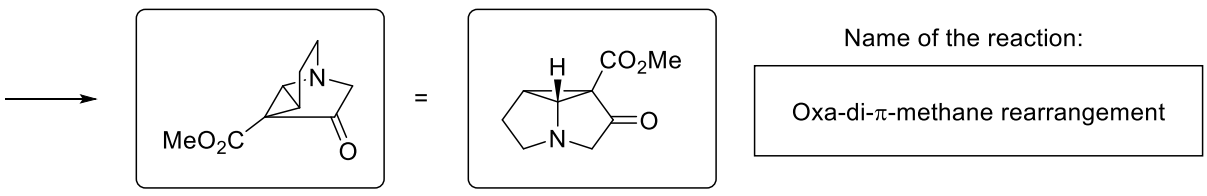
(±)-hirsutene

Name of the reaction: De Mayo reaction

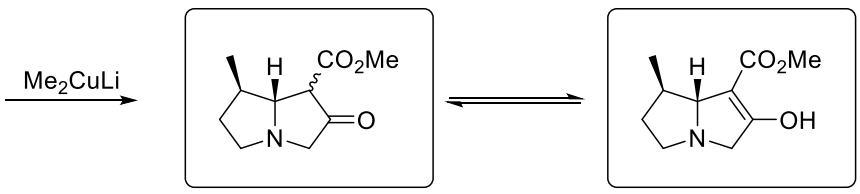
J. Chem. Soc. Chem. Comm. **1985**, *19*, 1282-1283.

2. The reaction shown below is a staple in organic photochemistry. Give the name of the reaction as well as the structures of the intermediates and products. What role do acetophenone and acetone play? Which hypersurface does the photoreaction occur on?





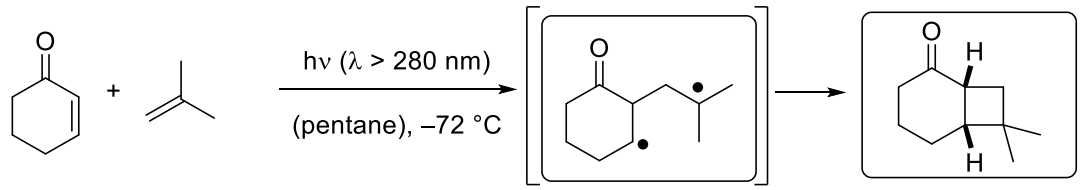
Name of the reaction: Oxa-di-π-methane rearrangement



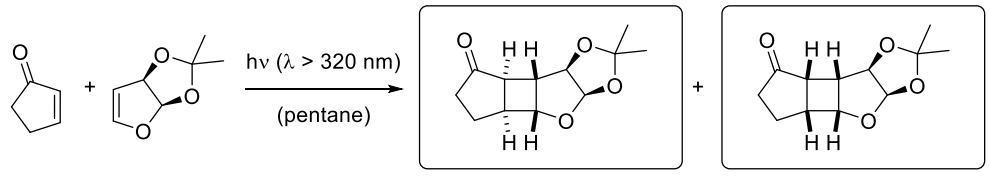
Org. Lett. **2003**, *5*, 3811–3813

3. Complete the following reaction schemes.

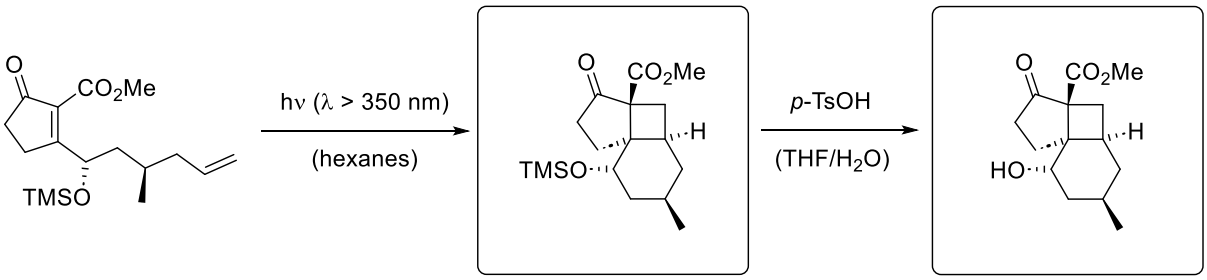
a)



J. Am. Chem. Soc. **1964**, *86*, 485-492.

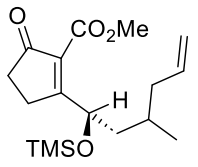


J. Am. Chem. Soc. **1992**, *114*, 2567-2576.



Model for stereoselectivity:

Ground state conformation:



→ 1,3-allylic strain

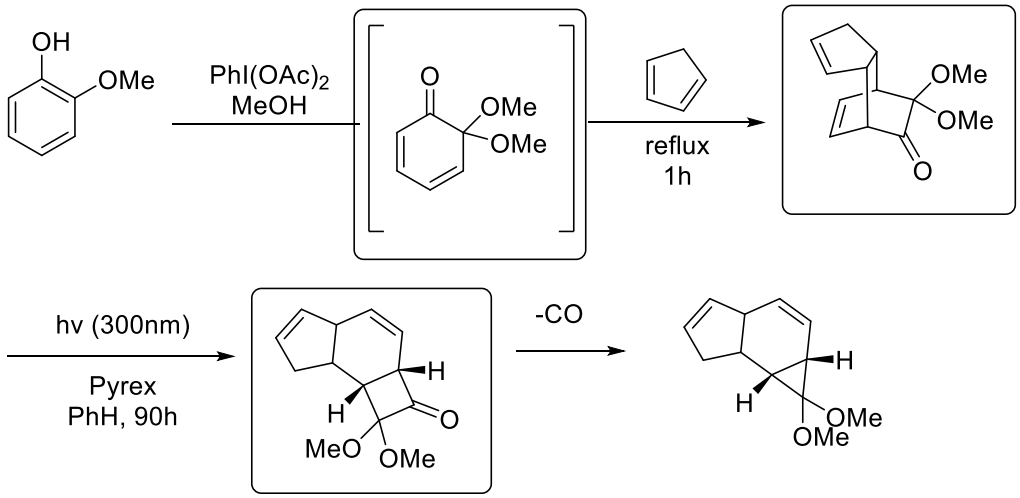
→ approach from the bottom face

Tetrahedron Lett. **1993**, *34*, 199-202.

