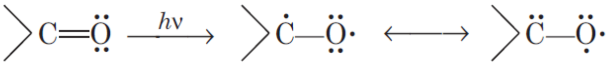
Module-IV

Photoreactions of Carbonyl compounds

The photochemical reactions of carbonyl group is initiated by $n \rightarrow \pi^*$ transition.
Promotion of an electron will lead to either a singlet state or a triplet state.
Photochemical reactions given by carbonyl group takes place either by singlet state or by triplet state or by both states.



Carbonyl compounds give four type of reactions. These reactions include:
(*i*) α-Cleavage.
(*ii*) β-Cleavage.
(*iii*) Intramolecular and intermolecular hydrogen abstraction by carbonyl oxygen.
(*iv*) Addition of carbonyl oxygen atom to a carbon-carbon multiple bond.

In many cases the four processes are competitive and the major process followed is sensitive to structural variations in the ketones and the choice of the solvents.

α-Cleavage or Norrish type I reaction

Norrish type I process is given by three types of ketones:

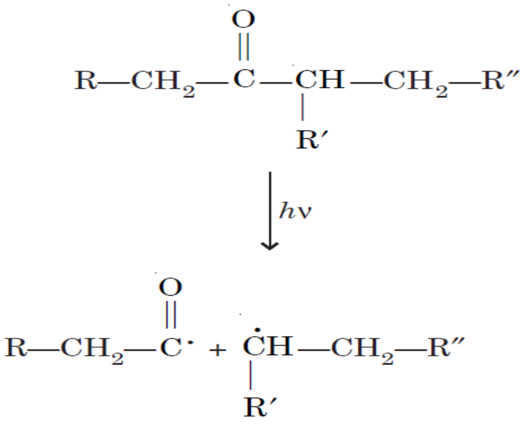
(*i*) Saturated acyclic ketones.
(*ii*) Saturated cyclic ketones.
(*iii*) β, γ-Unsaturated ketones.

Norrish type I process by Saturated acyclic ketones

Saturated carbonyl compounds undergo photoinduced decarbonylation in the gas phase. This process was first observed by R.G.W. Norrish and is known as Norrish Type I or α-Cleavage process. Norrish Type I process is commonly encountered in the gas phase. The solution phase reaction of this type is uncommon.

Primary Processes

Norrish Type I process is characterised by initial cleavage of the carbonyl carbon and *alpha* carbon bond to give an **acyl** and an **alkyl** radicals. This process is known as primary photochemical process (Scheme 1).

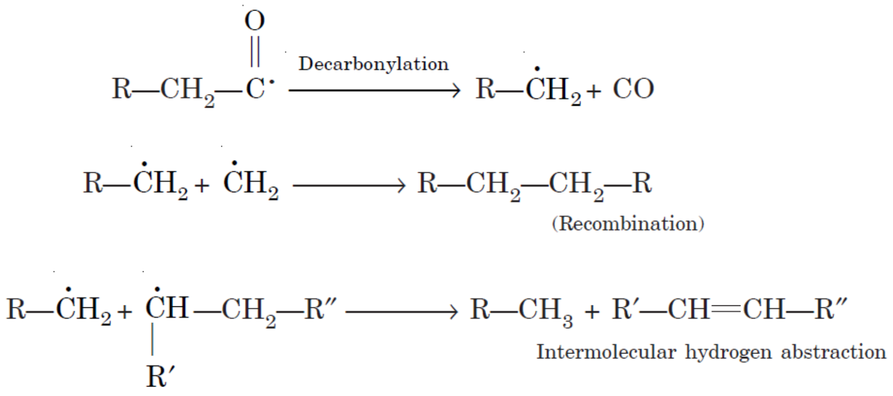


Scheme 1: Primary process

The initially formed acyl radical is stabilised by one of the secondary processes [(*a*) – (*c*)] shown in the Scheme 2. Similarly, the alkyl radical can be stabilised by recombination or disproportionation (Scheme 2).

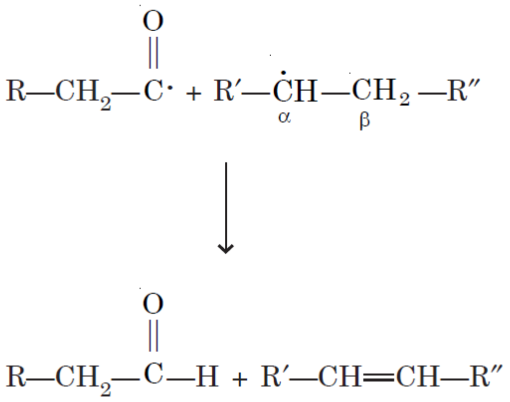
Secondary Processes

(*a*) Decarbonylation of acyl radical to give carbon monoxide and an alkyl radical. This alkyl radical can recombine to give an alkane or can undergo intermolecular hydrogen abstraction to form an alkane and an alkene [Scheme 2(*a*)].



Scheme 2 (*a*)

(*b*) Intermolecular hydrogen abstraction by the acyl radical from the alkyl radical to give an aldehyde and an alkene [Scheme 2(*b*)].

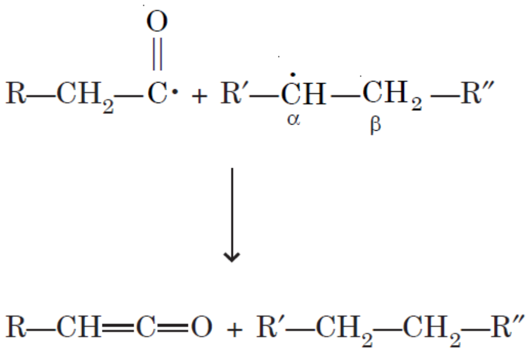


$$R{-}CH_2{-}\overset{\overset{O}{\|}}{C}\cdot + R'{-}\underset{\alpha}{\dot{C}H}{-}\underset{\beta}{CH_2}{-}R'' \longrightarrow R{-}CH_2{-}\overset{\overset{O}{\|}}{C}{-}H + R'{-}CH{=}CH{-}R''$$

Scheme 2 (*b*)

This process can only be possible if alkyl radical has atleast one β-hydrogen.

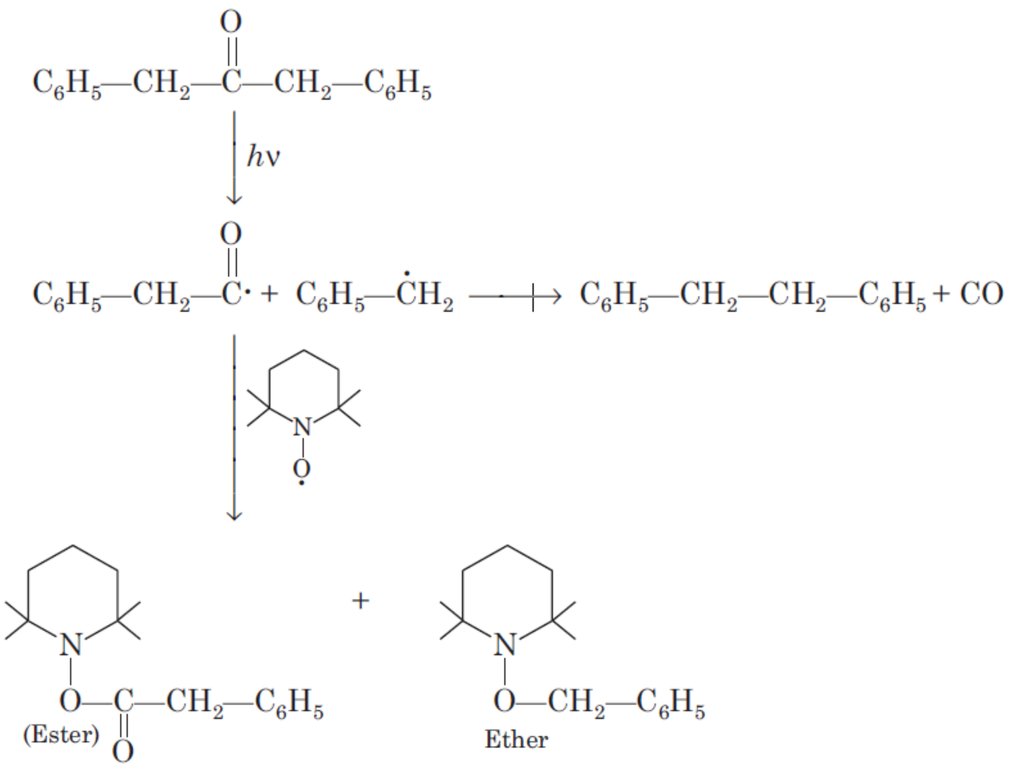
(*c*) Intermolecular hydrogen abstraction by the alkyl radical from the α-carbon of the acyl radical to form a ketene and an alkane [Scheme 2 (*c*)].



$$R{-}CH_2{-}\overset{\overset{O}{\|}}{C}\cdot + R'{-}\underset{\alpha}{\dot{C}H}{-}\underset{\beta}{CH_2}{-}R'' \longrightarrow R{-}CH{=}C{=}O + R'{-}CH_2{-}CH_2{-}R''$$

Scheme 2 (*c*)

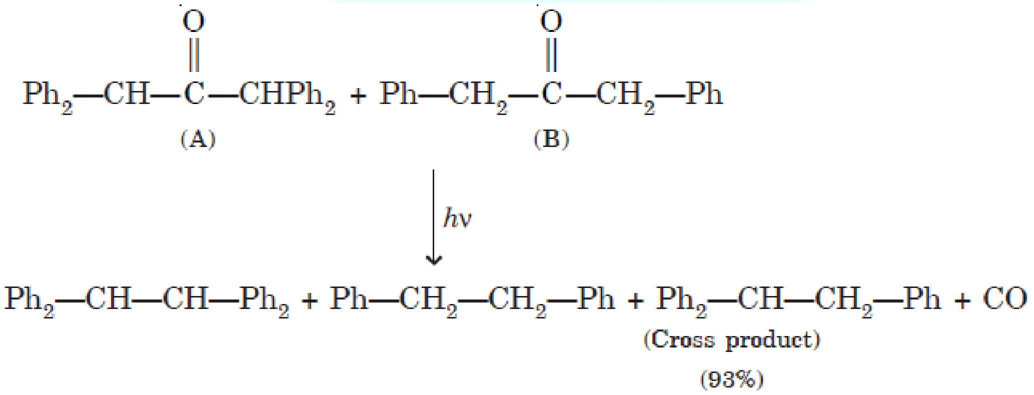
The main reaction of saturated acyclic ketones is decarbonylation.
Norrish Type I process is thus a two step radical mechanism.
The first step is a primary process and the second step is the secondary process.
Formation of acyl and alkyl radicals can be proved by trapping of these radicals by the use of suitable trapping agents.
2, 2, 4, 4-Tetramethylpiperidine-1-oxyl was used for the trapping and the radical fragments produced by the fission of 1, 3-diphenylacetone were trapped as an ester and an ether (Scheme 3).



Scheme 3

Formation of ether and ester confirms that there should be the formation of acyl and alkyl radicals.

The formation of radical intermediates is also readily demonstrated by photolysis of a mixture of ketones (A) and (B) which give products from mixed radical combination.



$$\underset{(A)}{Ph_2-CH-\overset{O}{\overset{\|}{C}}-CHPh_2} + \underset{(B)}{Ph-CH_2-\overset{O}{\overset{\|}{C}}-CH_2-Ph} \xrightarrow{h\nu} Ph_2-CH-CH-Ph_2 + Ph-CH_2-CH_2-Ph + \underset{\substack{\text{(Cross product)}\\(93\%)}}{Ph_2-CH-CH_2-Ph} + CO$$

This cross over experiment also confirmed the two steps radical mechanism.

Norrish Type I process occurs from both the excited singlet and the triplet states of $n \rightarrow \pi^*$ transition.

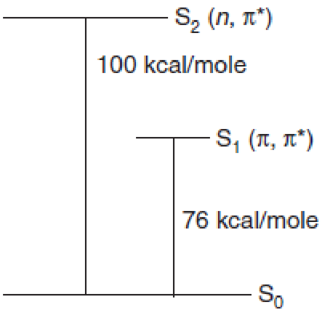
Photolysis of ditertbutylketone results in high yield of carbon monoxide (90%) from both the excited singlet and triplet states.

This clearly shows that the Norrish Type I processes occur from both the excited states. The lifetime of the singlet state is 4.5 – 5.6 × 10^{-9} sec as compared with 0.11 × 10^{-9} sec for the excited triplet state.

Since the reaction occurs from both the singlet and triplet excited states, the Type I process must occur about 100 times faster from triplet than from singlet excited state.

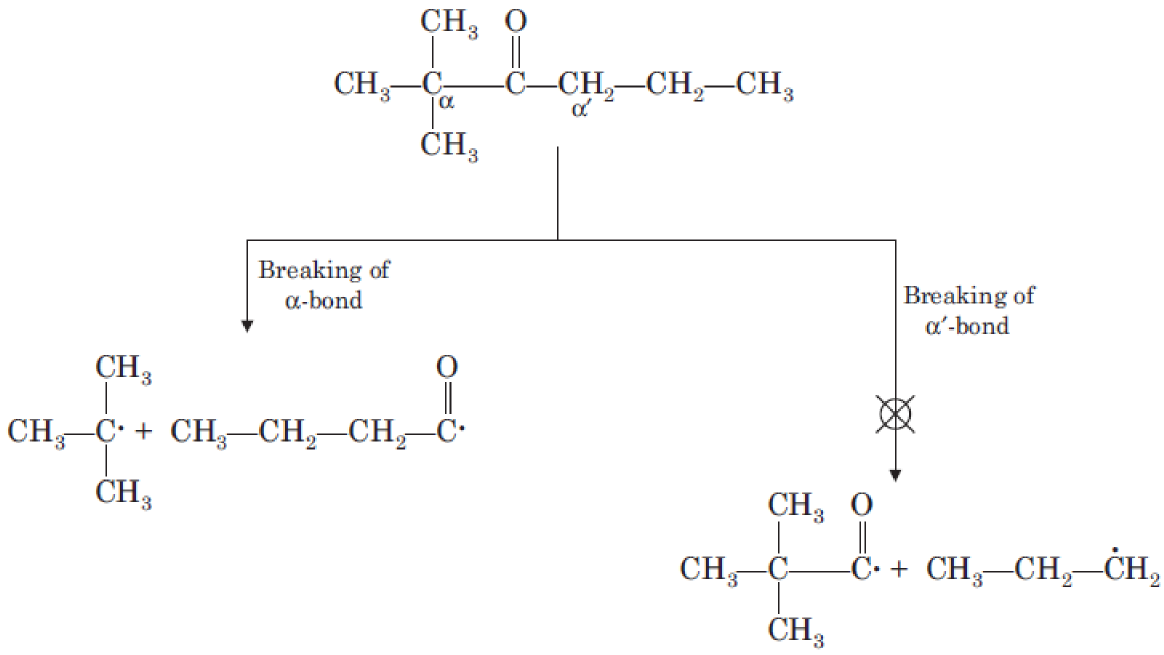
Studies with triplet quenchers, such as 1, 3-cyclopentadiene, have also shown that Norrish Type I processes occurs from both triplet and singlet excited states.

Norrish Type I cleavage is given mostly by those ketones whose $n \rightarrow \pi^*$ state is the lowest excited states. In most of the cases, the $n \rightarrow \pi^*$ state is the lowest excited state. However, α-cleavage in arylalkyl ketones and diaryl ketones is less efficient because $n \rightarrow \pi^*$ excited state is not the lowest excited state. In this case, there is a large barrier on the reaction coordinate (Fig. 7.1).

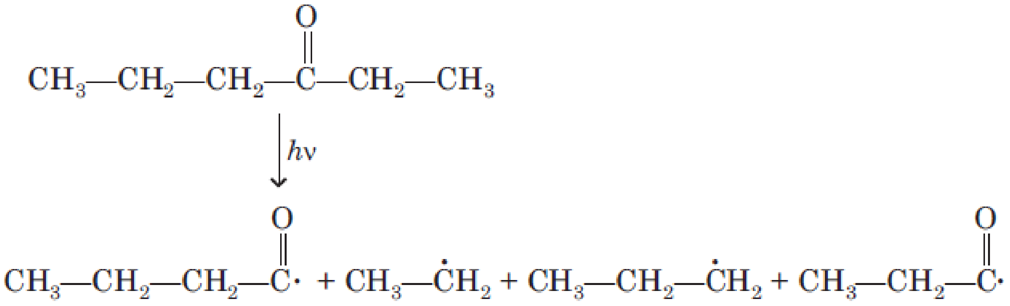


Energy of diphenyl ketone ($C_6H_5COC_6H_5$)

In Norrish Type I reactions there is a preference for the formation of most stable alkyl radical in case of unsymmetrical ketones.



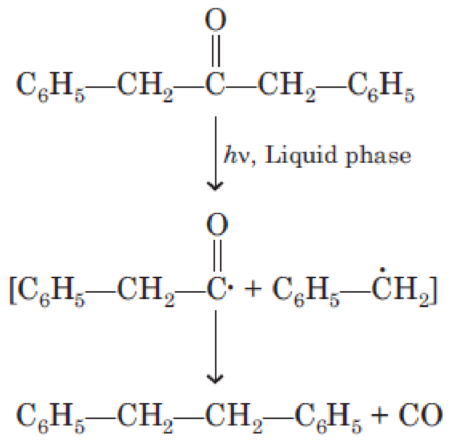
In the above case, only α-bond undergoes cleavage. If both alkyl substituents are same then there is little selectivity of bond cleavage.



$$\mathrm{CH_3{-}CH_2{-}CH_2{-}\overset{O}{\overset{\|}{C}}{-}CH_2{-}CH_3} \xrightarrow{h\nu} \mathrm{CH_3{-}CH_2{-}CH_2{-}\overset{O}{\overset{\|}{C}}\cdot + CH_3{-}\dot{C}H_2 + CH_3{-}CH_2{-}\dot{C}H_2 + CH_3{-}CH_2{-}\overset{O}{\overset{\|}{C}}\cdot}$$

The Norrish Type I process is mostly favoured by photolysis in the vapour phase and is less pronounced for photolysis in the inert solvents. In inert solvent formation of solvent cage takes place. Formation of solvent cage facilitates recombination of the initially generated radical pair. Thus low quantum yield of products is obtained in inert solvents.

Norrish Type I process is efficient in liquid phase only if a stable radical is formed. The stable radical includes allylic, benzylic, *tert* alkyl and acyl radicals.



$$\mathrm{C_6H_5{-}CH_2{-}\overset{O}{\overset{\|}{C}}{-}CH_2{-}C_6H_5} \xrightarrow{h\nu,\ \text{Liquid phase}} \mathrm{[C_6H_5{-}CH_2{-}\overset{O}{\overset{\|}{C}}\cdot + C_6H_5{-}\dot{C}H_2]} \longrightarrow \mathrm{C_6H_5{-}CH_2{-}CH_2{-}C_6H_5 + CO}$$

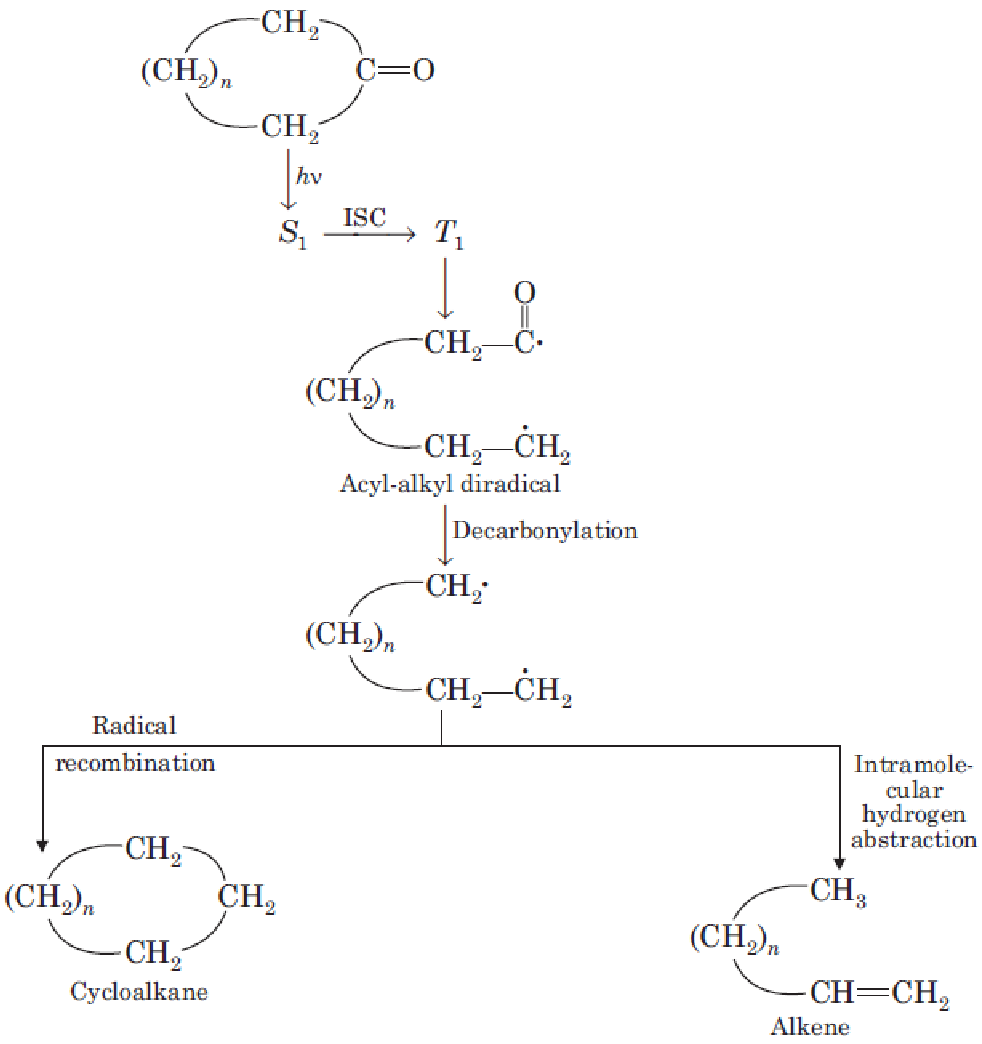
Norrish Type I reactions of saturated cyclic ketones

Cyclic ketones, in contrast to the acyclic ketones, show a greater tendency to undergo α-cleavage to furnish acyl-alkyl biradicals. Norrish Type I cleavage of acyclic ketones take place by singlet as well as by triplet excited state. In cyclic ketones, the reaction takes place exclusively by the triplet state. It is possible, however, that inter system crossing in cyclic ketones is so rapid that reaction from the singlet state would not be observed. The triplet state is atleast 100 times more reactive than the excited singlet state.

Available information indicates that the excited triplet state for Norrish Type I processes is n → π* triplet state. This was demonstrated first for the irradiation of cyclopentanone in both gases and in solution phases. Under both conditions, the product is 4-pentenal. Formation of 4-pentenal takes place at 313 nm and 254 nm. The formation of the aldehyde can be quenched by 1, 3-cyclopentadiene. This quenching experiment confirms the formation of the triplet state.

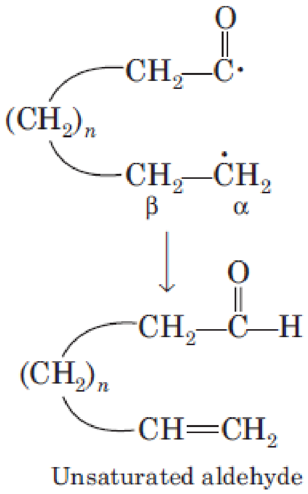
Norrish Type I process involves the initial cleavage of a carbonyl carbon-alpha carbon bond. Subsequent secondary processes [(a) to (c)] correspond to those observed for acyclic ketones.

(a) Decarbonylation of acyl-alkyl diradical to give carbon monoxide and a dialkyl radical. The dialkyl radical can recombine to give a cycloalkane or it undergoes intramolecular hydrogen abstraction to form an alkene. [Scheme 4 (*a*)].



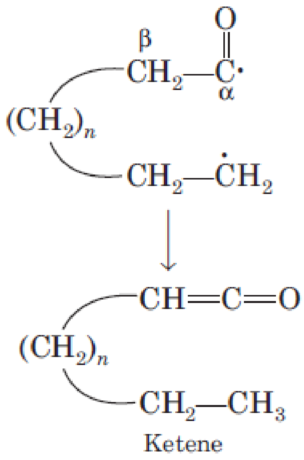
Scheme 4 (*a*)

(*b*) Intramolecular hydrogen abstraction by the acyl radical from the b-carbon of the alkyl radical to give an unsaturated aldehyde [Scheme 4 (*b*)].



Scheme 4 (*b*)

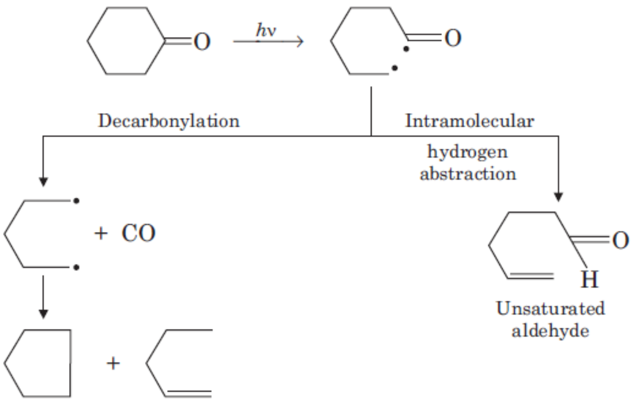
(*c*) Intramolecular b-hydrogen abstraction from the acyl radical by the alkyl radical to produce a ketene [Scheme 4 (*c*)].



Scheme 4 (*c*)

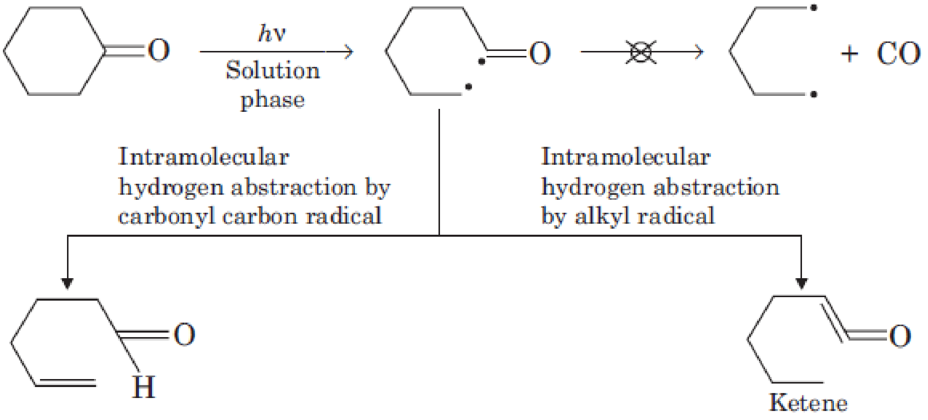
The biradical of cyclic ketones can undergo one of the two hydrogen transfer processes [(*b*) and (*c*)] *via* a cyclic transition state in which a hydrogen atom is transferred to one radical centre from the atom adjacent to other radical centre.

Photolysis of cyclic ketones in gases phase gives decarbonylation as well as intramolecular hydrogen abstraction. Intramolecular hydrogen abstraction mainly leads the formation of unsaturated aldehyde (Scheme 5).



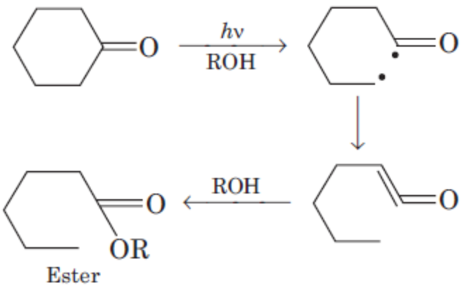
Scheme 5

In solution phase biradical pair is not usually stabilised by decarbonylation. In this case, biradical is mainly stabilised by intramolecular hydrogen atom transfer. This intramolecular hydrogen atom transfer leads to the formation of either unsaturated aldehyde or a ketene or both (Scheme 6).

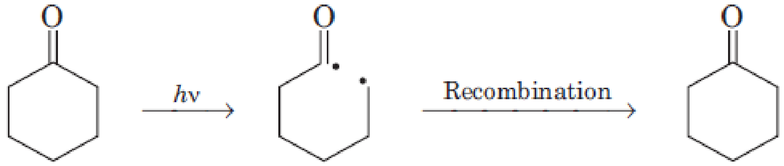


Scheme 6

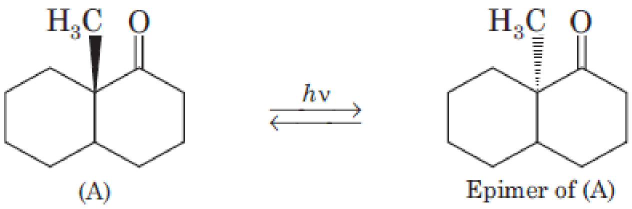
When photolysis is carried out in the presence of polar protic solvent than the main species is ketene. This ketene than undergoes solvent addition to give carboxylic acid (with water) or its derivative (ester with alcohol) as the only product.



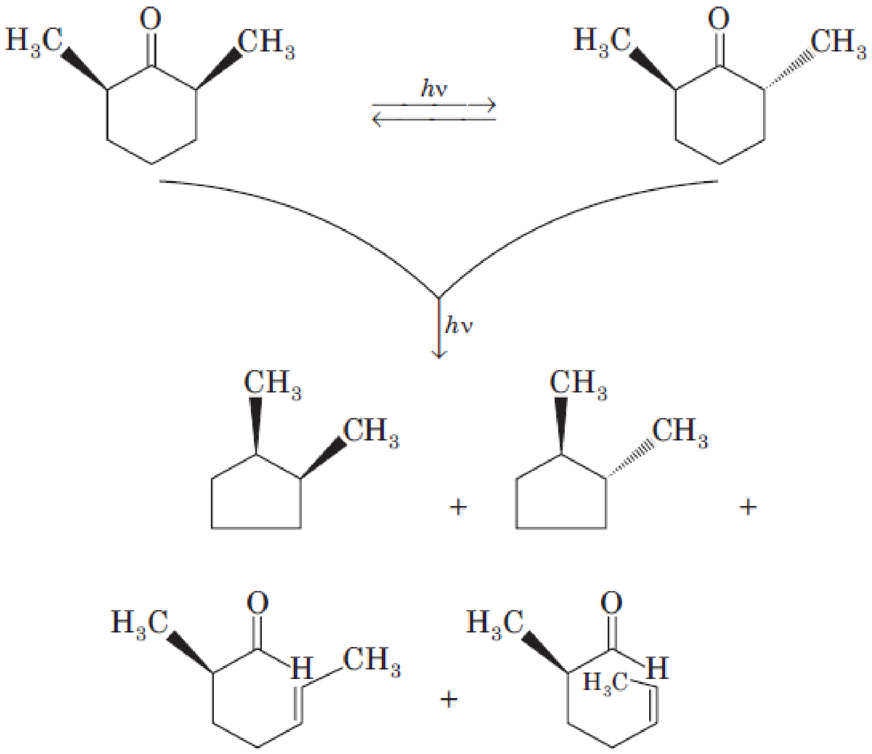
According to the biradical mechanism, there is a possibility of a back recombination reaction to reform the starting material.



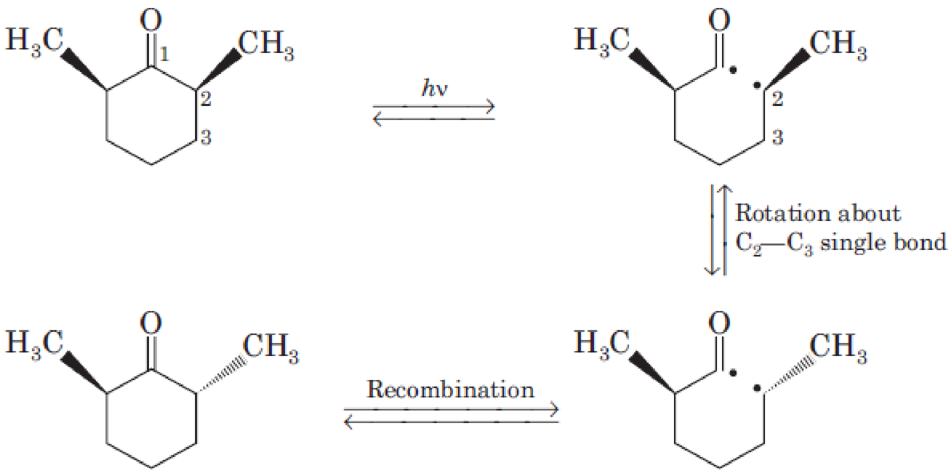
Use of suitably a-substituted cyclic ketones show that recombination reaction resulted in epimerisation at the a-carbon if a-carbon is a chiral.



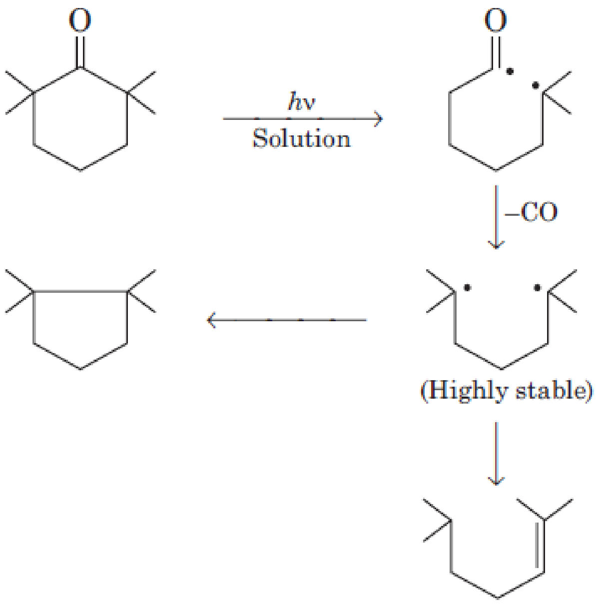
Experimentally it has been found that photolysis product formation *via* route [(*a*) – (*c*)] is faster than the photochemical interconversion of the epimers. Since there is the formation of epimeric mixtures each epimer afford the same mixture of products.



Each epimer affords the same mixture of products. This clearly indicates that the configurational integrity of the α-carbon is lost during the course of the reaction. This loss of integrity is due to the free rotation about C_2—C_3 bond in the diradical.

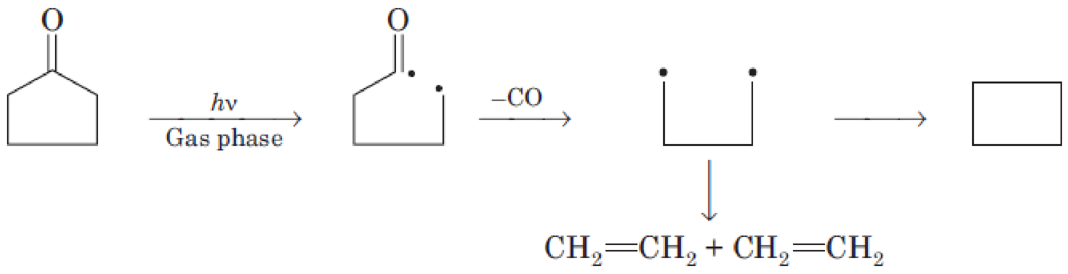


The recombination process is important even when hydrogen transfer reactions occur, but loss of carbon monoxide in solution phase photochemistry is a major reaction pathway only when the alkyl radical centres are stabilised by inductive effect, by b, c-unsaturation or by cyclopropyl conjugation. This reflects an increase in the rate of loss of carbon monoxide from the acyl-alkyl biradical in these systems. 2, 6-Dimethyl-cyclohexanone gives carbon monoxide on photolysis in solution at room temperature. 2, 2, 6, 6-tetramethylcyclohexanone gives carbon monoxide in a yield greater than 70%, 7, 7, 9, 9-tetramethylbicyclo [4, 3, 0] non-1, 6-en-8-one gives 100% yield of carbon monoxide and hydrocarbon products.

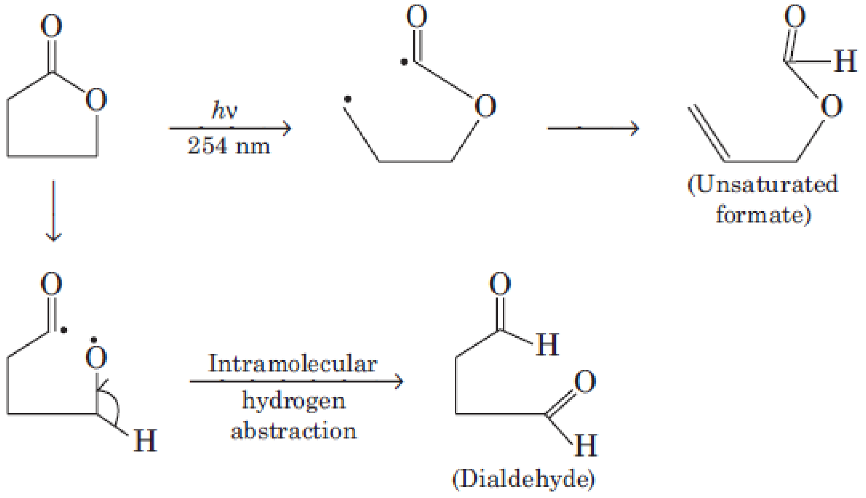


Norrish Type I process given by Cyclopentanones

Cyclopentanone also decarbonylates on irradiation in the gas phase at 147 nm. In this case also a two step process is involved, affording a biradical which decarbonylates to another biradical, which either fragment to ethylene or undergoes bond formation to cyclobutane. Fission to ethylene is much more efficient in comparison to cyclobutane formation (Scheme 7).



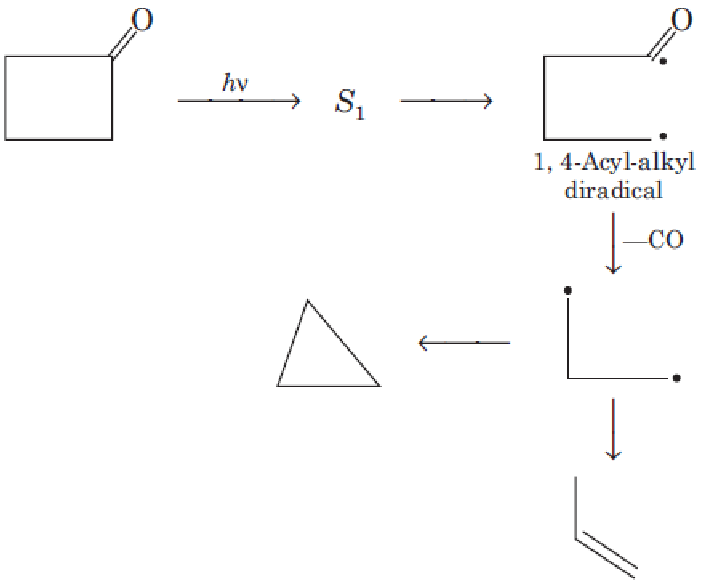
a-Cleavage is not given only by cyclic ketones. Other cyclic compounds such as lactones, lactams and cyclic anhydrides undergo α-cleavage to give a biradical species on photolysis in gas or solution phase.



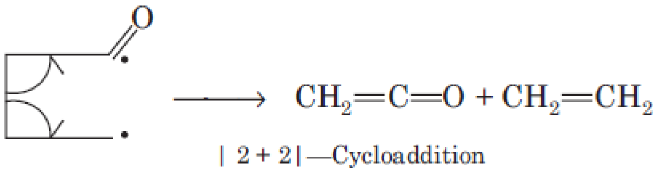
α-Cleavage given by Cyclobutanones

Cyclobutanone also gives a-cleavage reaction. The efficiency of a-cleavage reaction of cyclobutanone is ten times more than the cyclopentanone due to the angle strain. Angle strain and steric strain increases the efficiency of a-cleavage. The photochemistry of a-cleavage of cyclobutanone differs significantly from the photochemistry of a-cleavage of other cyclic ketones.

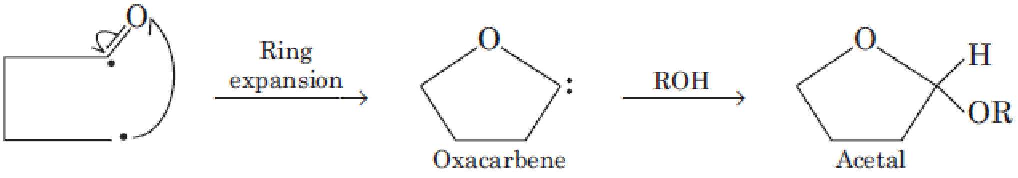
Unlike other ketones, cleavage occurs from S_1 ($n \rightarrow \pi^*$) and leads to the formation of a 1, 4-acylalkyl diradical. There are three following different pathways for stabilisation of the diradical:
(*i*) Loss of carbon monoxide and formation of 1, 3-diradical that undergoes either recombination to cyclopropane or an hydrogen abstraction to form propene.



(*ii*) By a subsequent b-cleavage and formation of ethylene and ketene.



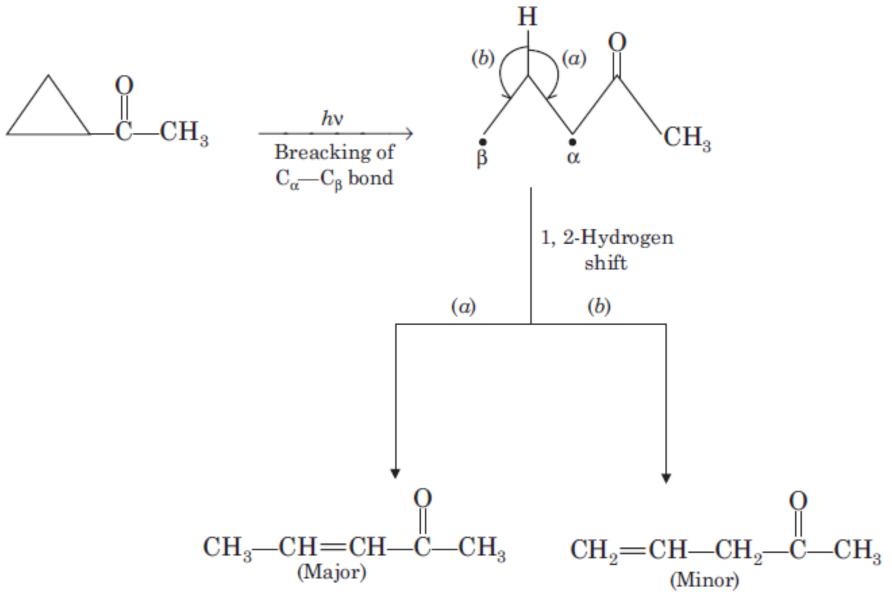
(*iii*) 1, 4-Acyl-alkyl biradical can undergo ring expansion by rebonding to oxygen to give **oxacarbene.** This carbene can be trapped by polar protic nucleophile solvents. The over all reaction is a ring expansion.