Organic Photochemistry – Exercise 4: 03/12/2024, 09.00 am

German group: CH27402 **English group: CH42306**

1. Liao and co-workers reported an elegant way of synthesizing the carbon framework of marasmanes. They started from Guajacol, which reacted with cyclopentadiene in a [4+2]-cycloaddition. The product was irradiated triggering a rearragnegement, which aster CO loss afforded the final product. Fill out the boxes and name the rearrangement.

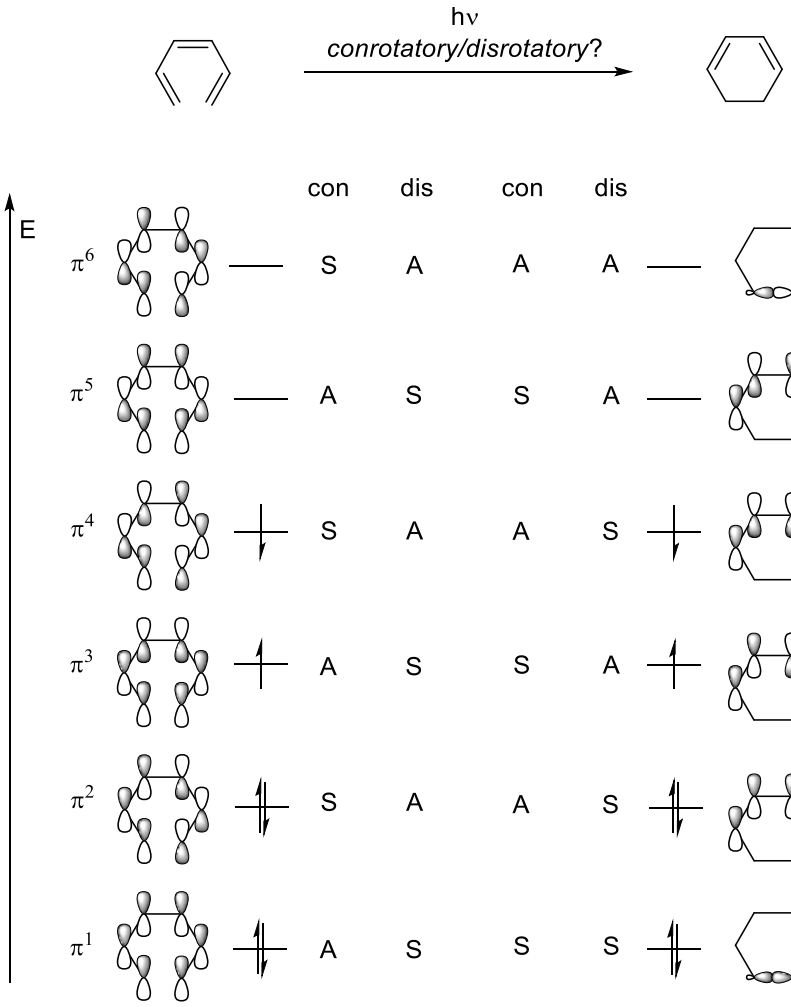


2. Electrocyclic reaction are an important class of reaction in organic chemistry. In this context the Woodward-Hoffman predict the outcome of these.

a) Pericyclic reactions are the consequence of orbital interactions. What are the underlying assumptions for these orbital–orbital interactions?

- interaction is stronger the closer the corresponding orbitals are in energy and/or the better the orbital overlap is
- filled shell repulsion: occupied orbitals repeal, occupied and unoccupied orbitals attract each other
- Coulombic attraction: positive charge on one molecule attracts any negative charge on the other (and repels any positive).

b) Consider hexa-1,3,5-triene as a model system for cyclizations. Does the photochemical [6π] cyclization to cyclohexa-1,3-diene occur in a conrotatory or disrotatory fashion? In the figure below, draw the molecular orbitals of both compounds and fill in the electrons for the S_1 state. Then, analyze the orbital symmetry for both conrotatory and disrotatory cyclization using the Woodward-Hoffmann rules, i.e. if the orbital is symmetric or asymmetric regarding the symmetry operation (conrotatory = C_2-symmetric, disrotatory = mirror-symmetric).



conrotatory $(\pi_1)^2+(\pi_2)^2+(\pi_3)^1+(\pi_4)^1 \longrightarrow (\sigma)^2+(\pi_1)^2+(\pi_2)^1+(\pi_3)^1$

A S A S → S A S A

photochemically allowed

3S + 3A ⟶ 3S + 3A

disrotatory $(\pi_1)^2+(\pi_2)^2+(\pi_3)^1+(\pi_4)^1 \longrightarrow (\sigma)^2+(\pi_1)^2+(\pi_2)^1+(\pi_3)^1$

S A S A → S S A S

photochemically **not** allowed

3S + 3A ⟶̸ 5S + 1A

cyclization of hexatriene in Woodward-Hoffmann notation:

components: π-orbitals = π (vs.: σ-orbitals = σ; p- or sp^x-orbital = ω)

electron count: 6

bond topology: antarafacial = a (vs.: suprafacial = s)