β-Cleavage reaction

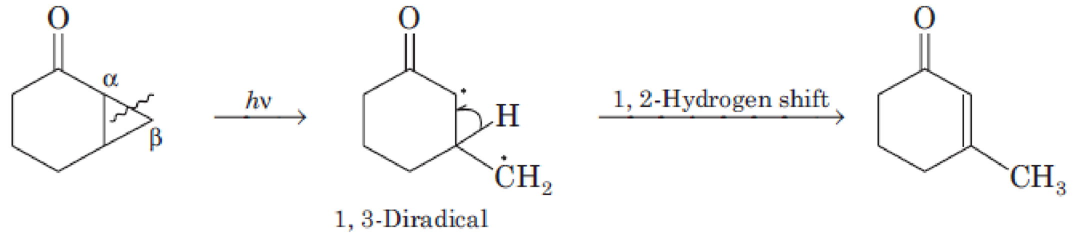
Some class of compounds have relatively weak C_α—C_β bonds which can undergo cleavage as a result of electronic excitation of the carbonyl group. Cyclopropyl ketones are one such class, and evidence for interaction between the carbonyl and cyclopropyl groups, which provides a mechanism by which energy may be transferred from the carbonyl group to the bond which is broken, is found in the UV spectrum.

The mechanism of the reaction has been shown to involve the formation of a biradical intermediate. Photolysis of acetyl cyclopropane leads to cleavage of the cyclopropane ring, and this is followed by a hydrogen shift.

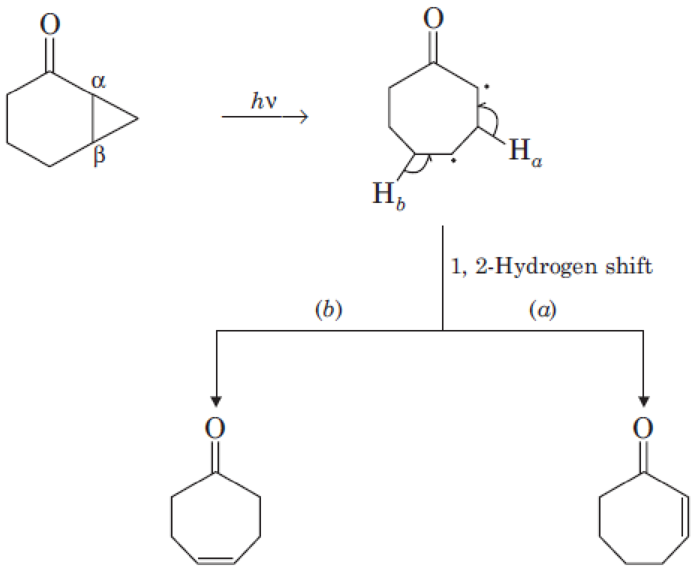


In a similar way, bicyclo [4, 1, 0] heptane-2-ones undergo cleavage of one of the cyclopropyl C—C bonds.

(*i*)

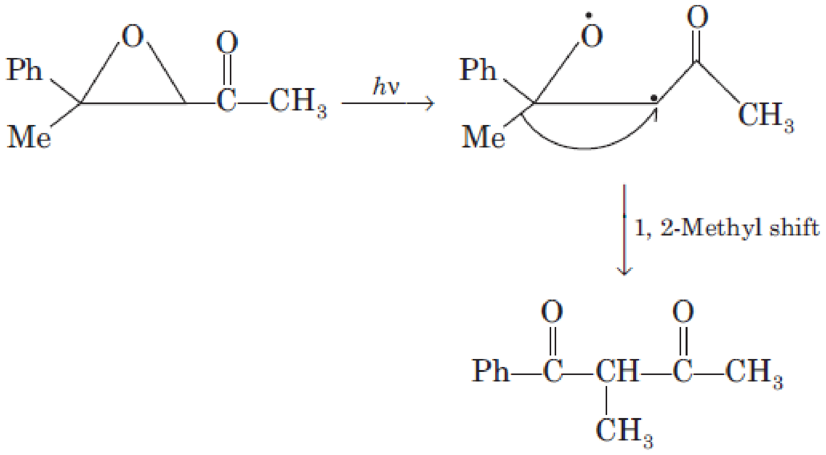


(ii)

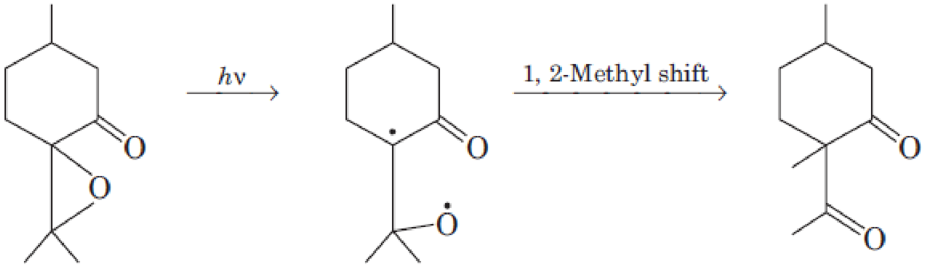


α, β-Epoxy ketones have also a relatively weak Cα—Cβ bond which can be cleaved in the excited state. Epoxy ketone reacts by way of b-cleavage and alkyl migration on photolysis. Mechanistically this reaction arises from a singlet $n\pi^*$ state and result is the fission of the C—O bond. The migratory aptitudes shown within such compounds is best explained *via* the involvement of a biradical species formed by C—O bond fission. Some examples are:

(i)

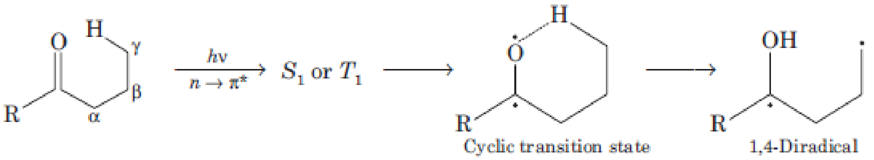


(ii)



Intramolecular and intermolecular hydrogen abstraction (γ-Hydrogen abstraction)

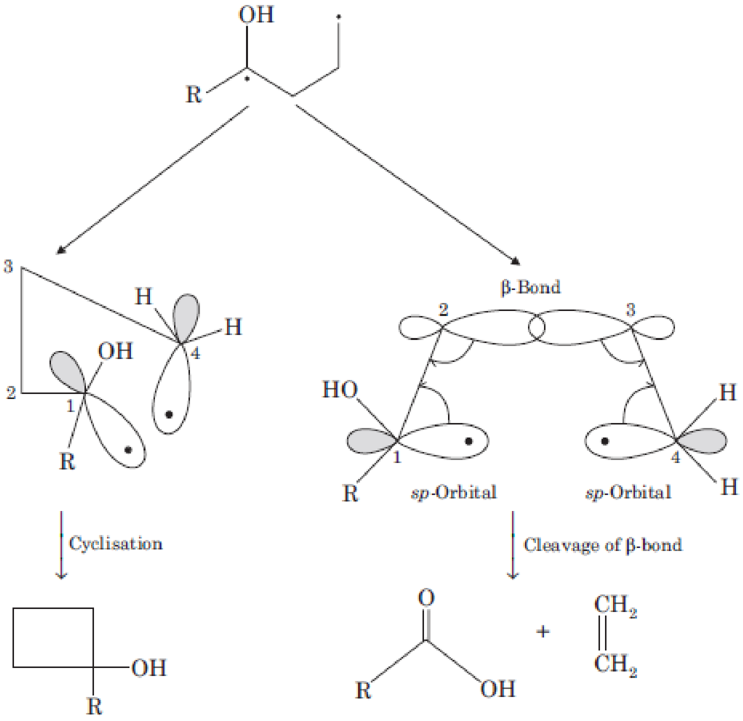
1, 3 (*n*, π*) excited carbonyl compounds having an accessible hydrogen atom in the γ-position undergo a characteristic 1, 5-hydrogen atom transfer by an intramolecular cyclic process with the formation of ketyl like 1, 4-diradical.



Depending on the conformation of the initially formed 1, 4-diradical, two different pathways to stabilisation are possible:

(*i*) If only the *sp*-orbitals of the radical centres can overlap, a cyclobutanol is the product.

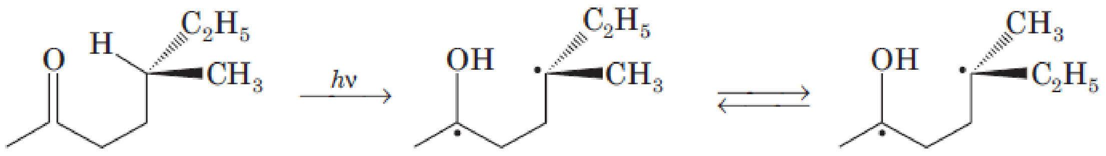
(*ii*) If the *sp*-orbitals of the radical centres are parallel to the β-bond, they participate in the formation of two double bonds (one in the enol and one in the alkene), a result of the cleavage of the β-bonds.



The second process of this reaction is known as Norrish Type II process which leads the formation of alkene and alkenol.

Although the reaction occurs from both the singlet and the triplet states of *n*, π* transition, the quantum yields from the singlet state are generally lower than the triplet state. In case of aryl-alkyl ketones, the reaction occurs only with the triplet state because aromatic ketones can undergo rapid intersystem crossing. Solvents also affect the efficiency of the reaction. The singlet state reactions are unaltered in the presence of polar solvents. Polar solvents such as alcohol, on the other hand, enhance the reaction from the triplet state.

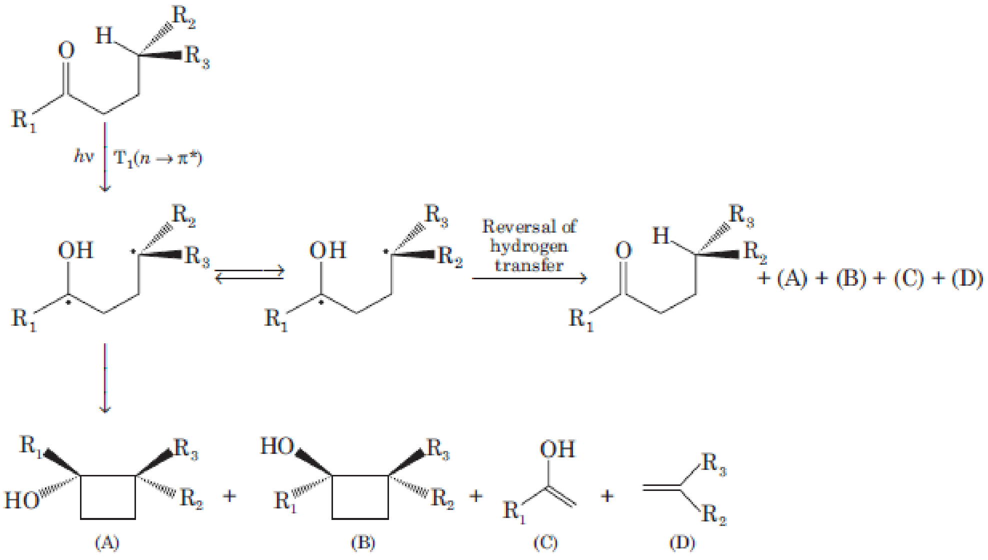
The quantum yield of the reaction is poor since radiationless deactivation from the S_1 and T_1 states and reversal of the hydrogen transfer can compete with reactions proceeding to products. The reversal process is confirmed by using the optical active ketone (1) having a chiral γ-carbon. Ketone (1) undergoes racemisation. Racemisation reaction confirmed that the reaction intermediate is 1, 4-diradical. This also confirmed the back transfer of hydrogen atom.



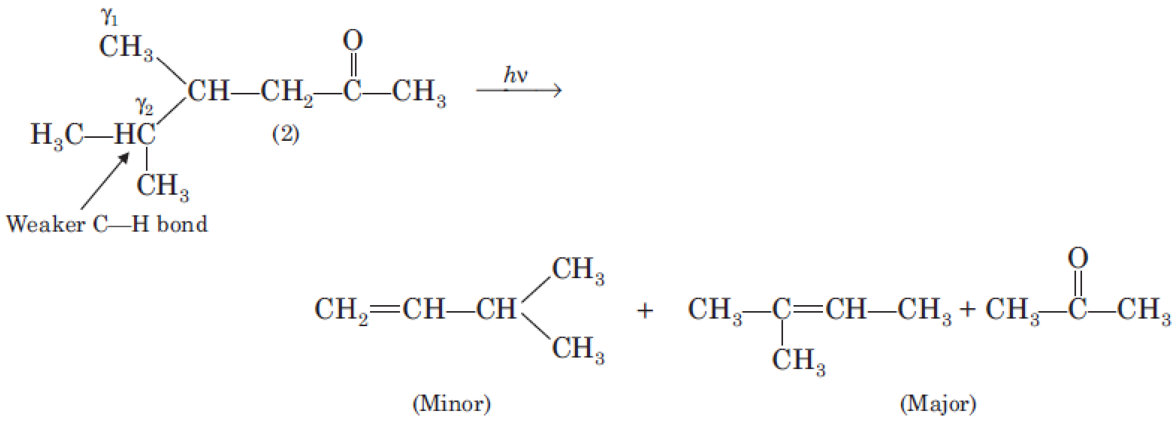
(1)

Back transfer of hydrogen atom *i.e.*, photoracemisation can be quenched by the addition of 1, 3-cyclopentadiene. This quenching experiment confirmed the formation of triplet state.

Participation of a 1, 4-diradical intermediate in the Norrish Type II reaction has been confirmed by trapping experiments and spectroscopic techniques. Formation of 1, 4-diradical has also been proven chemically. Photoracemisation of a ketone with a γ-chiral carbon atom and loss of the chirality in the product was observed.



When a molecule has two γ-carbons both having hydrogens, transfer of hydrogen in the Norrish Type II process is marked by a preference of cleavage of the weaker carbon-hydrogen bond as in case of ketone (2).



Intramolecular hydrogen abstraction is not possible if γ-carbon has no hydrogen.

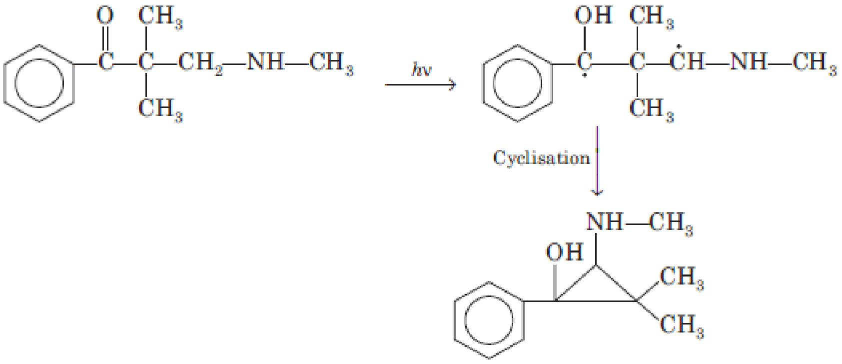
Hydrogen abstraction from other sites

While the normal reaction path of Norrish Type II process involves a six-membered cyclic transition state, alternative reaction paths are fairly common. In these cases either larger or small transition states provide diradicals which cannot fragment. Alternative routes are possible when γ-carbon has no hydrogen or biradical is stabilised by hetero atoms.

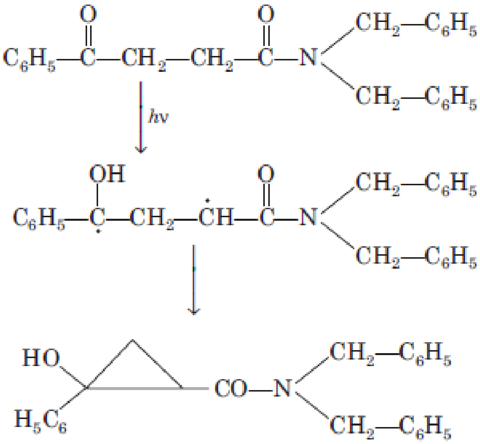
β-Hydrogen abstraction

β-Hydrogen abstraction can only be possible if substrate has no γ-hydrogen and the biradical is stabilised by the presence of hetero atoms.

(i)



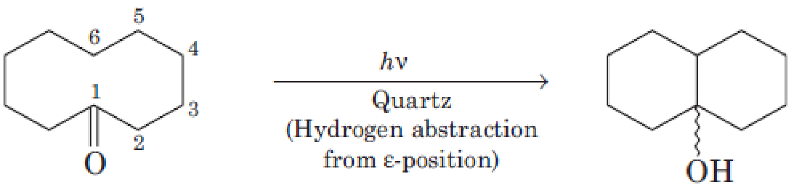
(ii)



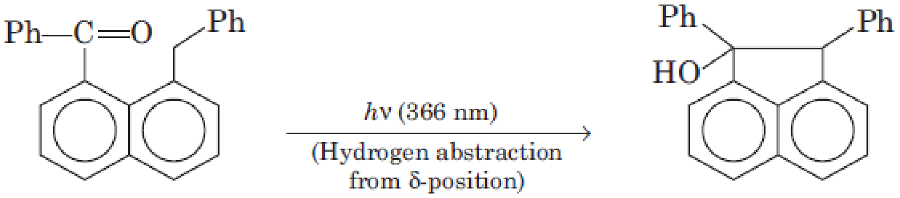
δ-and ε-Hydrogen abstraction

Intramolecular γ-hydrogen abstraction by an excited carbonyl oxygen is approximately 20 times faster than δ- and ε-hydrogen abstraction. Nevertheless, the tendency of the half-occupied *n*-orbital of the carbonyl oxygen to abstract a hydrogen atom from other position is considerable.

A necessary condition is the planarity of the transition state. An important example of this class is cyclodecanone. In this case intramolecular hydrogen abstraction takes place from C-6.

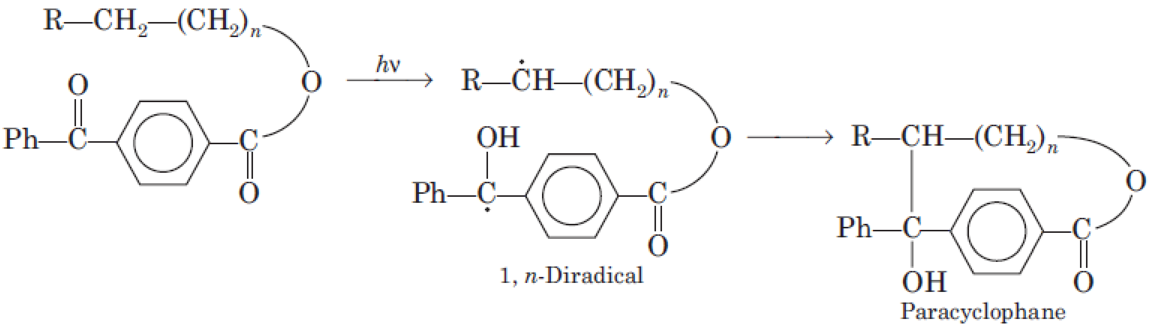


There are other systems where hydrogen abstraction through a six-membered cyclic transition state is not possible because there is no suitable placed hydrogen atom 1-(8-benzylnaphthyl)-phenyl ketone is such a compound.



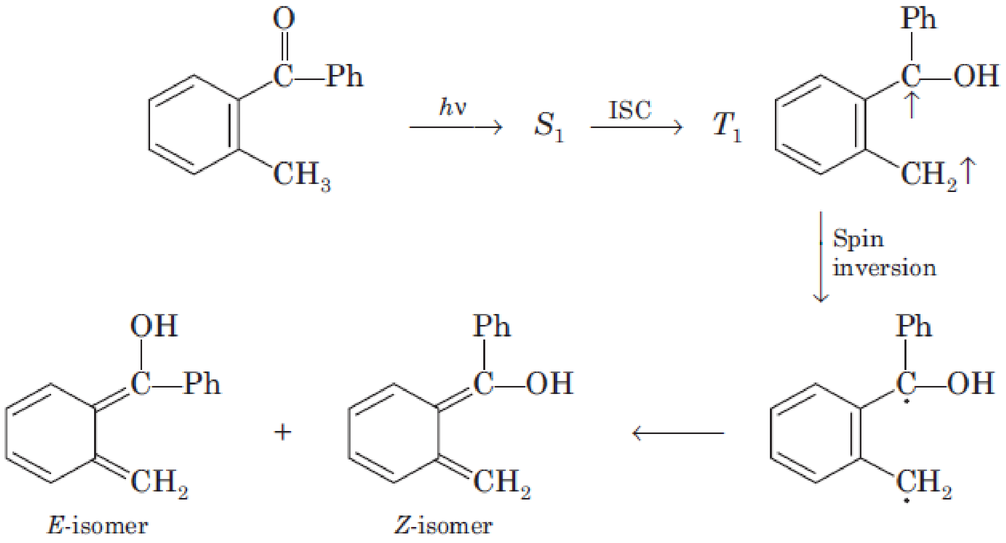
Hydrogen abstraction from distant sites

In the photolysis of alkyl esters of benzophenone-4-carboxylic acid, the planar transition state is possible only for ≥ 10, which leads to the formation of a ≥ 1, 18 biradical whose recombination produces a paracyclophane.

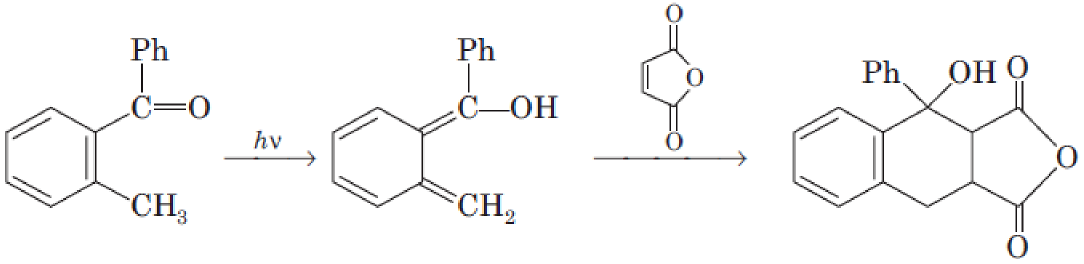


Formation of photoenols or photoenolization

The formation of photoenols arises by Norrish Type II process in *ortho* substituted aryl ketones and are produced by the following mechanism:



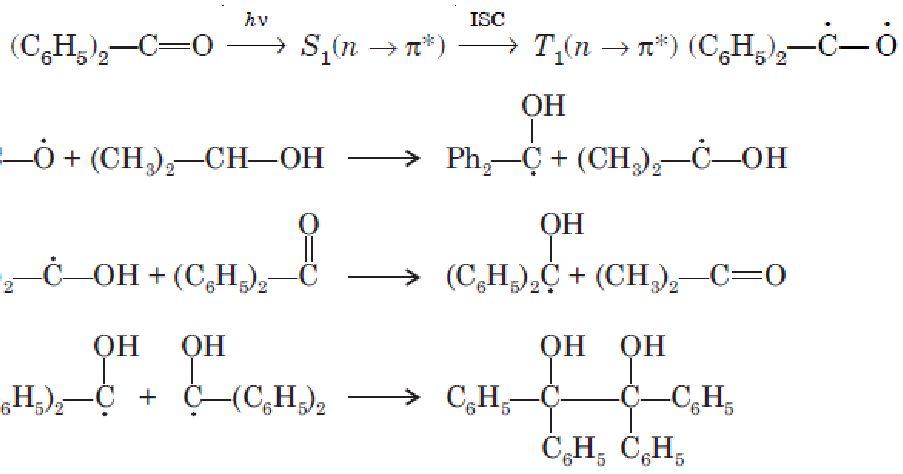
The photoenolisation can be quenched by molecular oxygen. This confirmed the formation of triplet biradical. The product of the reaction behaves as diene for Diels-Alder addition. Thus photoenols can be trapped by addition of dienophile.



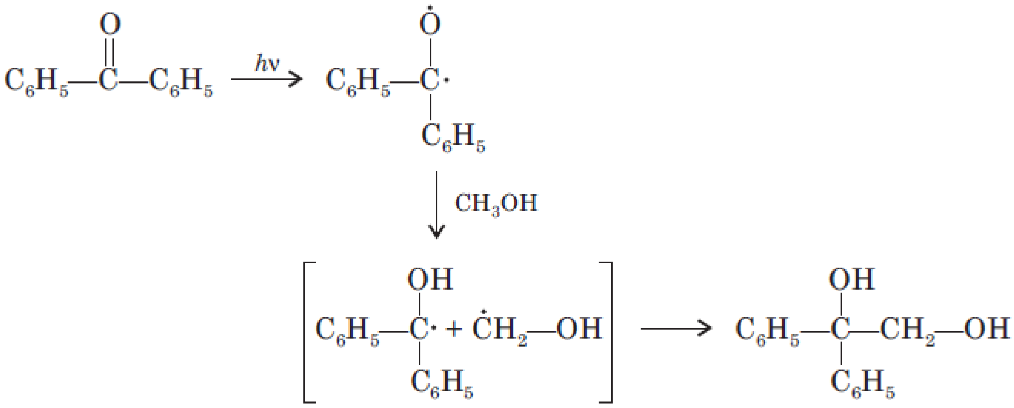
Intermolecular hydrogen transfer: intermolecular photo reduction

Photo reduction of carbonyl compounds is one of the best known of photo reactions. In its initial steps the mechanism involves transfer of a hydrogen atom to the oxygen atom of the carbonyl excited state from a donor molecule which may be solvent, an added reagent or ground state molecule of reactant. Ketone undergoes photo reduction in the presence of a variety of hydrogen atom donor. Hydrogen atom donors are secondary alcohol, toluene and cumene. This reaction is bimolecular reaction.

(i)



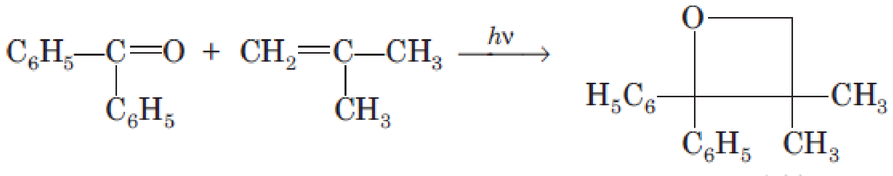
(ii)



This reaction takes place when concentration of benzophenone is very small (10^{-4} m).

Photocycloaddition reaction (Paterno-Büchi reaction)

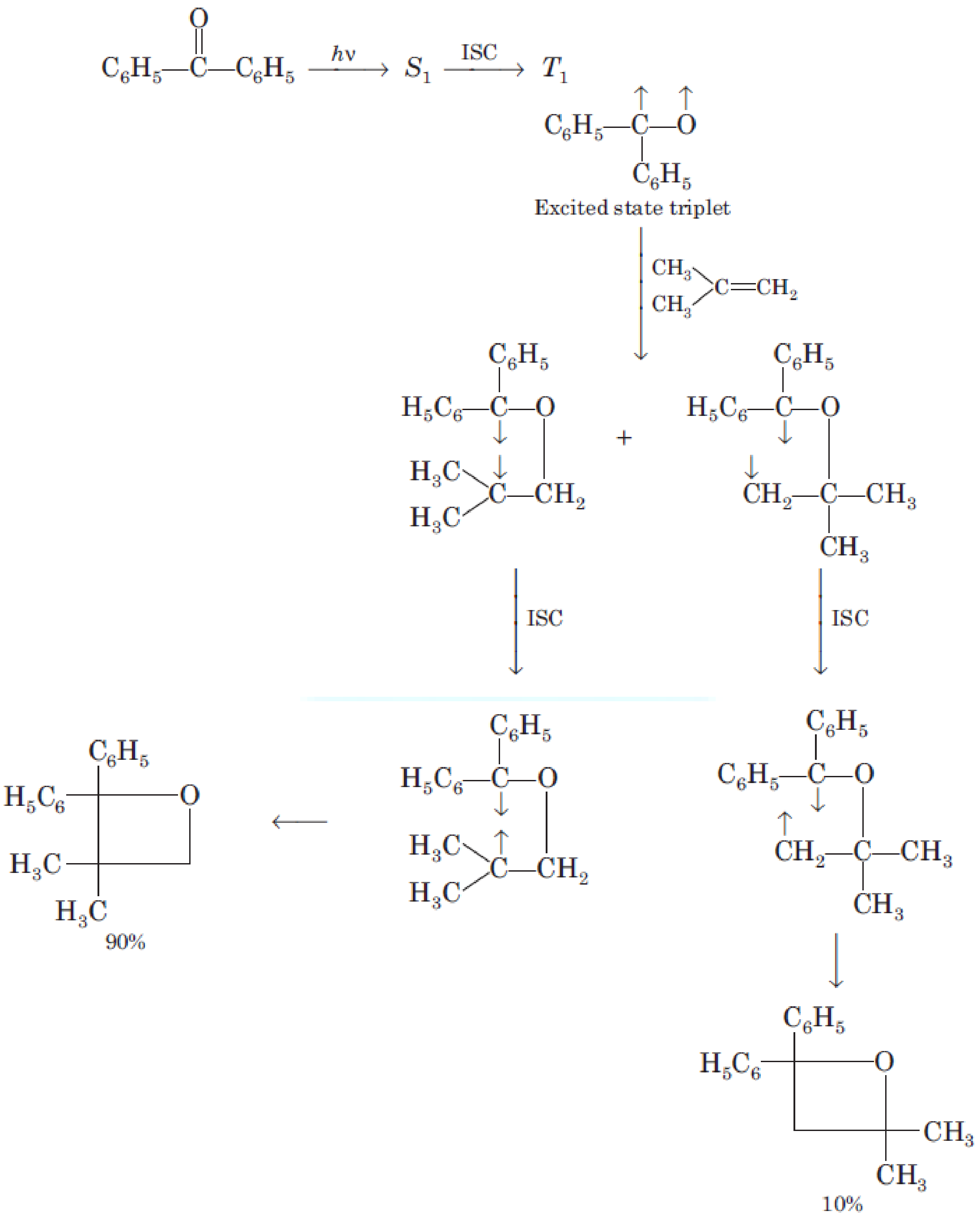
One of the first photocycloaddition reactions to be studied was the formation of oxetanes from addition of carbonyl compounds to alkenes. This reaction is known as the Paterno-Büchi reaction. For example, benzophenone with isobutene gives a high yield of an oxetane.



Paterno-Büchi reaction can be studied under two categories and the categories depend on the nature of alkenes.

Addition to electron-rich alkene

Mechanistic studies have shown that the reaction pathway varies according to the type of carbonyl compound and alkenes involved. Addition of simple aliphatic or aromatic ketones to electron rich alkenes involves attack on ground state alkene by the *n* →π* triplet state of the carbonyl compound in a non-concerted manner, giving rise to all possible isomers of the oxitane. The reaction is non-concerted because the reactive excited state is a triplet state. The initial adduct of this reaction is a triplet 1, 4-diradical, which must undergo spin inversion before product formation is complete. Stereospecificity is lost if the intermediate 1, 4-diradical undergoes bond rotation faster than ring closure (Scheme 8).



Scheme 9

Although the reaction is not stereospecific, there is a preference for one orientation of addition, which can be rationalised in terms of initial attack on the alkene by the oxygen atom of the excited carbonyl group to give a biradical intermediate. The existance of biradicals has been confirmed by picosecond spectroscopy. The more energetically stable of the two possible biradicals is formed more readily. Thus reaction is regioselective reaction. The consideration of biradical stability is certainly applicable to the prediction of the major product of the cycloaddition.

Two important rules for the successful synthesis of oxitanes have been put forward. These rules are as follows:

(*i*) Only carbonyl compounds with a low-lying $n \rightarrow \pi^*$ state will form oxitanes.

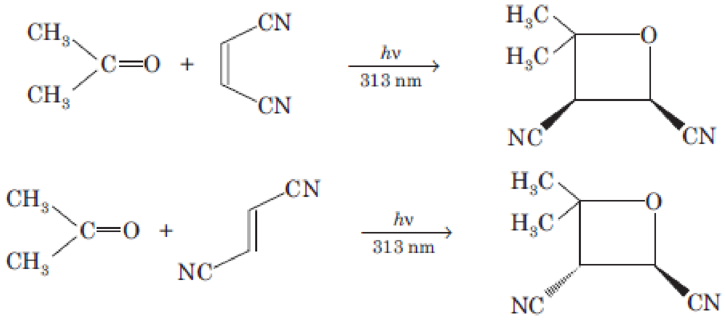
(*ii*) The energy of the carbonyl excited state must be less than that of the alkene to prevent energy transfer from the carbonyl excited state to the alkene.

As far as the addition of aromatic carbonyl compounds is concerned only the triplet state is reactive (because inter system crossing is very efficient in case of aromatic ketones) and consequently a triplet biradical intermediate is produced.

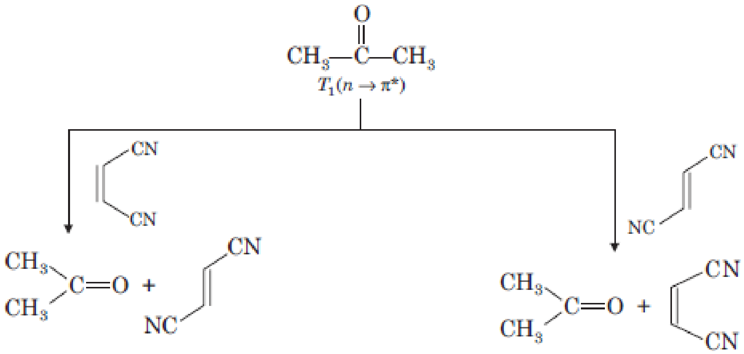
The reaction of alkyl ketones can be complicated by the less efficient inter system crossing thus permitting reaction of both the singlet and the triplet state. Both singlet and triplet state show equal reactivity for the reaction. The singlet state reaction obtained at high concentration of the alkene. On the other hand triplet state reaction obtained at low concentration of the alkene.

Addition to electron deficient alkenes

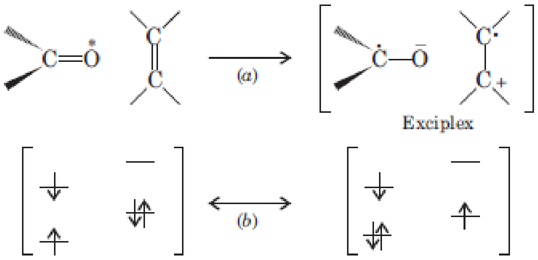
Photocycloaddition of aliphatic ketones to electron-deficient alkenes, particularly dicyanoethene, involves addition of singlet state ($n \rightarrow \pi^*$) excited ketone to ground state alkene. The reaction is stereospecific and the stereochemistry of the alkene is retained in the product oxitane.



The course of the photocycloaddition of electron-deficient alkenes to ketones follows certain rules. While oxitanes are formed only from $S1(n, \pi^*)$ state, the $T1(n, \pi^*)$ state stereo specifically sensitises the *cis-trans* isomerisation of electron-deficient alkenes and does not lead to oxitanes.



Stereospecificity of the oxitane formation with electron-deficient alkenes can be explained as follows:
It is suggested that in case of electron-deficient alkenes, oxitane formation takes place *via* formation of exciplex. Exciplex formation takes place between the singlet excited state of ketone and ground state of alkene. Exciplex is stabilised by charge transfer as well as energy transfer between the constituent molecules.

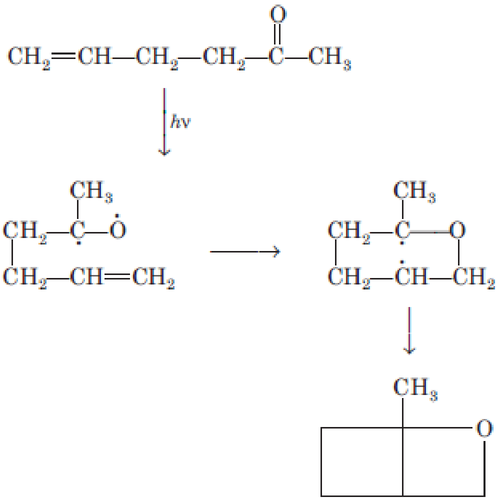


(*a*) Formation of an exciplex between a carbonyl excited state and an olefin ground state
(*b*) Charge transfer interaction in the formation of the carbonyl-olefin exciplex.

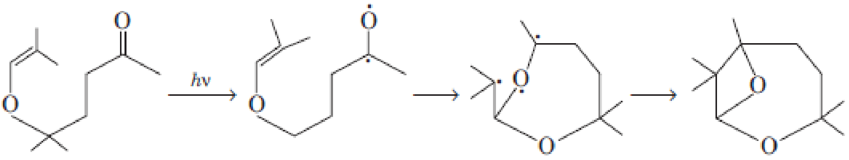
Intramolecular Paterno-Büchi reaction

Intramolecular Paterno-Büchi reaction is mainly given by γ–δ-enones. The efficiency of these reactions can be attributed to the rapid rate of intraction between the excited C O group and the ground C C group. This combination of substrates allows the formation of one regioisomer.
Thus yields are high and there is usually no byproduct(*s*). This reaction is highly efficient and versatile method for the synthesis of variety of compounds that are difficult or impossible to prepare by other methods.

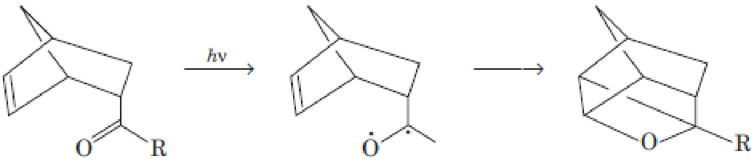
(i)



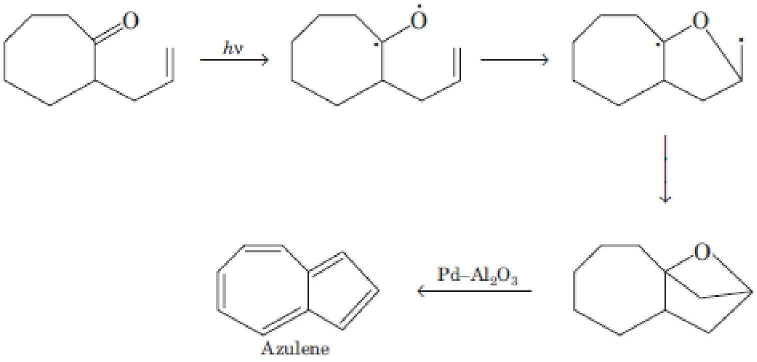
(ii)



(iii)



One of the most important reaction of this class is the preparation of azulene as follows:



Pericyclic reactions

- Pericyclic reactions are "**concerted reactions**" that have a cyclic transition state, in these reactions, electrons in one reactant or more are reorganized in a cyclic manner.
- A concerted reaction is a single step reaction in which a reactant is converted into the product without the intervention of an intermediate; here, bond breaking and bond making occur synchronously, though not necessarily symmetrically.

General characteristics of pericyclic reactions

Pericyclic reactions have the following general characteristics.

1. They do not involve any ionic or radical intermediate.

2. They take place in a single concerted step, i.e., bond breaking and bond formation are simultaneous.

3. They involve a ring of electrons moving around in a closed loop, and occur through cyclic transition states.

4. They are initiated by heat (thermolysis) or light (photolysis) and do not need any other reagent or chemical species.

5. They are highly stereospecific, i.e., these reactions involve a precise control of stereochemistry.

6. They are insensitive to the presence or absence of solvents and catalysts.

7. They are not influenced by structural changes within the molecule.

8. They are generally reversible in nature.

9. They are exhibited by unsaturated compounds.

Influence of thermal and photochemical conditions on pericyclic reactions

- The activation energy for the single transition state of a concerted pericyclic reaction may be provided by heat (thermal induction) or by ultraviolet light (photochemical induction).
- Some pericyclic reactions proceed only thermally while certain others proceed only photochemically.
- However, some of them occur under both thermal and photochemical conditions; the most remarkable observation about such reactions is that thermal and photochemical processes yield products with differing stereochemistry.
- In other words, for a pericyclic reaction that can take place under both thermal and photochemical conditions, the configuration of the product formed under thermal

conditions is different from the configuration of the product formed under photochemical conditions.

Types of pericyclic reactions

Pericyclic reactions include three different families of reactions, namely:

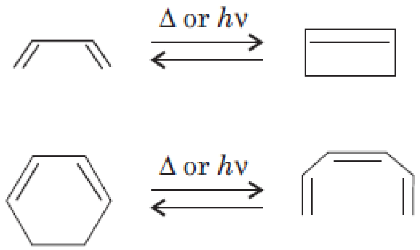
(1) Electrocyclic reactions,

(II) Cycloaddition reactions, and

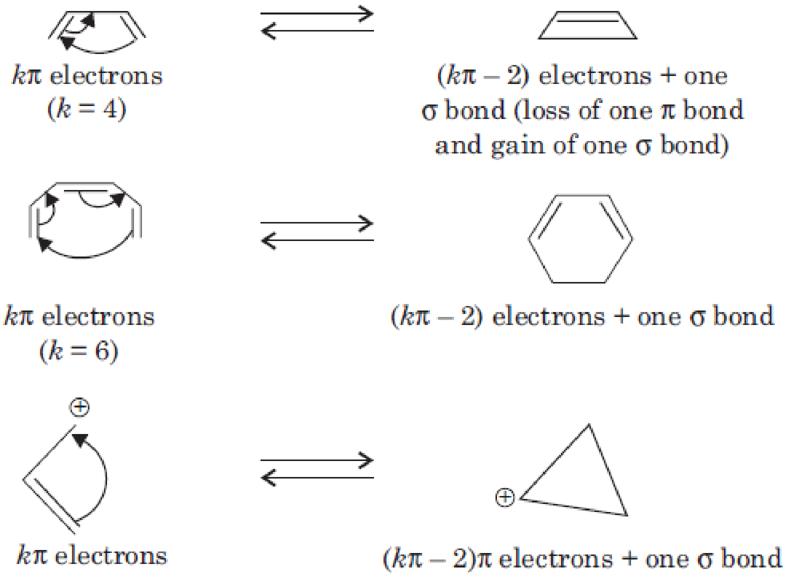
(III) Sigma tropic rearrangement reactions.