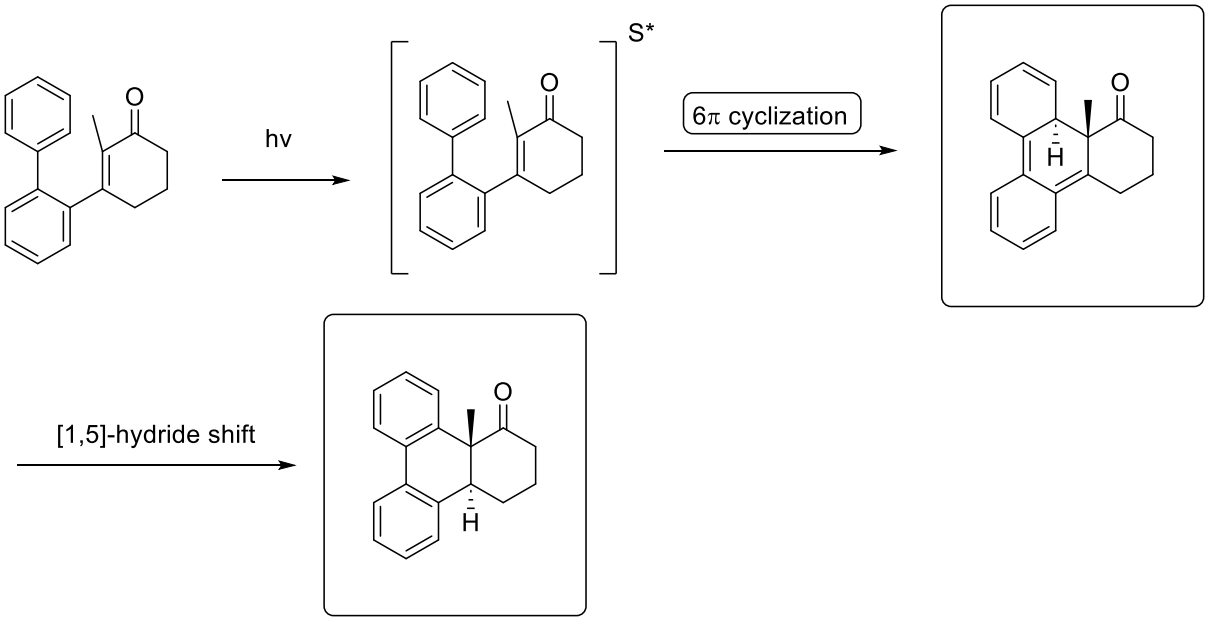
→ $[_\pi 6_a]$

other examples:

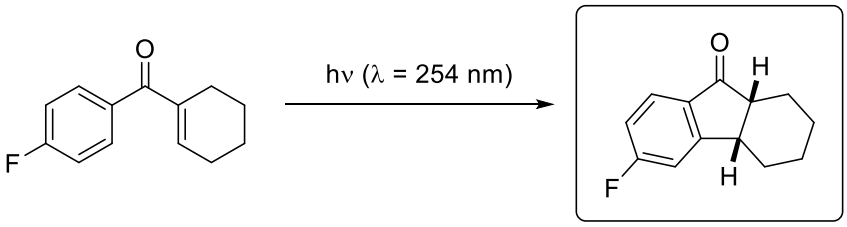
Diels-Alder reaction: $[_\pi 4_s + {}_\pi 2_s]$

Wagner-Meerwein shift of carbocation: $[_\omega 0_s + {}_\sigma 2_s]$

c) A more recent example of a [6π] cyclization was published by Rainer. Fill out the boxes and pay attention to the stereochemical outcome.



3. Give the product of the following reaction. What is the name of the reaction? Does it proceed in a disrotatory or in a conrotatory fashion?



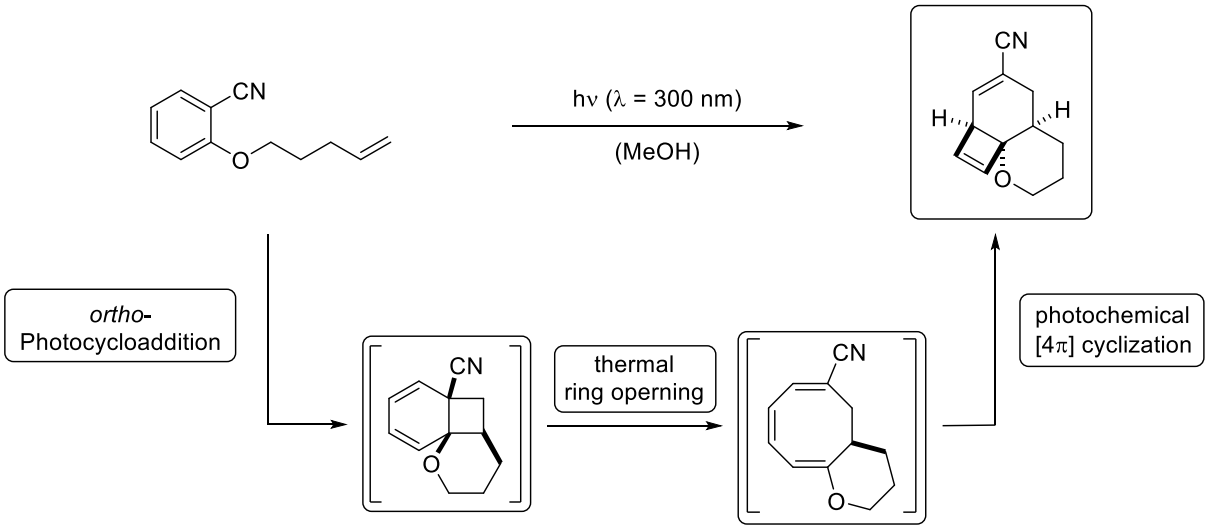
Name of the reaction: Photo-Nazarov reaction