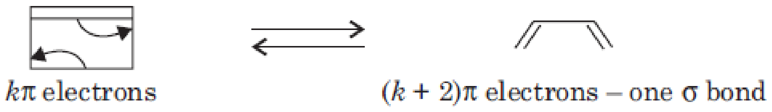
(I) ELECTROCYCLIC REACTIONS

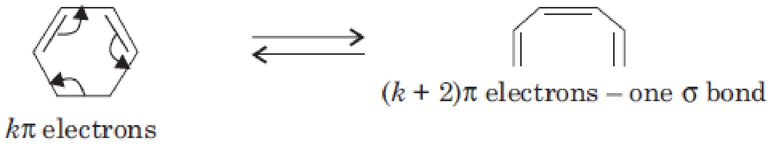
An electrocyclic reaction is the concerted interconversion of a conjugated polyene and a cycloalkene. Electrocyclic reactions are induced either thermally or photochemically.



All electrocyclic reactions are reversible reactions. Open-chain partner of the reaction is always conjugated system whereas cyclic partner may or may not contain conjugated system. In electrocyclic reactions either a ring is formed with the generation of a new σ bond and the loss of a π bond (*i.e.*, gain of one σ bond and loss of one π bond) or ring is broken with the loss of one σ bond and gain of one π bond.







Thus electrocyclic reactions can be classified into two categories:

(*i*) Electrocyclic opening of the ring, and

(*ii*) Electrocyclic closure of the conjugated system.

In electrocyclic closure of the ring (or ring closing electrocyclic reaction) if the π system of the open-chain partner contains *k*π electrons, the corresponding cyclic partner contains (*k* – 2)π electrons and one additional σ bond. In ring opening electrocyclic reaction if ring partner contains *k*π electrons, the open chain partner will contain (*k* + 2)π electrons with the loss of one σ bond.

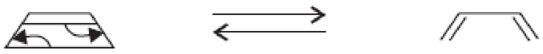
There are two possible stereochemistries for the ring-opening and ring-closing of electrocyclic reactions. They are:

1. Conrotatory process (or motion), and
2. Disrotatory process (motion).

Conrotatory and disrotatory motions in ring opening reactions

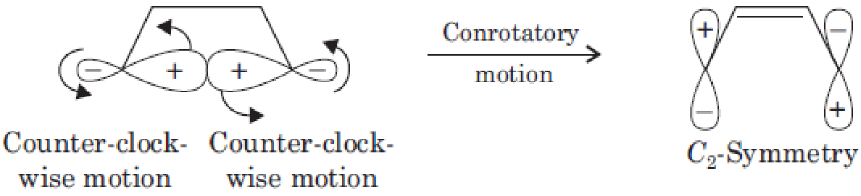
The most common example of the ring opening reaction is the conversion of cyclobutene to 1, 3-butadiene.

This conversion can only be possible if a σ (*sigma*) bond between *C*3—*C*4 of cyclobutene must break during the course of the reaction.



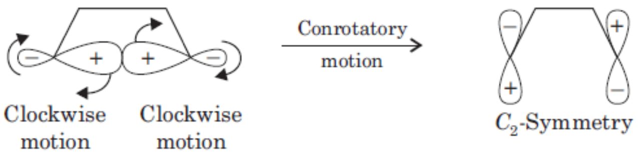
Ring opening reaction

This σ (*sigma*) bond may break in two ways. *First*, the two atomic orbital components of the σ (*sigma*) bond may both rotate in the same direction, clockwise or counter-clockwise. This process is known as **conrotatory motion**.



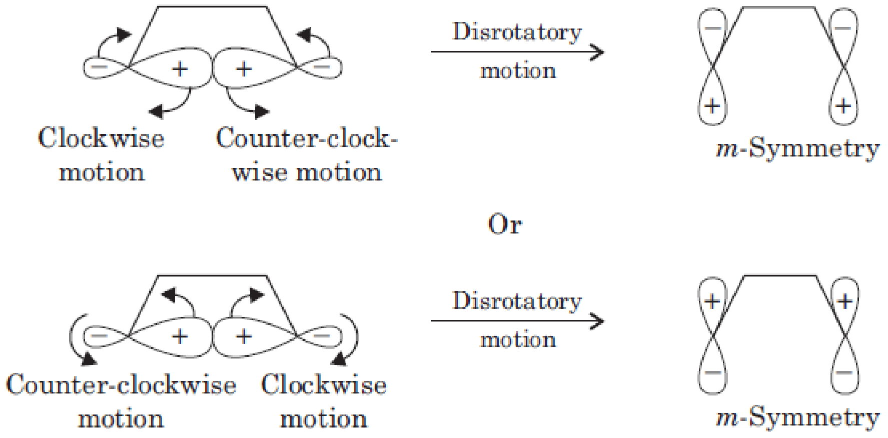
Second, the atomic orbitals may rotate in opposite directions, one clockwise and the other counter-clockwise. This process of ring-opening is known as **disrotatory motion.**

Or



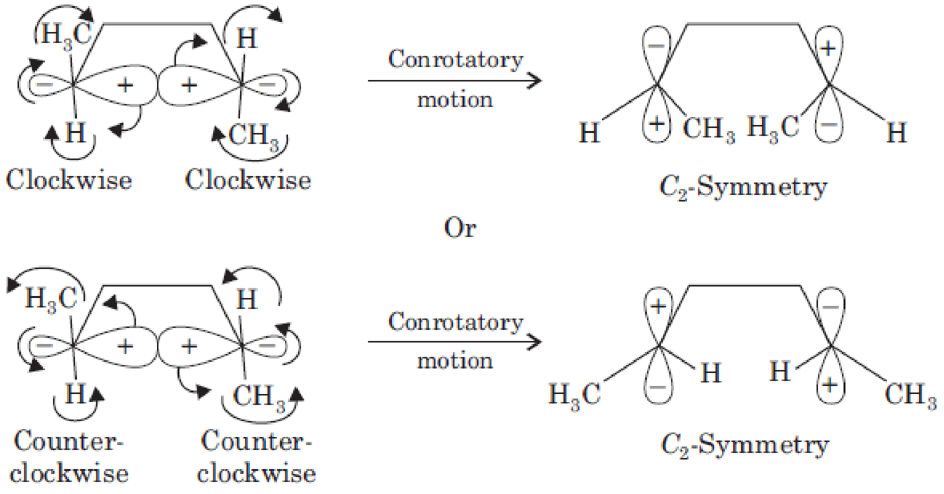
Conrotatory ring-opening

Second, the atomic orbitals may rotate in opposite directions, one clockwise and the other counter-clockwise. This process of ring-opening is known as **disrotatory motion**

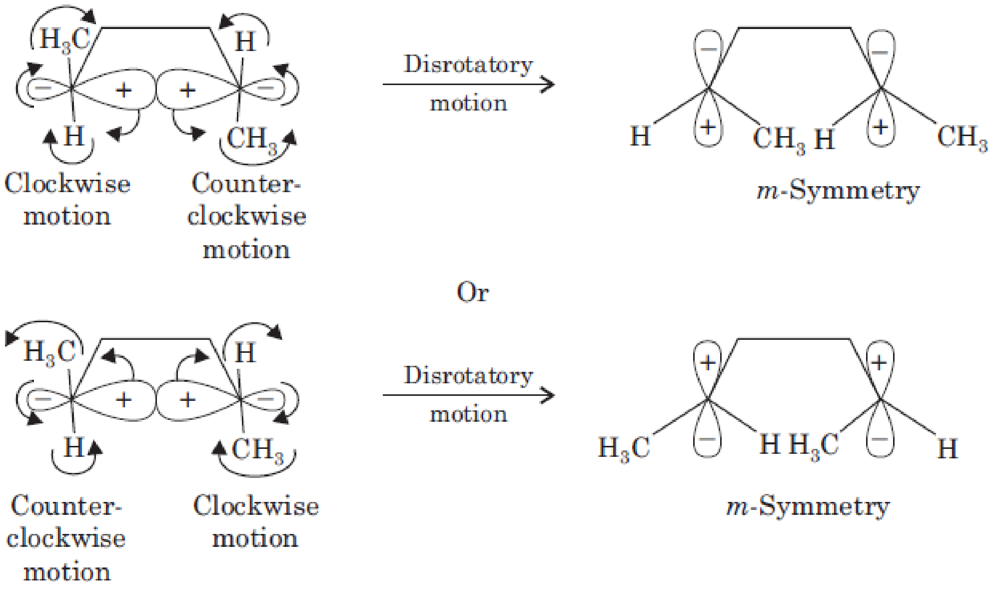


Disrotatory ring-opening

The substituents present on the carbons of the rotating orbitals may also rotate in the direction of the rotating orbitals. Thus in the conrotatory motion substituents rotate in the same direction and in disrotatory motion substituents rotate in the opposite directions.



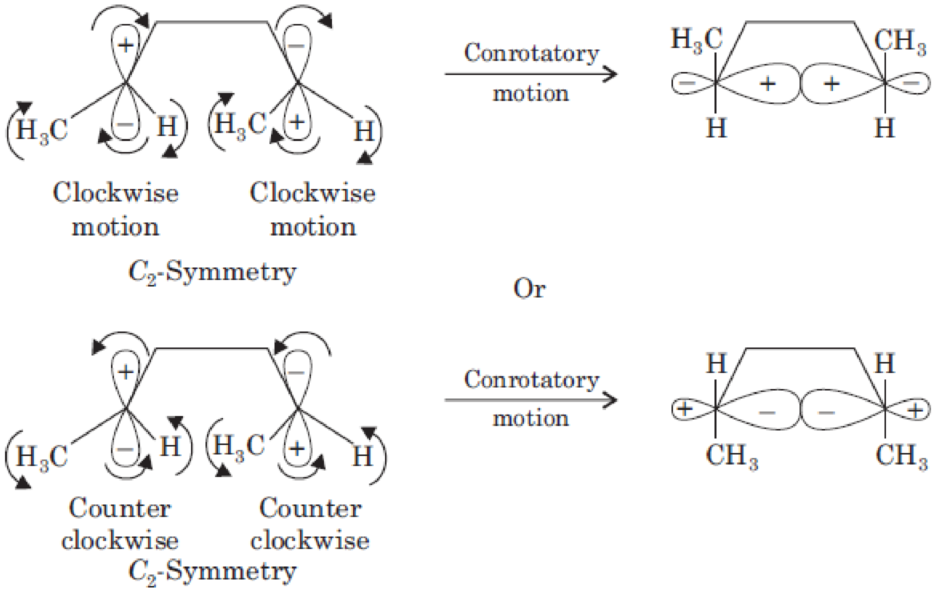
Conrotatory ring-opening, orbitals and groups migrate in the same direction



Disrotatory ring-opening, orbitals and groups migrate in the opposite directions

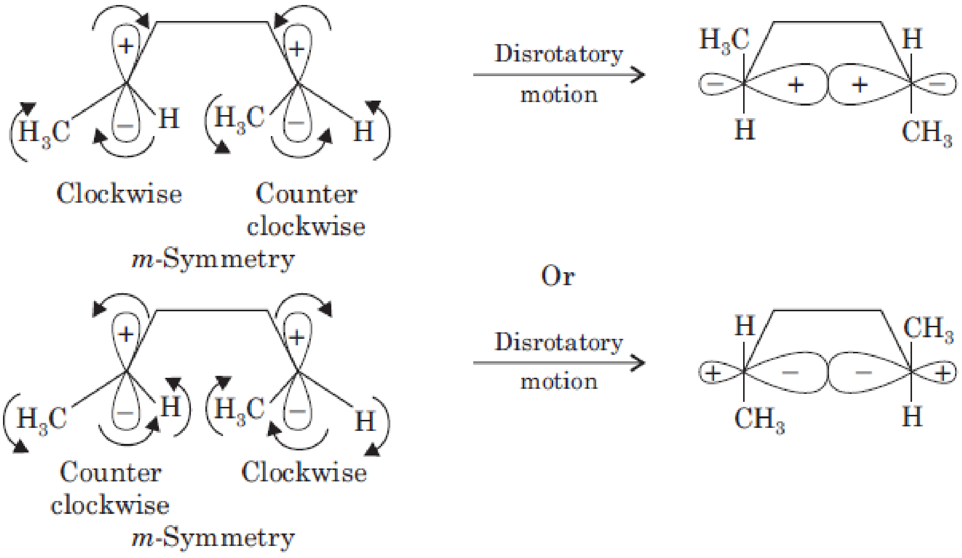
Conrotatory and disrotatory motion in ring – closing reactions

When an electrocyclic reaction takes place, the carbon at each end of the conjugated π system must turn in a concerted fashion so that the *p* orbitals can overlap (and rehybridised) to form σ bond that closes the ring. This turning can also occur in two stereochemically distinct ways. In a conrotatory closure the orbitals and groups of the two carbon atoms turn in the same direction, clockwise or counter-clockwise.



Conrotatory closure of the ring

In a disrotatory closure the orbitals and groups of the two carbon atoms turn in the opposite direction, one clockwise and other counter-clockwise.



Disrotatory ring-closure

From these examples it is clear that **orbitals having *m*-symmetry always give disrotatory motion.** Whereas **orbitals having C_2-symmetry give conrotatory motion**.

The reason behind this rule can be easily understood by recalling that overlap of wave functions of the same sign is bonding (and symmetry allowed reaction) whereas overlap of wave functions of opposite sign is antibonding (and symmetry forbidden process).

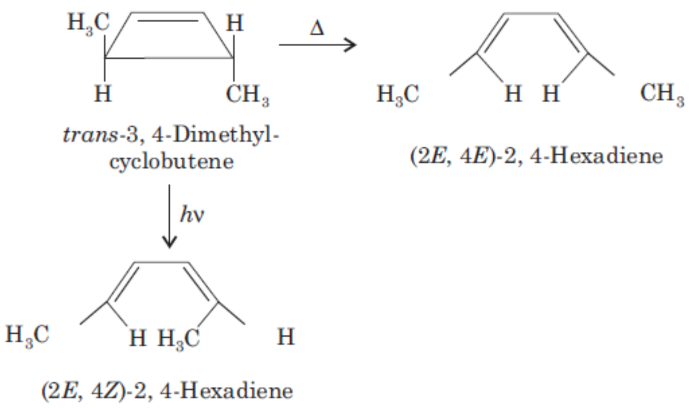
Electrocyclic reactions are highly stereospecific. An intriguing feature about electrocyclic reactions is that the stereochemistry of the product is dependent on whether the reaction is thermally **induced or photo-induced.**

Open chain conjugated system having 4nπ conjugated electrons

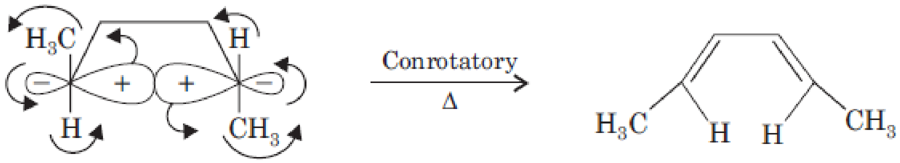
Let us consider the simplest example in which a cyclobutene derivative opens to a 1, 3-butadiene derivative, *i.e.*, open-chain conjugated system has **4*n* conjugated π electrons.**

In thermal condition *trans*-3, 4-dimethylcyclobutene gives (2*E*, 4*E*)-2, 4-hexadiene. Thus, this reaction is completely stereospecific.

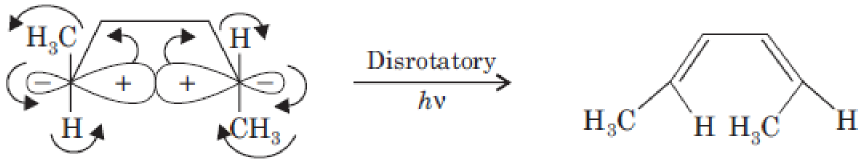
In the photochemical condition the same substrate gives (2*E*, 4*Z*)-2, 4-hexadiene. In this case too, the reaction is completely stereospecific. Thus the reaction can be performed thermally or photochemically, and under either condition the reaction is completely stereospecific.



Stereochemistry of the thermal reaction-1 (of the 4*n*π system) can only be explained if process should be conrotatory.



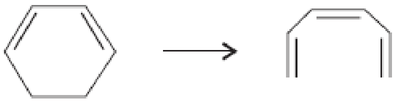
Stereochemistry of the photochemical reaction-2 (of the 4*n*, π system) can only be explained if process should be disrotatory.



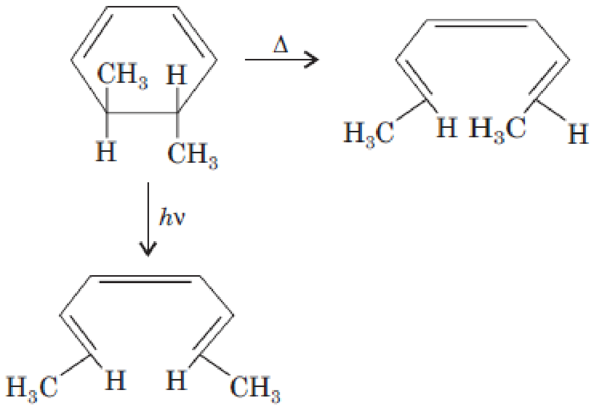
From the above two examples it is clear that **thermally induced electrocyclic reaction involving 4*n*π conjugated electrons require conrotatory motion and photochemically induced electrocyclic reaction require disrotatory motion.**

Open chain conjugated system having (4n+2)π conjugated electrons

The simplest example of this category is the ring-opening of 1, 3-cyclohexadiene into 1, 3, 5-hexatriene.



In thermal condition 5, 6-*trans*-dimethyl-1, 3-cyclohexadiene is converted exclusively to (2*E*, 4*Z*, 6*Z*)-2, 4, 6-octatriene. In the photochemical condition the same substrate is converted exclusively to (2*E*, 4*Z*, 6*E*)-2, 4, 6-octatriene.



These two conversions are also highly stereospecific. Stereochemistry of these two reactions (*i.e.*, reaction-3 and 4) can only be explained if process should be disrotatory in thermal condition and conrotatory in photochemical condition.

On the basis of these experimental results the stereochemistry of electrocyclic reactions can be summarised by noting that thermally induced electrocyclic reactions involving $4n\pi$ electrons require conrotatory motion. Under similar conditions, electrocyclic reactions involving $(4n + 2)$ π electrons follow disrotatory motion. Similarly, photo-induced electrocyclic reactions involving $4n\pi$ electrons require disrotatory motion. Under similar conditions, electrocyclic reactions involving $(4n + 2)$ π electrons follow conrotatory motion.

A summary of the type of motion to be expected from different polyenes under thermal and photochemical conditions is shown in Table

Number of π electrons	*Condition (mode of activation)*	*Motion*
$4n$	(*i*) Thermal (*ii*) Photochemical	Conrotatory Disrotatory
$4n + 2$	(*i*) Thermal (*ii*) Photochemical	Disrotatory Conrotatory

The above experimental results can be explained by the four theories given for pericyclic reactions.

Frontier molecular orbital (FMO) method

A methodology for quickly predicting whether a given pericyclic reaction is allowed by examining the symmetry of the highest occupied molecular orbital (HOMO) (in case of unimolecular reaction) and, if the reaction is bimolecular, the lowest unoccupied molecular orbital (LUMO) of the second partner.

Thus, electrocyclic reaction is analysed by HOMO of the open chain partner because reaction is unimolecular reaction. The stereochemistry of an electrocyclic process is determined by the symmetry of the highest occupied molecular orbital (HOMO) of the open chain partner, regardless of which way the reaction actually runs. In thermal condition

HOMO is always ground state HOMO whereas in photochemical condition HOMO is always first excited state HOMO.

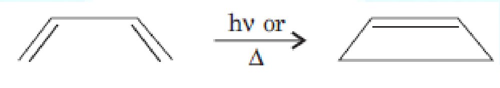
If the highest occupied molecular orbital has *m* symmetry, the process will be disrotatory. On the other hand, if HOMO has *C*2-symmetry then the process will be conrotatory.

Symmetry in HOMO	*Mode of rotation*
m-Symmetry	Disrotatory
C_2-Symmetry	Conrotatory

For any electrocyclic reaction there are two conrotatory and two disrotatory modes of ring cleavage and ring closure. The two conrotatory modes can give same or different products. Similarly, the two disrotatory modes can also give the same or different products.

Cyclisation of 4nπ systems

1. Electrocyclic ring-closure reaction given by butadiene: 1, 3-butadiene is the first member of the conjugated polyene having 4*n*π electrons.



Thermal-induced cyclisation: When 1, 3-butadiene is heated, reaction takes place from the ground state. The electrons that are used for the σ (*sigma*) bond formation are in the HOMO (ψ_2 in this case). Pertinent *p* orbitals in ground state HOMO has C_2-symmetry. For the new σ (*sigma*) bond to form, rotation must be conrotatory. Disrotatory motion would not place the in-phase lobes together.

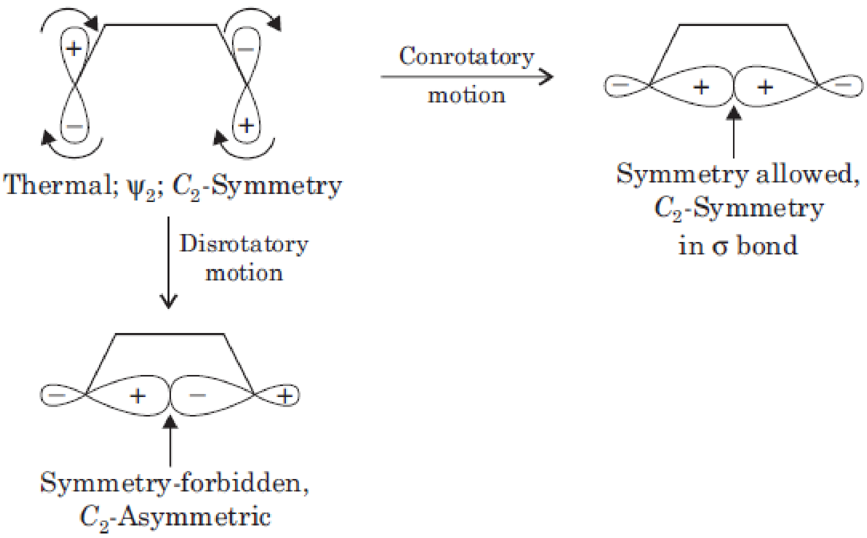
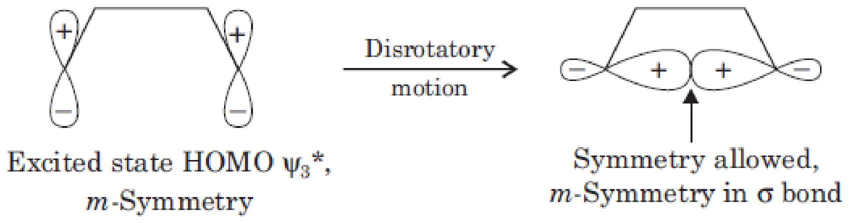
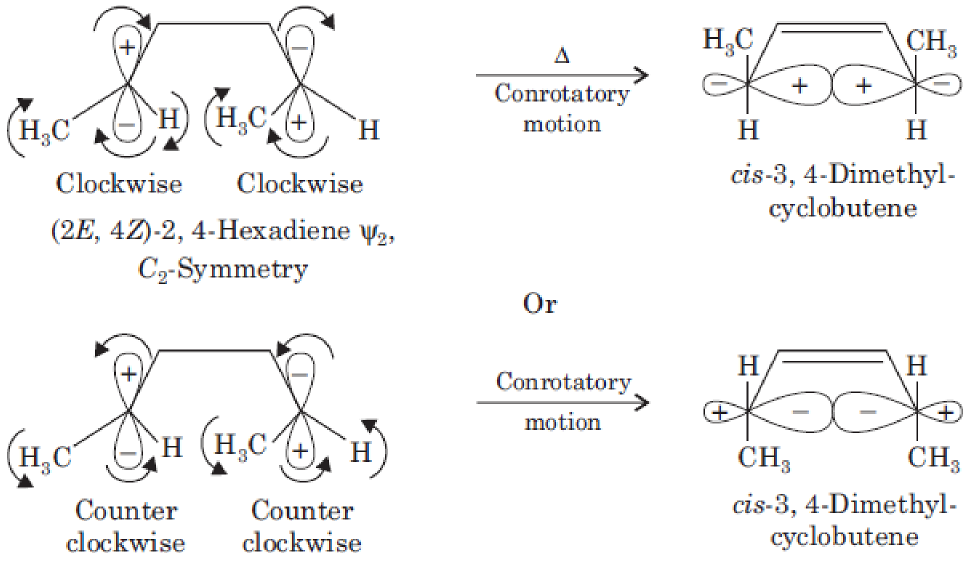


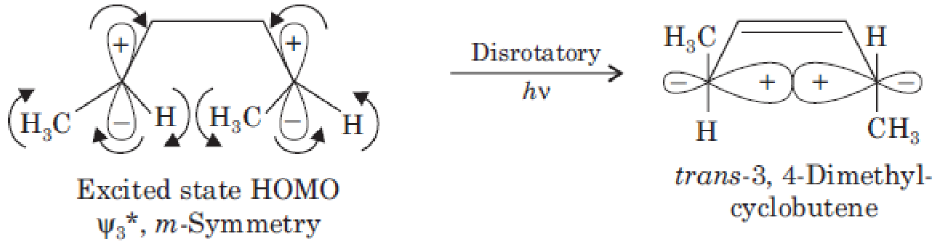
Photo-induced cyclisation: In photo-induced cyclisation, the first excited HOMO of 1, 3-butadiene is ψ3* which has *m* symmetry. For the new σ (*sigma*) bond to form, rotation must be disrotatory.



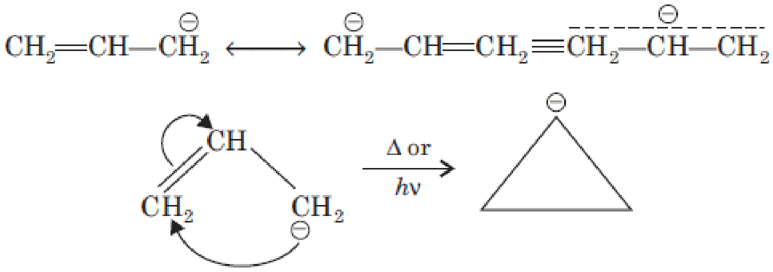
Let us return to (2*E*, 4*Z*)-2, 4-hexadiene to see why the *cis*-3, 4-dimethylcyclobutene results from the thermal cyclisation and the *trans*-isomer from the photo cyclisation. In the case of the thermal cyclisation the ground state HOMO is ψ2 which has C_2-symmetry. Thus, conrotatory motion is required for σ (*sigma*) bond formation. Both methyl groups rotate in the same direction, as a result they end up on the same side of the ring or *cis* is the product.



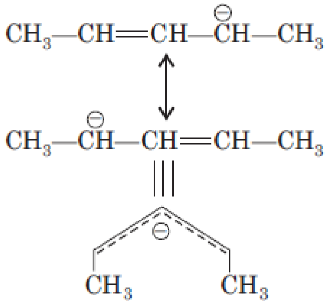
In the case of photocyclisation the excited state HOMO is ψ3* which has *m*-symmetry. Thus, disrotatory motion is required for the σ bond formation. In disrotatory motion, one of the methyl groups, rotates up and the other rotates down. The result is that both methyl groups are *trans* in the product.

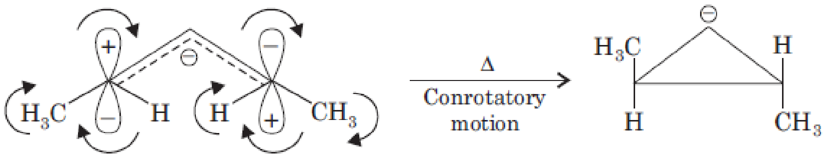


2. Electrocyclic ring-closure given by allyl carbanion: Allyl carbanion is also a 4*nπ* conjugated system.

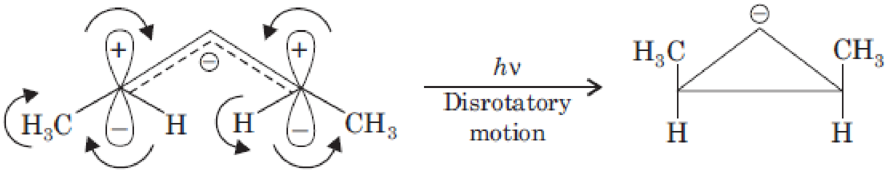


HOMO of the allyl carbanion in the ground state is ψ_2 which has C_2-symmetry. Therefore, conrotatory motion is the mode of cyclisation in the thermal condition.





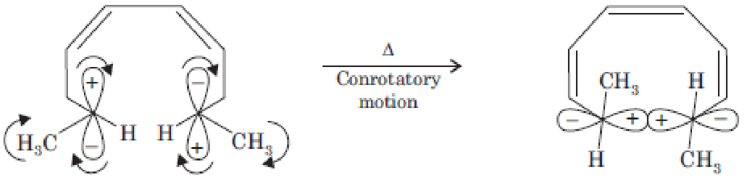
In case of photocyclization, the excited HOMO is ψ_3^* which has *m*-symmetry. Thus, disrotatory motion is required for σ (*sigma*) bond formation.



3. Electrocyclic ring-closure reaction given by 1, 3, 5, 7-octatetraene: 1, 3, 5, 7 octatetraene and its derivatives contain 4*nπ* conjugated electrons.

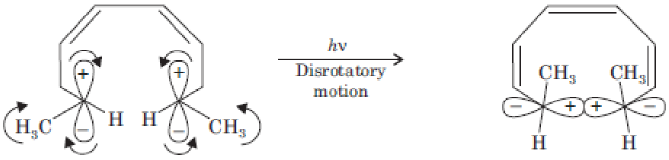
Consider the electrocyclic ring-closure of (2*E*, 4*Z*, 6*Z*, 8*E*)-2, 4, 6, 8-decatetraene in thermal and photochemical conditions.

Thermal-induced cyclisation: The tetraene is a 4*n* polyene. Its ground state HOMO is ψ_4 which has C_2-symmetry. Therefore, conrotatory motion is the mode of cyclisation.



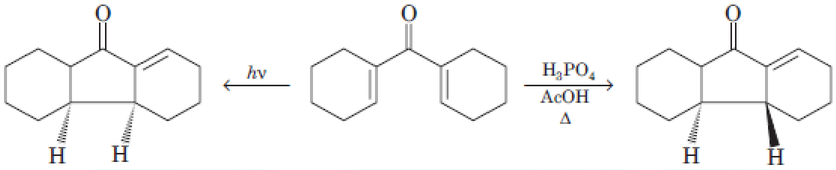
trans-7, 8-Dimethyl-1, 3, 5-cyclotriene

Photo-induced cyclisation: In case of photo-induced cyclisation the excited state HOMO is ψ5* which has *m*-symmetry. Thus disrotatory motion is the mode of cyclisation.

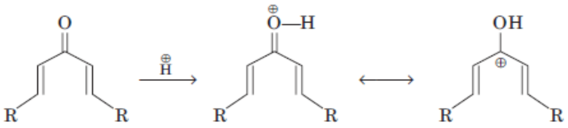


cis-7, 8-Dimethyl-1, 3, 5-cyclooctatriene

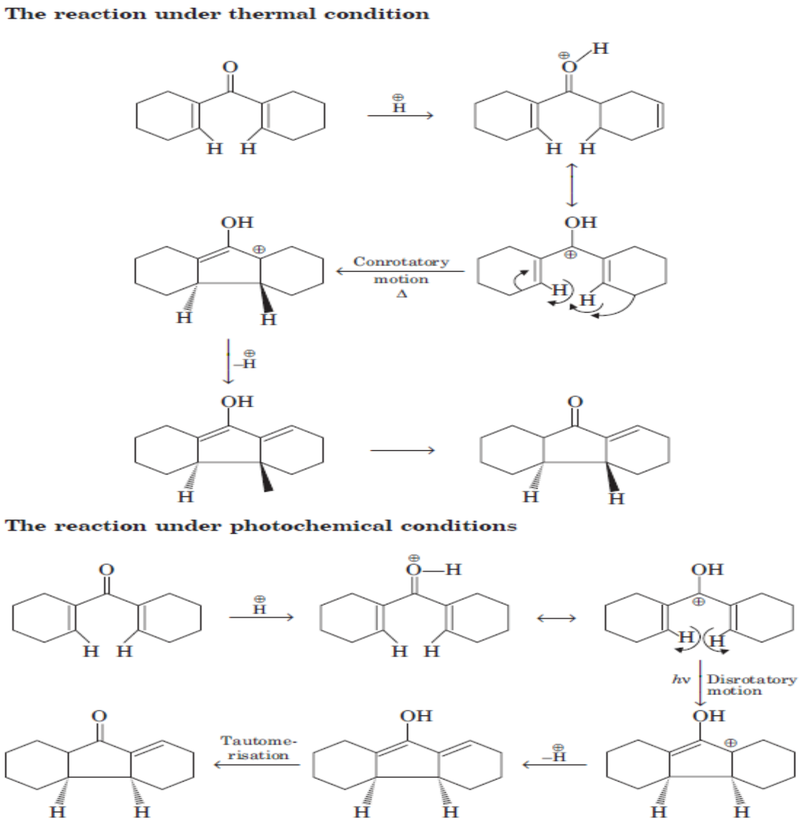
4. Nazarov cyclisation: Nazarov cyclisation is given by 1, 4-pentadiene-3-one and its derivatives. The product of the reaction is cyclopentenone. The reaction is conrotatory electrocyclic ring-closure under thermal condition and disrotatory ring-closure under photochemical conditions.



Nazarov cyclization’s require acid. Under acidic condition the substrate converts into cation which has 4π conjugated electrons.



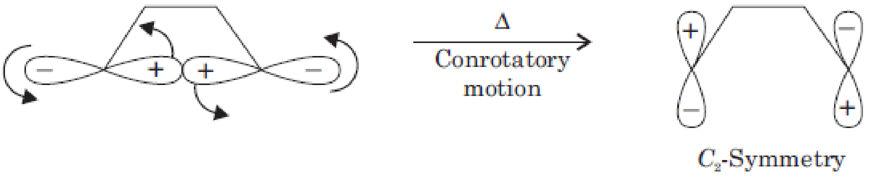
Under thermal condition, the motion is conrotatory and under photochemical conditions the motion is disrotatory because the conjugated system has (4*n*) π conjugated electrons.



Electrocyclic ring opening in which Polyene has 4np electrons

Conversion of cyclobutene to butadiene

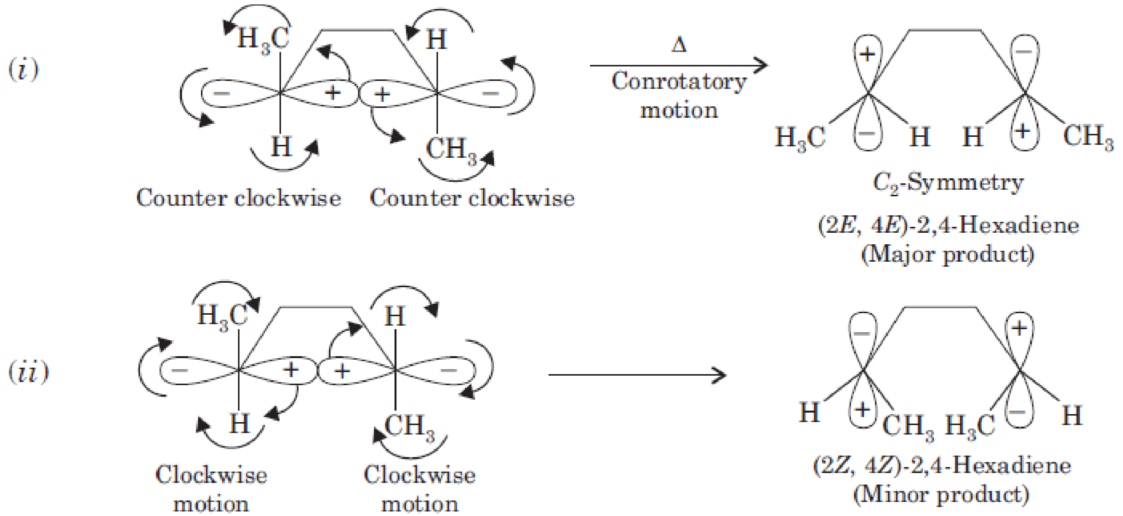
(A) ***Thermal-induced ring opening:*** In the ring-opening reactions stereochemistry of the product is determined by the symmetry of the ground state HOMO of the open-chain partner. The ground state HOMO of the butadiene and its derivative will be ψ_2 which has C_2-symmetry. The cyclobutene ring must open in such a fashion that the σ bond orbitals transform into the HOMO of the product having C_2-symmetry. To get C_2-symmetry in the product HOMO, motion should be conrotatory in the ring opening of the reaction.



Thus, if the open-chain polyene has $4n\pi$ electrons then the process is always *conrotatory* in thermal condition whether the reaction is ring-closure or ring opening.

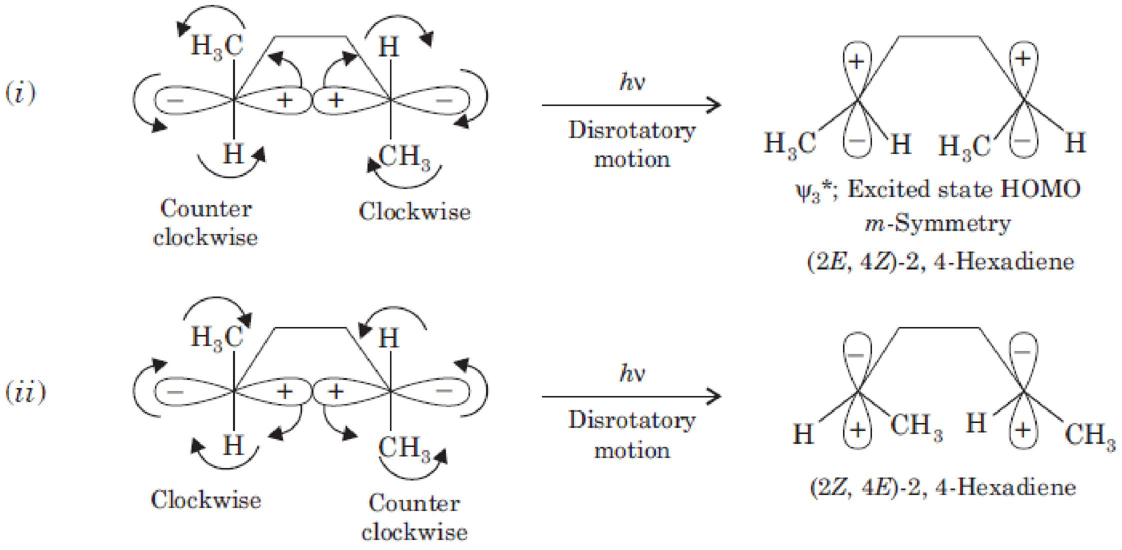
Let us take the stereochemistry of the ring opening of *trans*-3, 4-dimethylcyclobutene.

There is possibility of two modes of conrotatory motion, counter clockwise and clockwise motions.



Thus, the thermal process is conrotatory with two products possible in the above case. The conrotation in the second case (clockwise rotation) leads to severe steric interactions between two methyl groups. This interaction is avoided in the first process (rotation is counter clockwise) in which two methyl groups move away from each other, and this is the favoured process.

(B) ***Photo-induced ring opening:*** The photo state HOMO of the open chain butadiene and its derivative will be ψ_3* which has *m*-symmetry. Thus, the cyclobutene ring must be open in such a fashion that the σ bond orbitals transform into the excited state HOMO of the product having *m*-symmetry. To get *m*-symmetry in excited state HOMO of the product, motion should be disrotatory in the ring-opening of the reaction. There is also possibility of two modes of disrotatory motion.

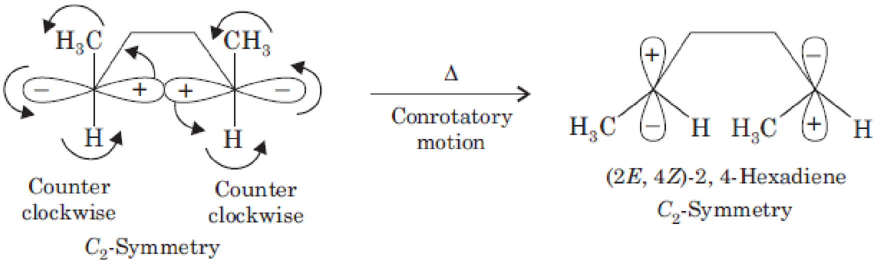


Thus, photo-induced process is disrotatory with either possible disrotation giving same product.

Let us take the conversion of *cis*-3, 4-dimethylcyclobutene into 2, 4-hexadiene.