Nature of cyclization: disrotatory

Organic Photochemistry – Exercise 6: 09/01/2025, 11.00 am

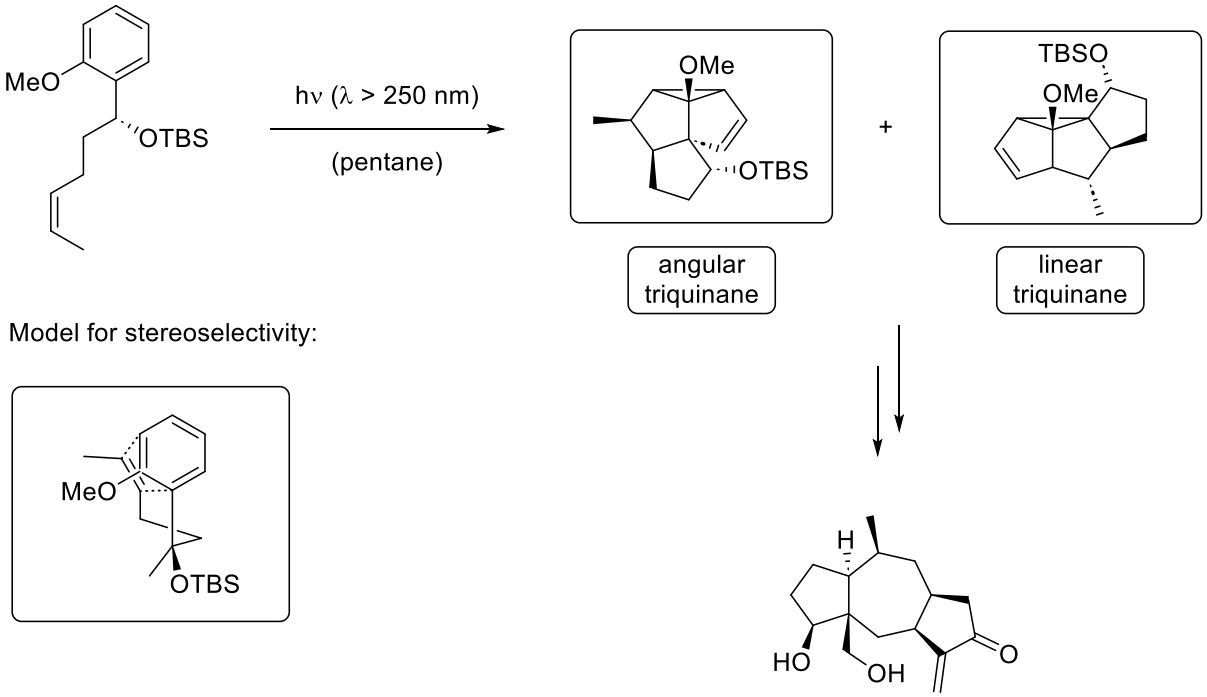
German group: CH22210 **English group: CH42306**

1. The following transformation is the result of a three-component reaction cascade. Please fill in the product along with the two intermediates and label the individual steps.



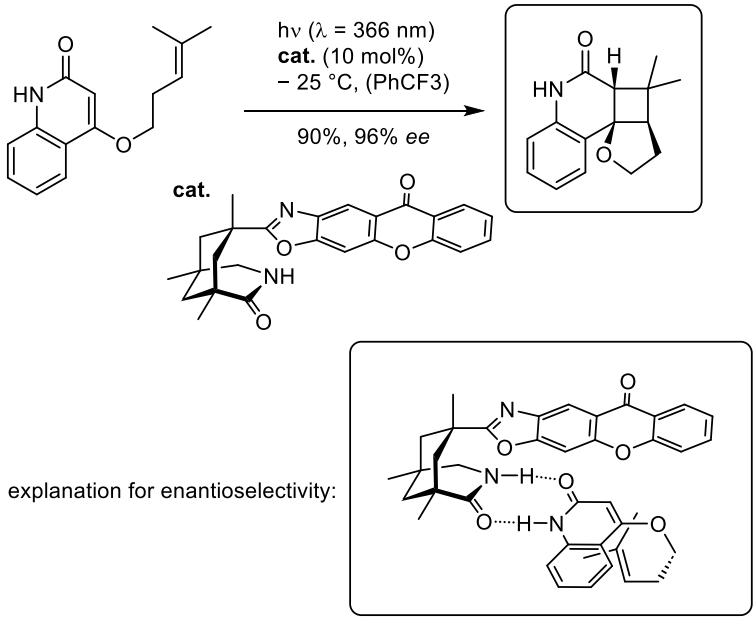
Lit: J. Org. Chem. 2018, 83, 3069−3077.

2. In the synthesis of rudmollin, the given starting material was irradiated, resulting in the formation of two isomers. Both isomers were further converted into the natural product. Please fill in the products and the model explaining the observed stereoselectivity. What are the names of the isomers?



Lit: Tetrahedron Lett. 1986, 27,
1857−1860.https://www.sciencedirect.com/science/article/pii/S0040403900843944

3. An enantioselective version of a common reaction in synthetic photochemistry is shown in the reaction below. Give the structure of the product (absolute configuration!) and the name of the reaction. How is enantioselectivity induced by the chiral xanthone catalyst? Draw the catalyst-substrate complex that explains how the enantioface differentiation is achieved in this transformation.



Angew. Chem. Int. Ed. **2009**, *48*, 6640−6642.