Thermal ring-opening

(*i*)



(*ii*)

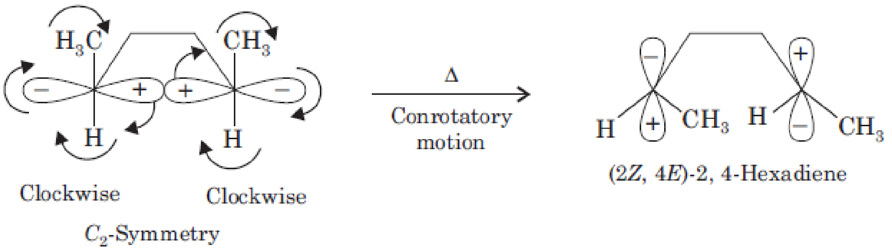
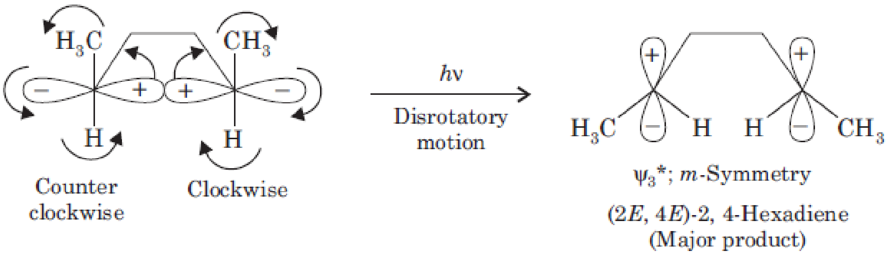
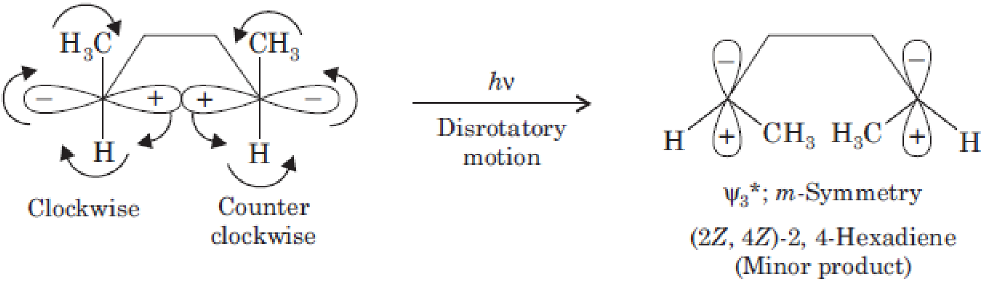


Photo-induced ring-opening

(*i*)



(*ii*)

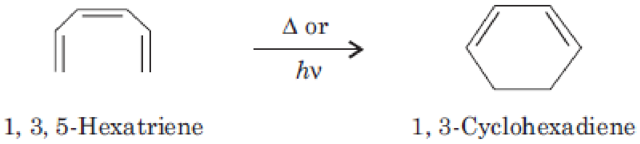


In case of *cis*-3, 4-dimethylcyclobutene, the thermal process is conrotatory with either possible conrotation giving the same product. The photochemical process is disrotatory with two possible products.

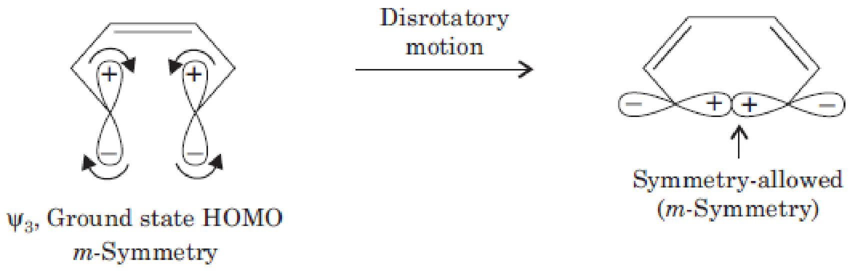
Cyclisation of (4n+2)p systems

1. Electrocyclic ring-closure reaction given by 1, 3, 5-hexatriene

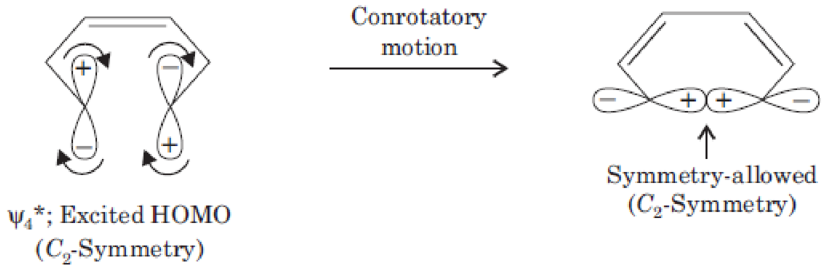
1, 3, 5-Hexatriene is the most common example of the polyene having ($4n + 2$)π conjugated electrons.



(A) ***Thermal-induced cyclisation:*** ψ_3 is the ground state HOMO of 1, 3, 5-hexatriene which has *m*-symmetry. Therefore, the thermal cyclisation proceeds by disrotatory motion.

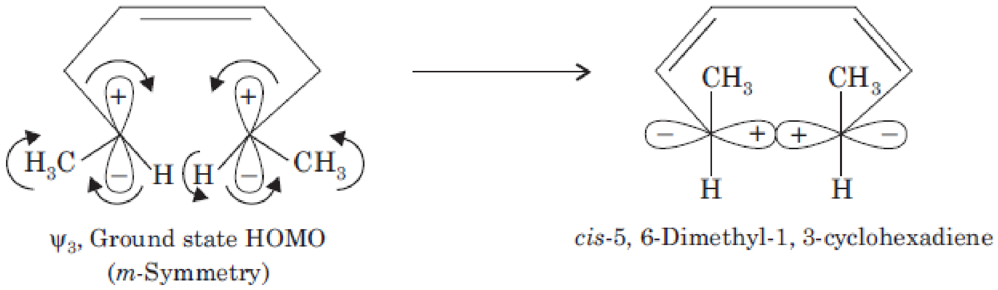


(B) ***Photo-induced cyclisation:*** When an electron of 1, 3, 5-hexatriene is promoted by photon absorption, ψ_4* becomes the HOMO. This excited state HOMO has C_2-symmetry. Therefore, photo-induced cyclisation proceeds by conrotatory motion.

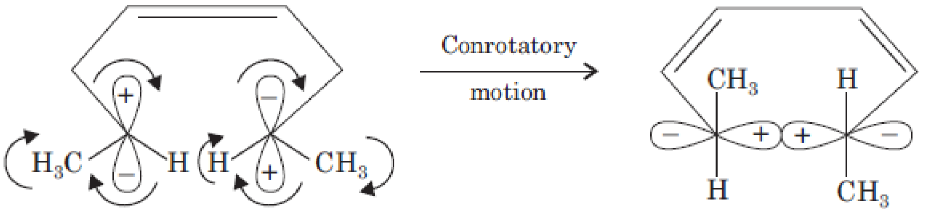


Consider the stereochemistry of the thermal and photo-induced closure of (2*E*, 4*Z*, 6*E*)- 2, 4, 6-octatriene to 5, 6-dimethyl-1, 3-cyclohexadiene.

(A) ***Thermal-induced cyclisation:*** In the case of the thermal induced cyclisation, the ground state HOMO is ψ_3 which has *m*-symmetry. Thus, disrotatory motion is required for sigma bond formation.



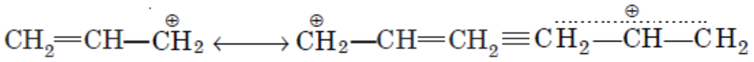
(B) ***Photo-induced cyclisation:*** In case of photo-induced cyclisation, the excited state HOMO is ψ_4* which has C_2-symmetry. Therefore, conrotatory motion is required for σ (*sigma*) bond formation.



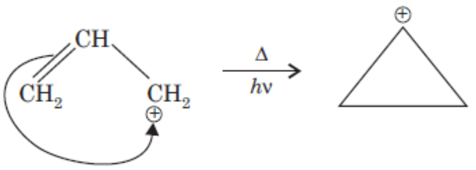
trans-5, 6-Dimethyl-1, 3-cyclohexadiene

2. Electrocyclic ring-closure reaction given by allyl carbocation

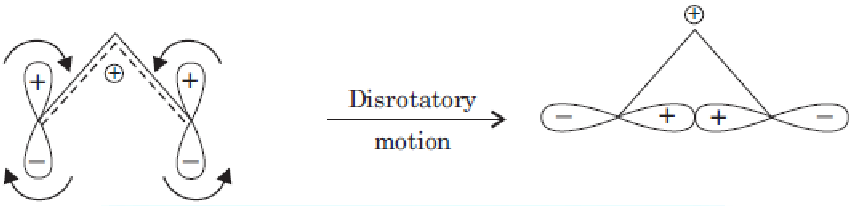
Allyl carbocation contains $(4n + 2)\pi$ conjugated electrons.



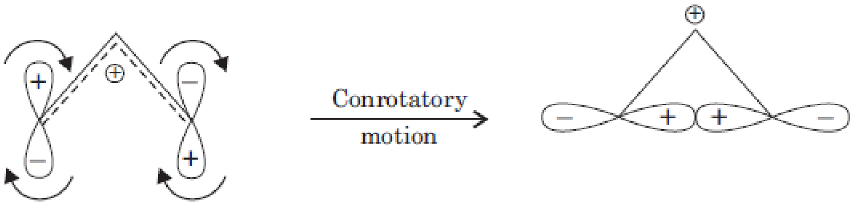
$$CH_2{=}CH{-}\overset{\oplus}{C}H_2 \longleftrightarrow \overset{\oplus}{C}H_2{-}CH{=}CH_2 \equiv \overset{\oplus}{\overline{CH_2{-}CH{-}CH_2}}$$



(A) ***Thermal-induced cyclisation:*** HOMO of the allyl carbocation in the ground state is ψ_1 which has *m*-symmetry. Therefore, disrotatory motion is the mode of cyclisation in the thermal condition.



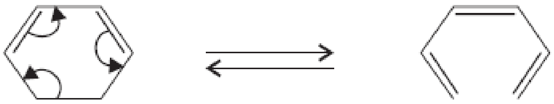
(B) ***Photo-induced cyclisation:*** HOMO of the allyl carbocation in the excited state is ψ_2 which has C_2-symmetry. Thus, conrotatory motion is required for σ (*sigma*) bond formation.



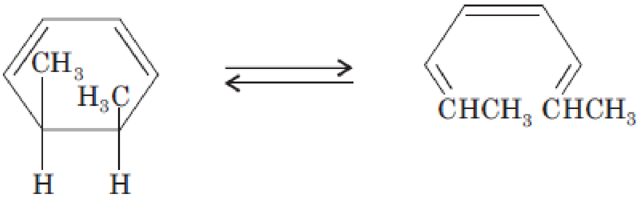
Electrocyclic ring – opening in which Polyene has (4n+2)p electrons

1. Conversion of 1, 3-cyclohexadiene to 1, 3, 5-hexatriene system

The most common example of this class is the conversion of 1, 3-cyclohexadiene to 1, 3, 5-hexatriene.



Let us take the example of the ring opening of a *cis*-5, 6-dimethyl-1, 3-cyclohexadiene into 2, 4, 6-octatriene.

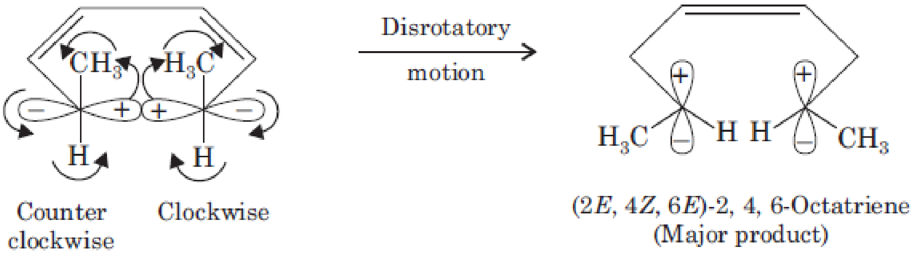


(A) ***Thermal ring-opening:*** As mentioned earlier that in the ring opening reactions stereochemistry of product is determined by the symmetry of the ground state HOMO of the open-chain partner. The ground state HOMO of the triene will be ψ3 which has *m*-symmetry. The cyclohexadiene ring therefore, must open in such a fashion that σ bond orbitals transform into the ground state HOMO of the product having *m*-symmetry. To get *m*-symmetry in the HOMO of the product, motion should be disrotatory in the ring opening of the reaction.

Ground state HOMO is ψ_3 which has *m*-symmetry. Therefore, motion is disrotatory

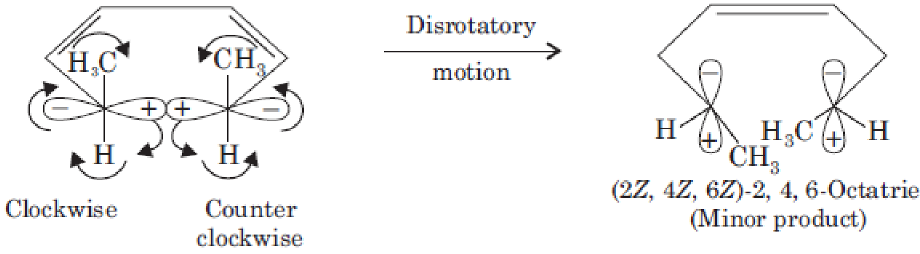
Two modes of disrotatory motions can take place as follows:

(*i*)



(2*E*, 4*Z*, 6*E*)-2, 4, 6-Octatriene
(Major product)

(*ii*)



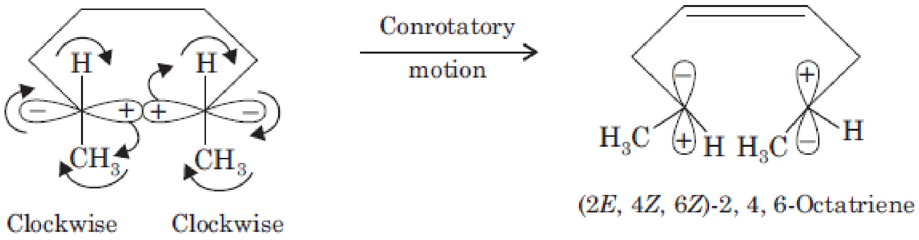
(2*Z*, 4*Z*, 6*Z*)-2, 4, 6-Octatriene
(Minor product)

Thus, the thermal process is disrotatory with two possible products, one is major and the other is minor due to the steric reasons.

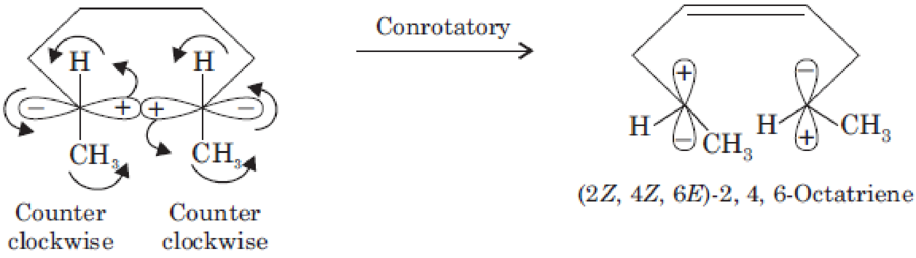
(B) ***Photo-induced ring-opening:*** The photo state HOMO of the triene system is ψ_4^* which has C_2-symmetry. To get C_2-symmetry in the product, motion should be conrotatory in the ring opening reaction.

Consider the two modes of conrotatory motions:

(*ii*)

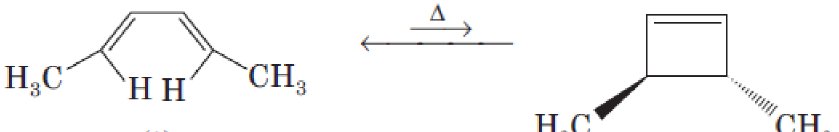


(*i*)



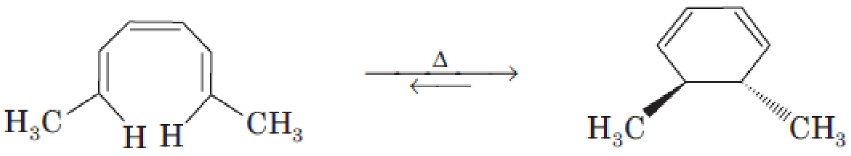
Selection rules and microscopic reversibility

The selection rules are based on the orbital symmetry of the open-chain conjugated polyene reactant. However, it is important to understand that these rules refer to the rates of pericyclic reactions. These rules have nothing to say about the positions of the equilibrium involved. Thus, the electrocyclic reaction of the diene (1) to give a cyclobutene favours the diene at equilibrium because of the strain in the cyclobutene.



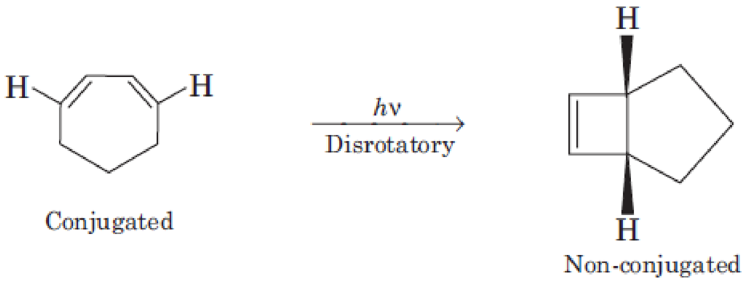
(1)

On the other hand, electrocyclic reaction of conjugated triene (2) favours the cyclic compound because σ (*sigma*) bonds are stronger than π (*pi*) bonds, and because six-membered rings are relatively stable.



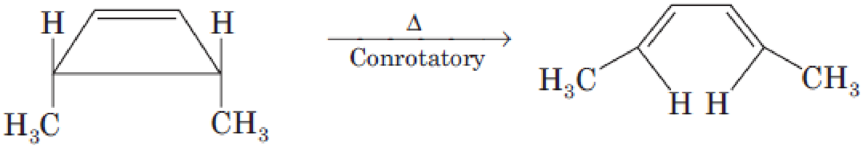
(3)

It is also common for a photochemical reaction to favour the less stable isomer of an equilibrium. For example, in the given reaction, the conjugated diene absorbs UV light, but the bicyclic compound does not, hence, the photochemical reaction favours the latter.



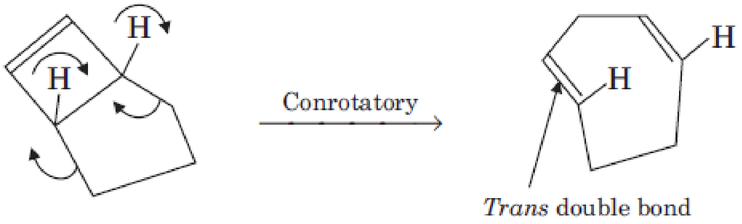
In summary, the selection rules do not indicate which component of the equilibrium will be favoured—only whether the equilibrium will be established at a reasonable rate.

The principle of microscopic reversibility (*i.e.*, any reaction and its reverse proceed by the forward and reverse of the same mechanism) assures us that selection rules apply equally well to the forward and reverse of any pericyclic reaction, because the reaction in both directions must proceed through the same transition state. Hence, an electrocyclic ring-opening must follow the same selection rules as its reverse, an electrocyclic ring closure. Thus, the thermal ring-opening reaction of the cyclobutene (3), like the reverse ring closure reaction, must be a conrotatory process.



(3)

In the following electrocyclic ring opening reaction, the allowed thermal conrotatory process would give a highly strain molecule containing a *trans* double bond within a small ring.



Although the selection rules suggest that the reaction could occur, it does not because of the strain in the product (*trans* cycloalkenes with seven or fewer carbons have never been observed). Thus, allowed reactions are sometimes prevented from occurring for reasons having nothing to do with selection rules.

The Woodward – Hoffmann rule for electrocyclic reactions

Fortunately, all the conclusions that can be drawn laboriously from correlation diagrams can be drawn more easily from a pair of rules, known as the *Woodward-Hoffmann* rules. Rules distil the essence of the idea into two statements governing all pericyclic reactions, one rule of thermal reactions and its opposite for photochemical reactions. Correlation diagrams explain why they work, but we no longer depend upon constructing such diagrams.

Woodward – Hoffmann rule for electrocyclic thermal reactions

A thermal (ground state) electrocyclic reactions is symmetry allowed when the total number of $(4q + 2)s$ and $(4r)a$ components is odd.

Photochemical electrocyclic reactions

An electrocyclic reaction in the first electronically excited state is symmetry allowed when the total number of $(4q + 2)$ *a* and $(4r)s$ is odd.

Component

A component is a bond or orbital taking part in a pericyclic reaction as a single unit. A double bond is a π^2 component. The number *two* is the most important part of this designation and simply refers to the number of electrons. The prefix π tells us the type of electrons. A component may have any number of electrons, for example 1, 3-butadiene is a π^4 component. Component may not have mixtures of π and σ electrons. Component either contains only σ electrons or contains only π electrons. Designations $(4q + 2)$ and $(4r)$ simply refer to the number of electrons in the component where *q* and *r* are integers (0, 1, 2, 3, 4, ..., *n*). An alkene is a π^2 component and so it is of the $(4q + 2)$ kind where $q = 0$ while diene is a π4 component and so it is of the $(4r)$ kind where $r = 1$.

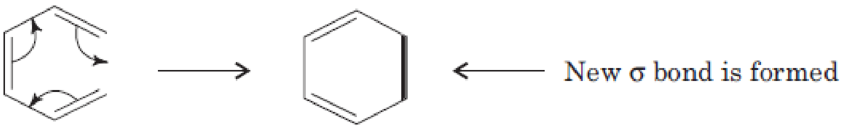
Suffix *s* and *a*

In electrocyclic reaction *s* means when upper (or lower) lobe of one frontier orbital overlaps with upper (or lower) lobe of other frontier orbital and *a* means when upper lobe of one orbital overlaps with lower lobe of other.

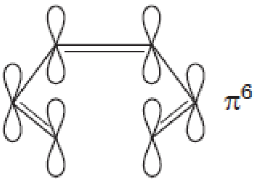
Let us start with hexatriene ring closure. As a preliminary, we would just note that hexatriene is, of course, a 6π electrons (π^6) conjugated system and, on forming cyclohexadiene, the end two orbitals have to form a σ bond.

So, now for the Woodward-Hoffmann treatment:

1. Draw the mechanism for the reaction

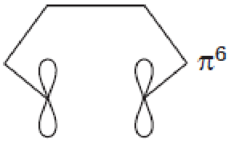


2. Choose the components. All the bonds taking part in the mechanism must be included and no others.



3. Make the three-dimensional drawing of the way the components come together for

the reaction putting in orbitals at the ends of the components.