Organic Photochemistry – Exercise 7: 21/01/2025, 09.00 am

German group: CH27402 **English group: CH42306**

1. Define the term redox (or reduction) potential. What is the general conclusion you can draw if a redox pair has a negative/positive redox potential?

Redox potential: Tendency of a compound to lose or acquire electrons (expressed in Volts).
The greater the redox potential, the higher the propensity of a compound to acquire electrons.

- ➔ *Positive redox potential → easier reduction*
- ➔ *Negative redox potential → easier oxidation*

2. Explain why photoexcited transition metal complexes are both stronger oxidants and stronger reductants than their corresponding ground state species.

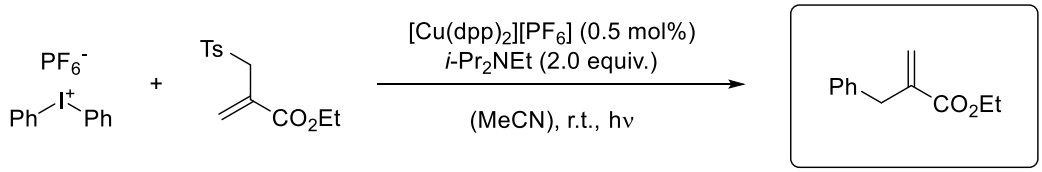
Excitation leads to electron hole/pair separation.
Electron is located at the ligand, higher energy than in the ground state.

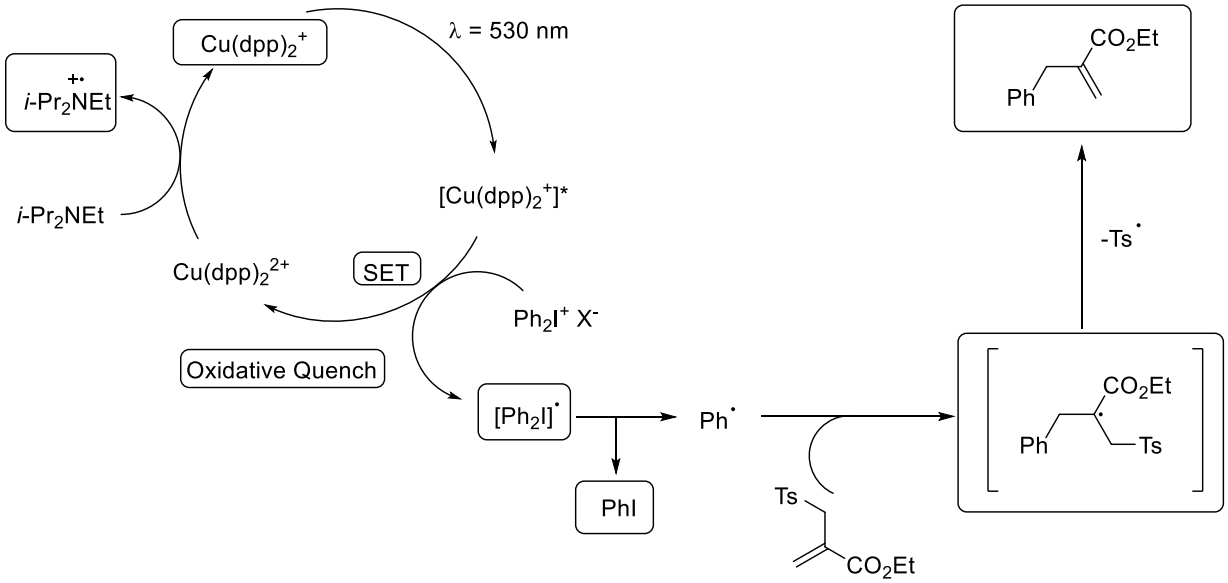
- ➔ *Better reductant*

Electron hole at the central metal is lower in energy than ground state LUMO.

- ➔ *will accept electron more readily*
- ➔ *better oxidant*

3. Aryl radicals are important synthetic intermediates. Aryl iodonium and aryl diazonium salts behave similarly and can both be used to access the aryl radicals in the presence of a photoredox catalyst. Fill in the boxes, make comments on why aryl iodonium and aryl diazonium salts but not aryl sulfonium salts will react in this reaction.

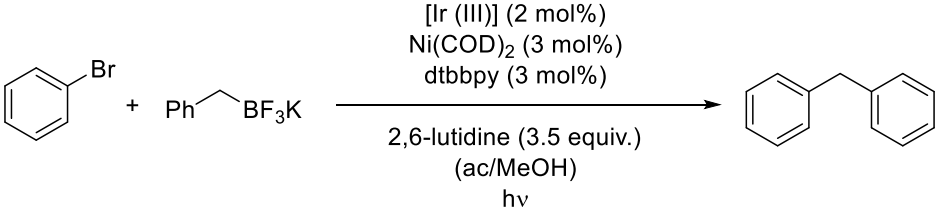


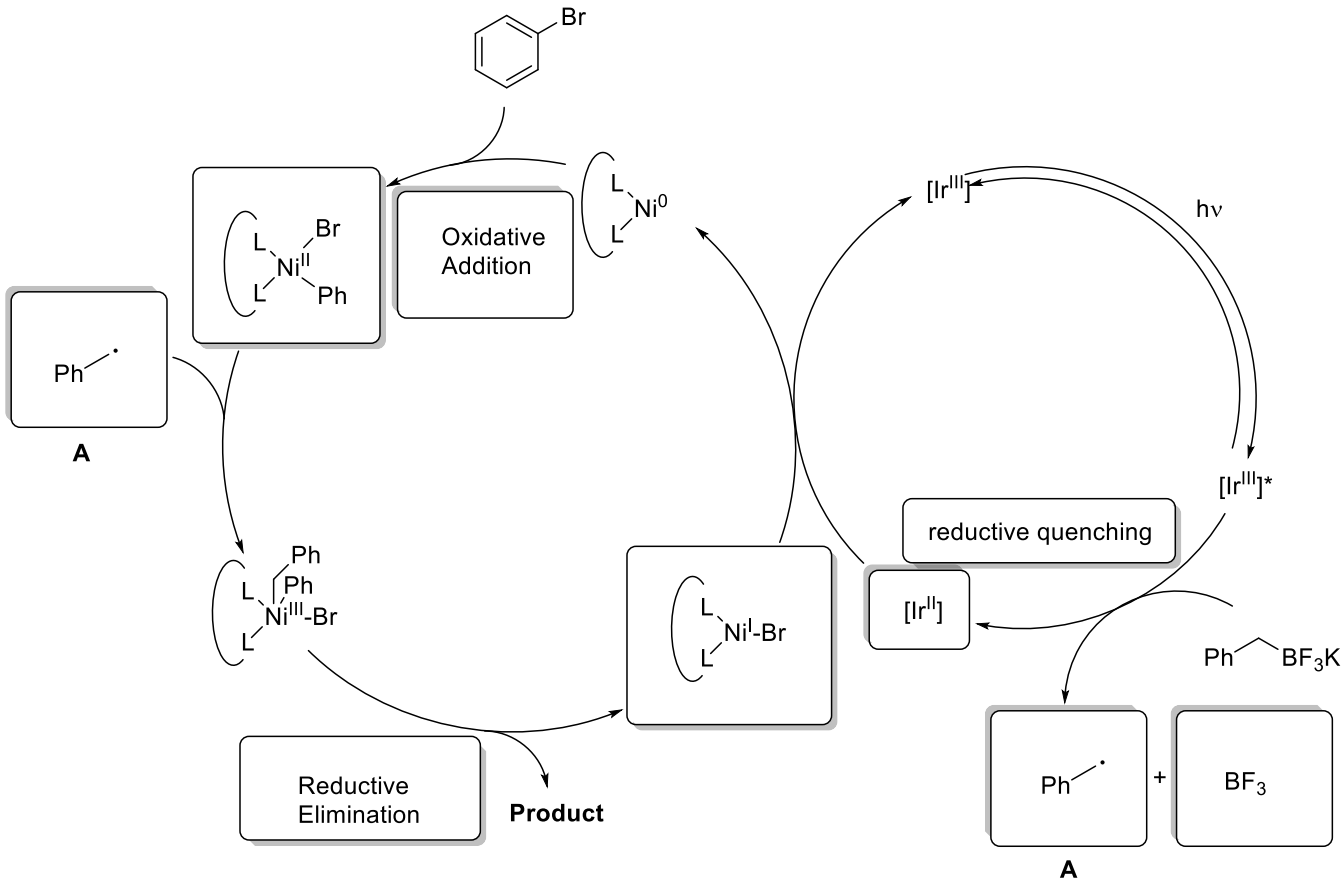


Aryl iodonium and diazonium salts show a range of reduction potentials between −0.2 V to −0.1 V (SCE), in contrast to −1.2 V (SCE) for the corresponding aryl sulfoniums. These are thus much harder to reduce.

Chem. Eur. J. 2013, 19, 10809 – 10813

4. Photoredox catalysis can be paired with transition metals catalysis. This approach presents an alternative to classical cross-coupling reactions. Fill the gaps in the catalytic cycle. Apart from the structures, use labels you learned for cross-coupling reactions.





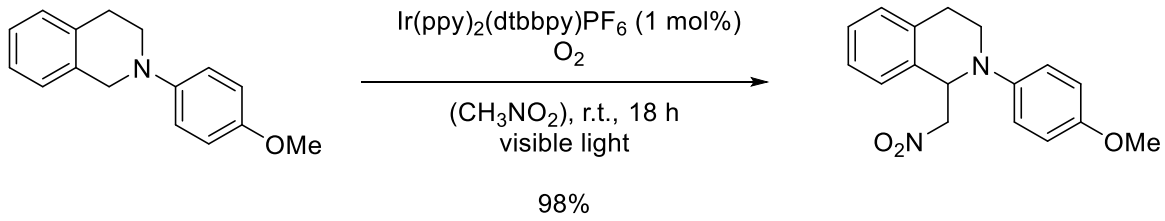
Science 2014, 345, 433-436.

Organic Photochemistry – Exercise 8: 04/02/2025, 09.00 am

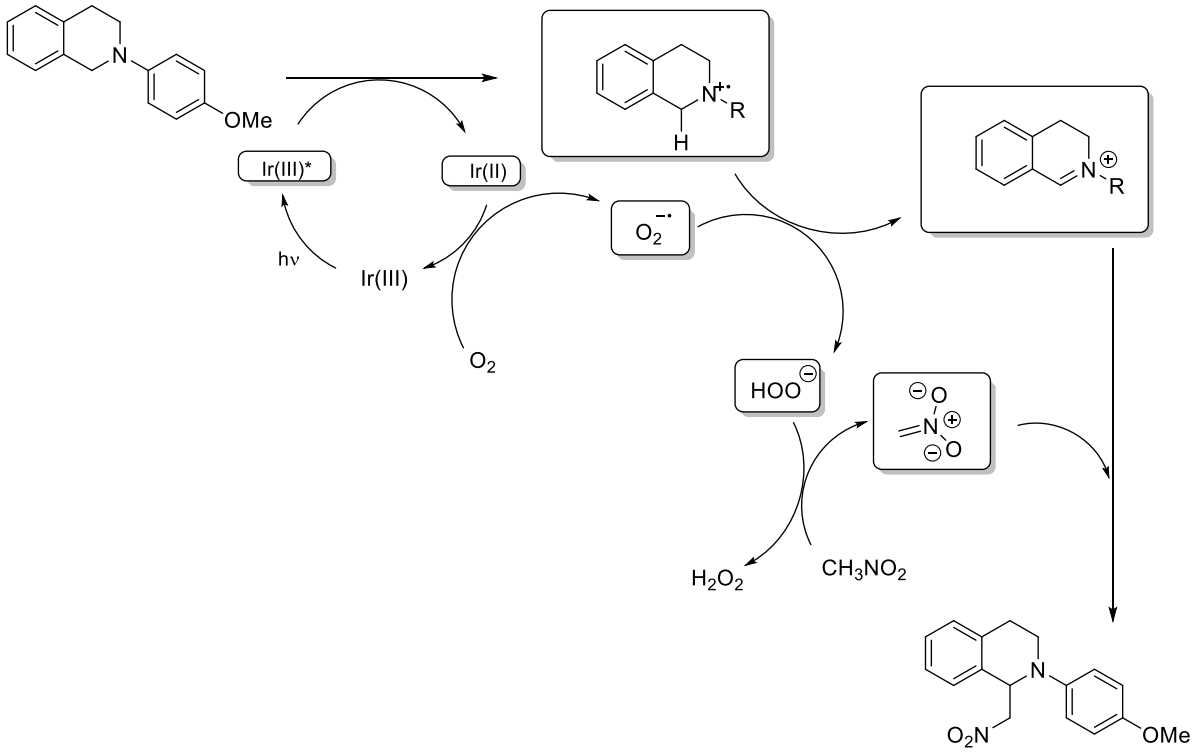
German group: CH27402 **English group: CH42306**

1.

Iminium ions generated by photoredox catalysis can react with nucleophiles to form new carbon-carbon bonds. An early example is the photoredox-catalysed aza-*Henry* reaction shown below.



Fill in the missing intermediates, which lead to the formation of the depicted product. What is the role of molecular oxygen in this reaction?



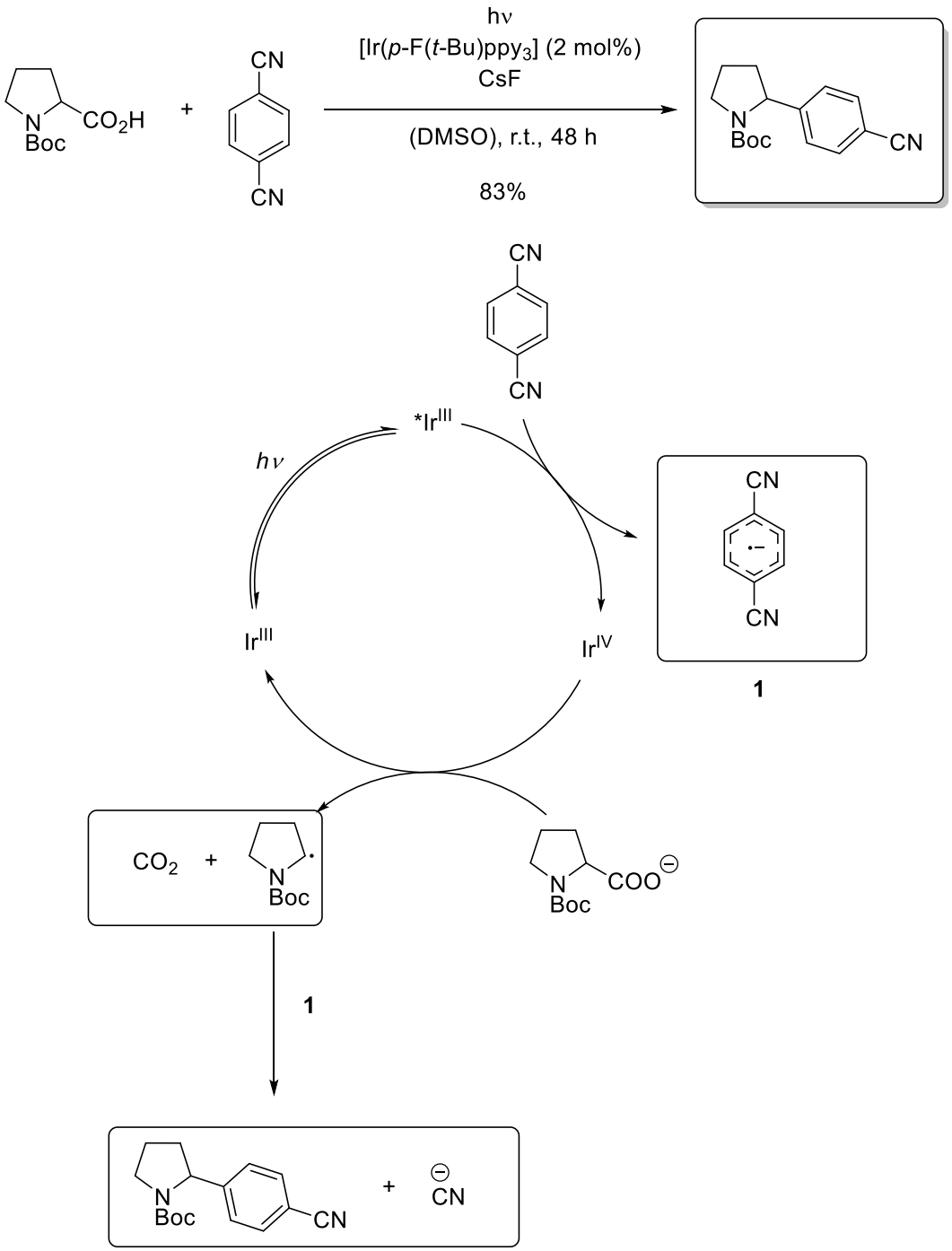
Role of molecular oxygen: Terminal oxidant

JACS **2010**, *132*, 1464.

2.

Iridium catalysts [($E_{1/2}^{red}$ [Ir^{IV}/*Ir^{III}] = –1.67 V vs. SCE)] can be employed for the radical decarboxylation of α-amino acids. The radical intermediates generated can be coupled to cyano-substituted aromatic compounds [1,4-dicyanobenzene ($E_{1/2}^{red}$ = –1.61 V vs. SCE)]. Please give the product of the following

reaction and draw the photoredox cycle. Is the transformation net oxidative, reductive or redox neutral?

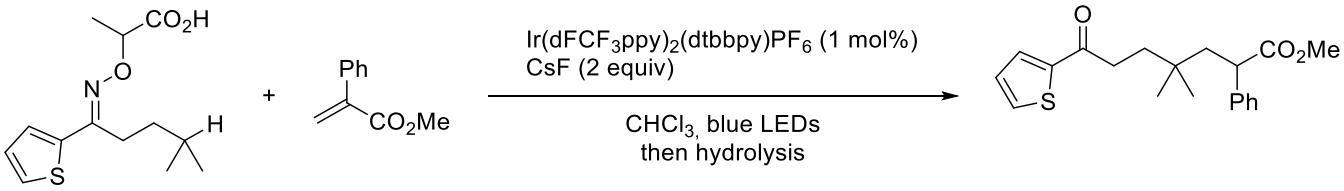


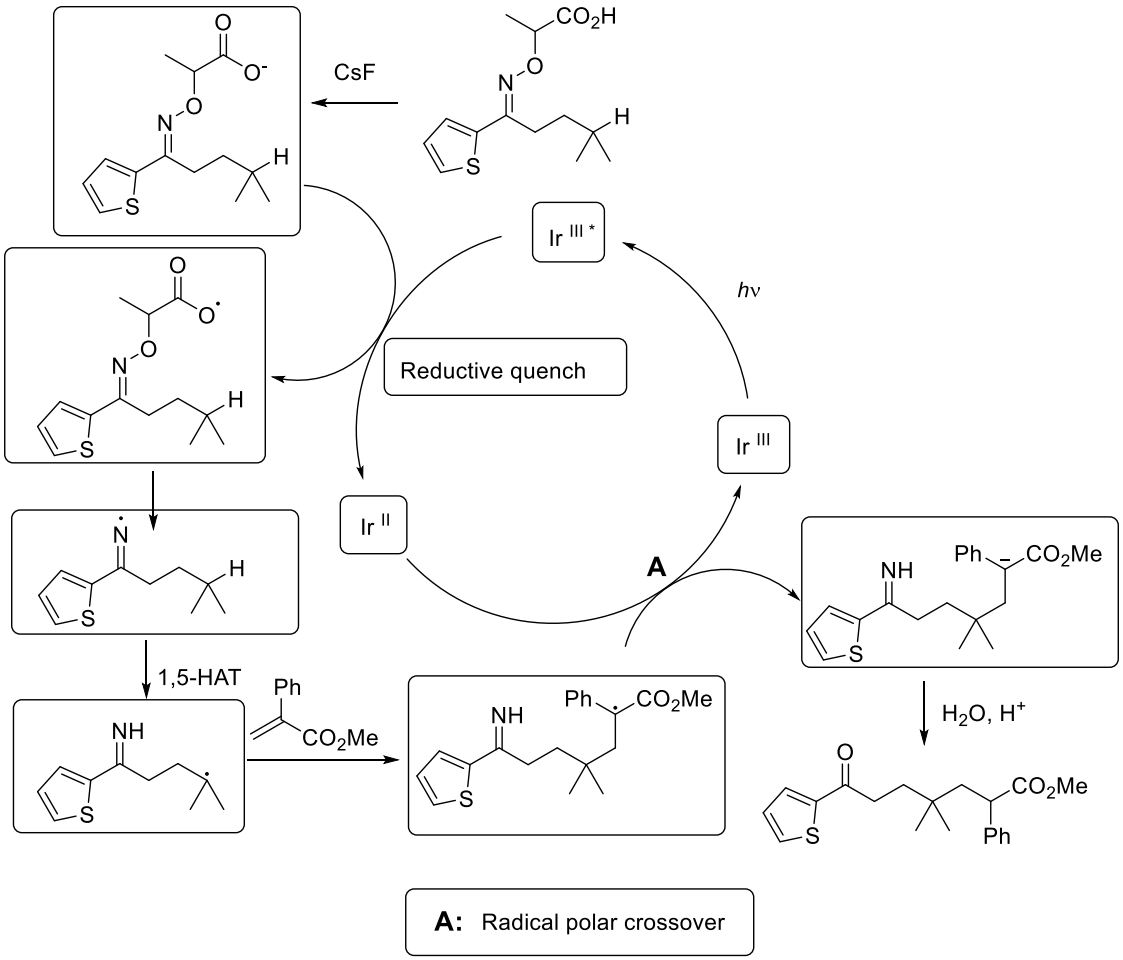
Redox neutral: substrates participate in both the reductive and oxidative steps of the photocatalytic cycle, with no change to the overall oxidation state from starting materials to product.

J. Am. Chem. Soc. **2014**, *136*, 5257-5260.

3.

The following light mediated reaction allows the selective C-H γ-functionalization of various ketones. Fill in the missing intermediates and products of this light mediated transformation. Is this process going through oxidative or reductive quenching? Which term describes what happens in step **A**?





Angew. Chem. Int. Ed. **2018**, *57*, 1692.