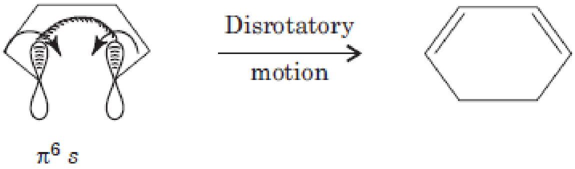


These orbitals are simple *p*-orbitals and do not make up HOMOs or LUMOs or any particular MOs. Do not attempt to mix frontier orbitals and Woodward-Hoffmann description of correlation of pericyclic reactions.

4. Join up the component(s) where new bond(s) are to be formed. Make sure you join orbitals that are going to form new bonds.

In this case formation of new σ bond takes place by two possible cases:

Case I: When component is s. In this case overlapping will be possible if motion is disrotatory.



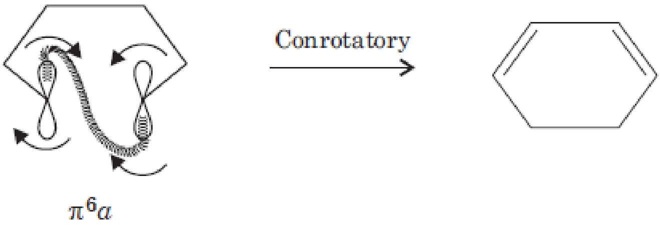
Notice that we call the component '*s*' because the upper lobes of the two *p*-orbitals were joining together. If upper lobe of one orbital and lower lobe of another orbital is joined together then component will be '*a*'.

Number of (4*q* + 2) *s* component = 1

Number of (4*r*) *a* component = $\frac{0}{Total = 1\ (odd)}$

Thermal: Allowed
Photochemical: Forbidden

Case II: *When component is 'a'. In this case overlapping will be possible if motion is conrotatory.*

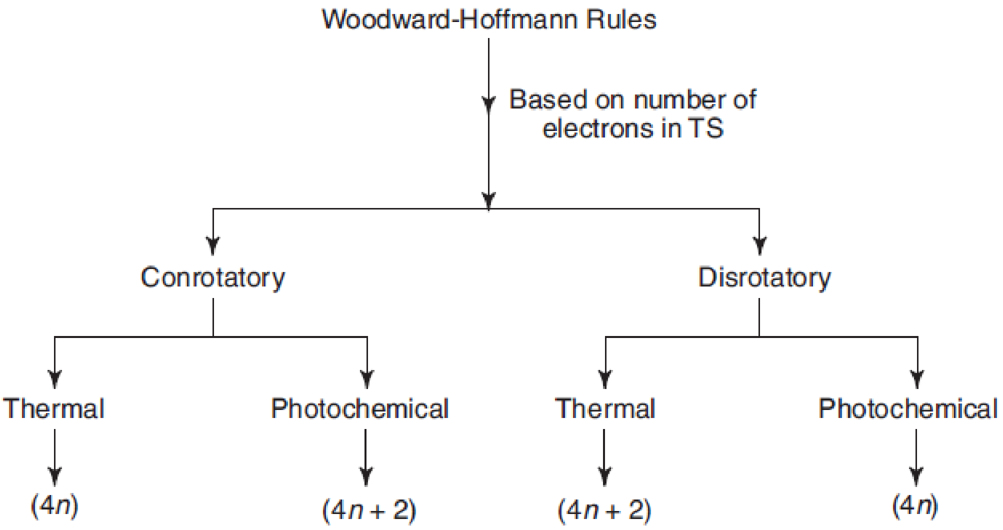


Number of (4*q* + 2)*a* = 1

Number of $(4r)\ s = \frac{0}{Total=1\ (odd)}$

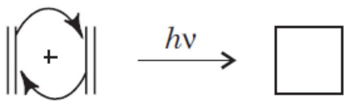
Thermal: Forbidden
Photochemical: Allowed

Thus, we can conclude the following results from Woodward-Hoffmann rule for electrocyclic reactions:

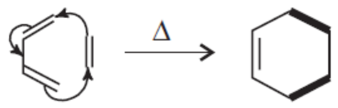


Cycloaddition Reactions

A cycloaddition is a reaction in which two unsaturated molecules undergo an addition reaction to yield a cyclic product. Formation of cyclic product takes place at the expense of one π (*pi*) bond in each of the reacting partner and gain of two σ (*sigma*) bonds at the end of the both components having π (*pi*) bonds. Thus, in this reaction there is loss of two π (*pi*) bonds of the reactants and gain of two σ (*sigma*) bonds in the product.



Loss of two π bonds and
gain of two σ bonds



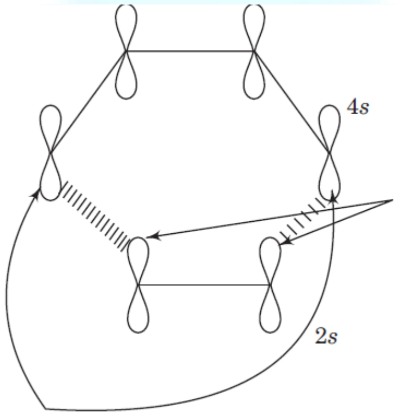
Loss of two π bonds and gain of two σ bonds. Formation of σ bonds at the end of the two components.

The cycloaddition reactions are classified with respect to three facts of the reaction:

(*i*) The number of electrons of each unit participating in cycloaddition.
(*ii*) The nature of orbitals undergoing change (π or σ).
(*iii*) The stereochemical mode of cycloaddition (*supra*, *syn* or *antara*, *anti*).

The reaction in equation (1) is a [2 + 2] cycloaddition reaction because the reaction involves two electrons from one reacting component and also two electrons from the other. The reaction in equation (2) is a [4 + 2] cycloaddition.

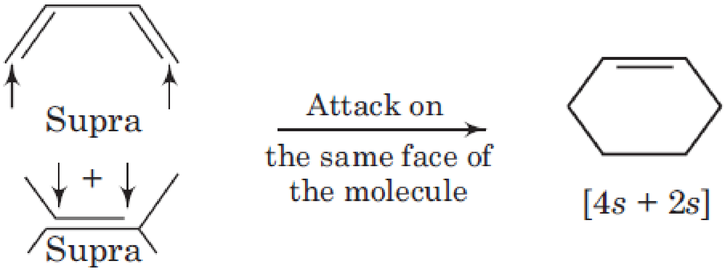
The stereochemical mode is given by a subscript *s* or *a* which indicates whether the addition occurs in a *supra* or *antara* mode on each unit. A cycloaddition may in principle occur either across the same face or across the opposite faces of the planes in each reacting component. If reaction occurs across the same face of a π system, the reaction is said to be *suprafacial* with respect to that π system. The suprafacial is nothing more than a *syn* addition.



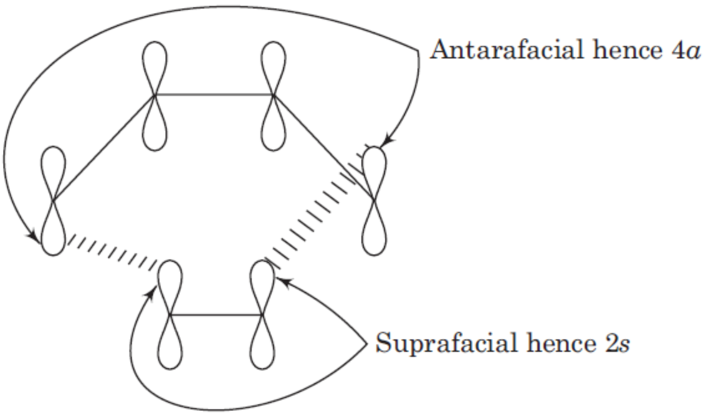
Both lobes are above the plane of the molecule or both lobes are in same plane, hence suprafacial

Both lobes are below the plane of the molecule or both lobes are in same plane, hence suprafacial

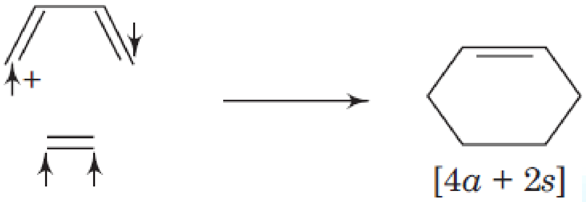
This addition reaction is thus [4*s* + 2*s*] cycloaddition reaction.
This can also be represented as follows:

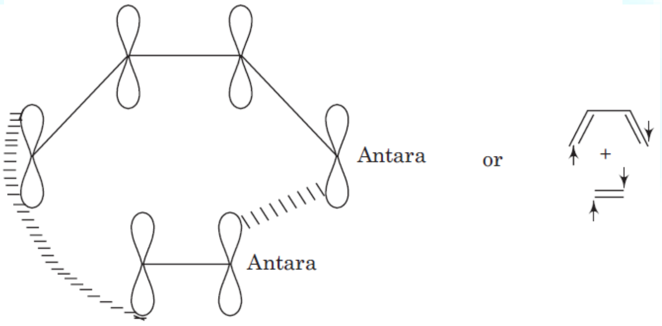


If the reaction bridges opposite faces of a π system, it is said to be antarafacial. An antarafacial is just an *anti* addition.



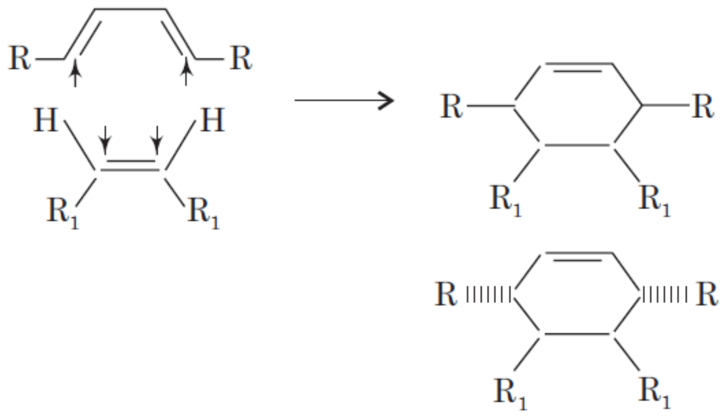
This mode of addition reaction is thus [4*a* + 2*s*] cycloaddition reaction. This can be represented as:





$[4a + 2a]$ Cycloaddition reaction

In antarafacial, attack takes place with one bond forming to one surface but other bond forming to other surface. It is rare, it does not occur in any reaction. **Almost all cycloaddition reactions are suprafacial on both components.**



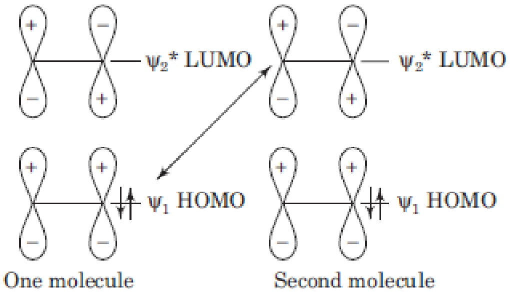
Frontier molecular orbital (FMO) method

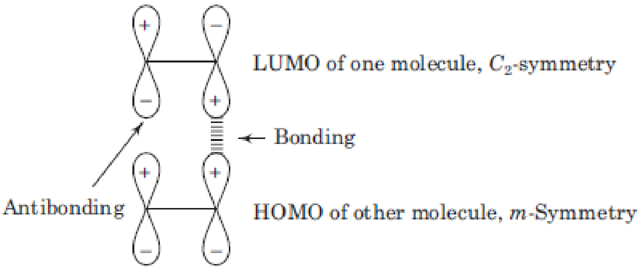
In order, for a cycloaddition to occur, there must be bonding overlap between *p*-orbitals at the terminal carbons of each π-electron system, this is where the new σ bonds are formed. Let us explain this point with a [4 + 2] cycloaddition. Let us suppose that diene (4π component) behaves as electron donor and the dienophile (2π component) as the electron acceptor (or vice-versa). Obviously, there will be its valence electrons—the electrons in its HOMO (ψ_2). The 2π component will accept these electrons to form the new bonds. The molecular orbital used to accept these electrons must be empty since molecular orbital cannot contain more than two electrons. Therefore, the molecular orbital which accepts electron should be LUMO of the 2π component. Thus, one component used its HOMO and the other component used its LUMO for overlapping. Simultaneously with the merging of the π orbitals, these orbitals also undergo hybridisation to yield the new sp^3 σ bonds.

[2+2] Cycloaddition reactions

(A) Thermal Induced [2 + 2] Cycloaddition Reactions

Thermal induced [2 + 2] cycloaddition reactions are symmetry forbidden reactions. When ethylene is heated, its π electrons are not promoted, but remain in the ground state ψ_1. If we examine the phase of the ground state HOMO of one ethylene molecule and the LUMO of another ethylene molecule we can see why cyclisation does not occur by the thermal induction.





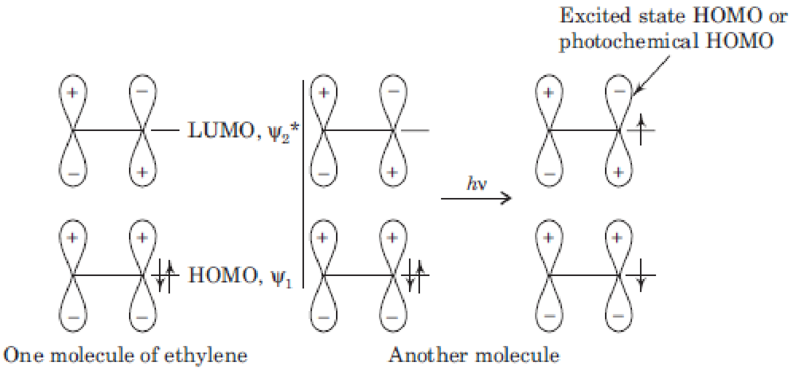
Phase wrong for overlap, symmetry forbidden.

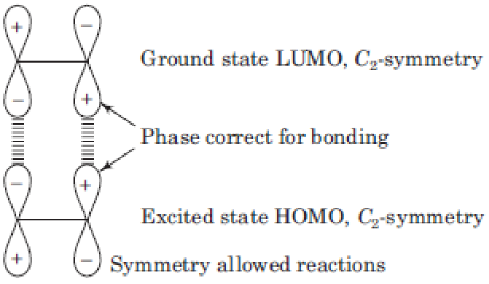
For bonding to occur, the phase of the overlapping orbitals must be same. This is not the case for the ground state HOMO and LUMO of two ethylene molecule or any other [2 + 2] system. Because the phase of the orbitals are incorrect for bonding, a thermally induced [2 + 2] cycloaddition is said to a symmetry forbidden reaction.

(B) Photo-Induced [2 + 2] Cycloaddition Reactions

When ethylene is irradiated with photon of UV light, a π electron is promoted from ψ_1 to ψ_2* orbital in some, but not all, of the molecules. The result is a mixture of ground state and excited state ethylene molecules.

Thus photo-induced cycloaddition takes place between photochemical HOMO of one molecule and ground state LUMO of other molecule.

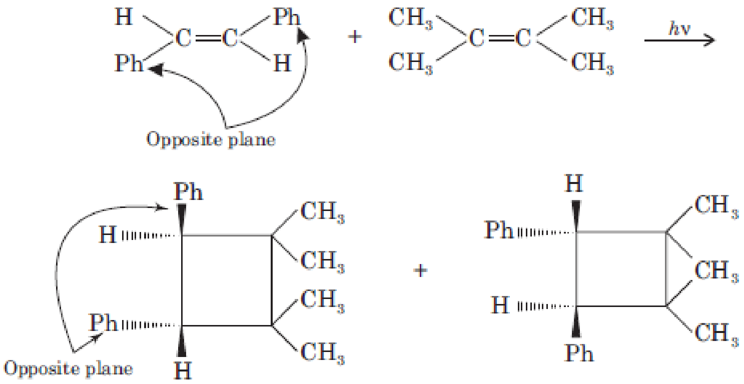


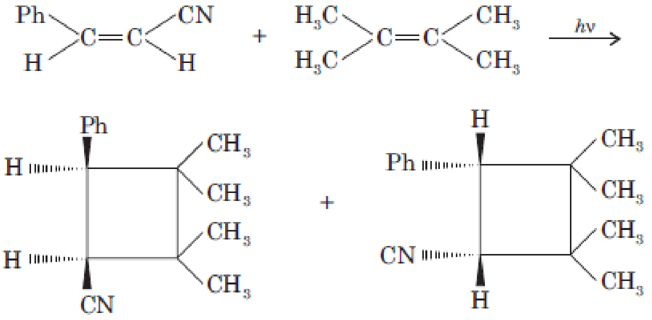


From the example it is clear that for cycloaddition reaction both HOMO and LUMO should have same symmetry otherwise reaction will be symmetry forbidden. For symmetry allowed reaction if HOMO has *m*-symmetry then LUMO should also have *m*-symmetry. Similarly if HOMO has C_2-symmetry then LUMO should also have C_2-symmetry.

Stereochemistry

Stereochemical integrity is maintained in cycloaddition reaction because reaction is concerted reaction,





[4+2] Cycloaddition reactions

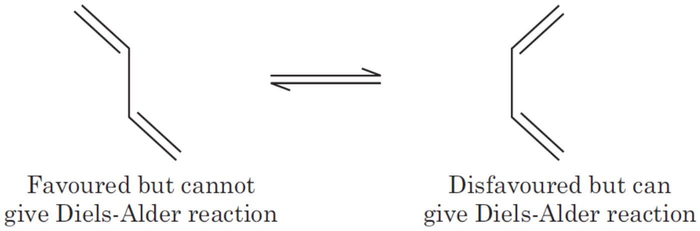
Diels-Alder reaction is the best known [4 + 2] cycloaddition reaction. This reaction is thermally allowed reaction. Diels-Alder reaction is photochemically forbidden. Since Diels-Alder reaction is the most common [4 + 2] cycloaddition reaction, let us first discuss the general description of this reaction.

Diels-Alder reactions occur between a conjugated **diene** and an alkene (or alkyne), usually called the **dienophile**.

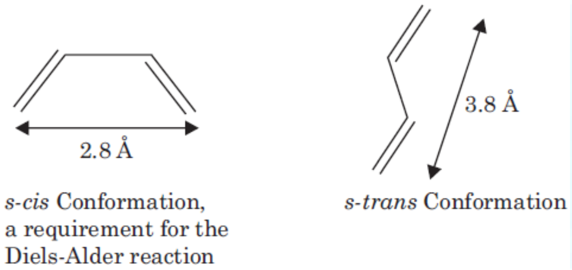
(A) The Dienes

The diene of the Diels-Alder reaction is electron rich, while the dienophile is electron poor. Some Diels-Alder reactions with electron-poor dienes and electron-rich dienophiles are also known, but these are relatively rare. Simple dienes such as 1, 3-butadiene are sufficiently electron-rich to be effective dienes for Diels-Alder reaction. The presence of electron releasing groups such as alkyl groups, phenyl groups or alkoxy groups may further enhance the reactivity

of dienes.
The diene component of the Diels-Alder reaction can be open-chain or cyclic but it must have *s-cis* conformation. Butadiene normally prefers the *s-trans* conformation with the two double bonds as far away from each other as possible for steric reasons. The barrier to rotation about the central σ bond is small (about 30 kJ/mole at 25°C) and rotation to the less favourable but reactive *s-cis* conformation is rapid.



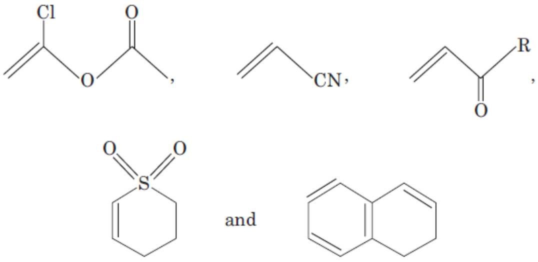
Cyclic dienes that are permanently in the *s-cis* conformation are exceptionally good for Diels-Alder reaction. On the other hand, cyclic dienes that are permanently in the *s-trans* conformation and cannot adopt the *s-cis* conformation will not give the Diels-Alder reaction at all. If the diene is in the *s-trans* conformation, the dienophile could not '**reach**' both ends of the diene at the same time.



(B) The Dienophile

The most common dienophiles are the electron-poor alkenes and alkynes. Since electron-poor alkenes and alkynes are prone to react with a diene, these are called dienophiles (lover of dienes). Thus the simple alkenes and alkynes such as ethylene and acetylene are not good dienophiles. A good dienophile generally has one or more electron-withdrawing groups pulling electron density away from the π bond.

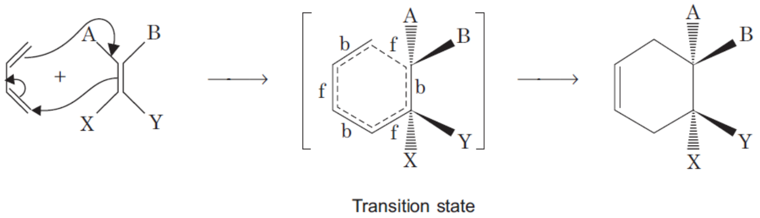
Dienophiles that do undergo the Diels-Alder reaction include conjugated carbonyl compounds, nitro compounds, nitriles, sulphones, arylalkenes, arylalkynes, vinyl ethers, vinyl esters, haloalkenes and dienes.



Some dienophiles for the Diels-Alder reaction

(C) Mechanism of Diels-Alder Reaction

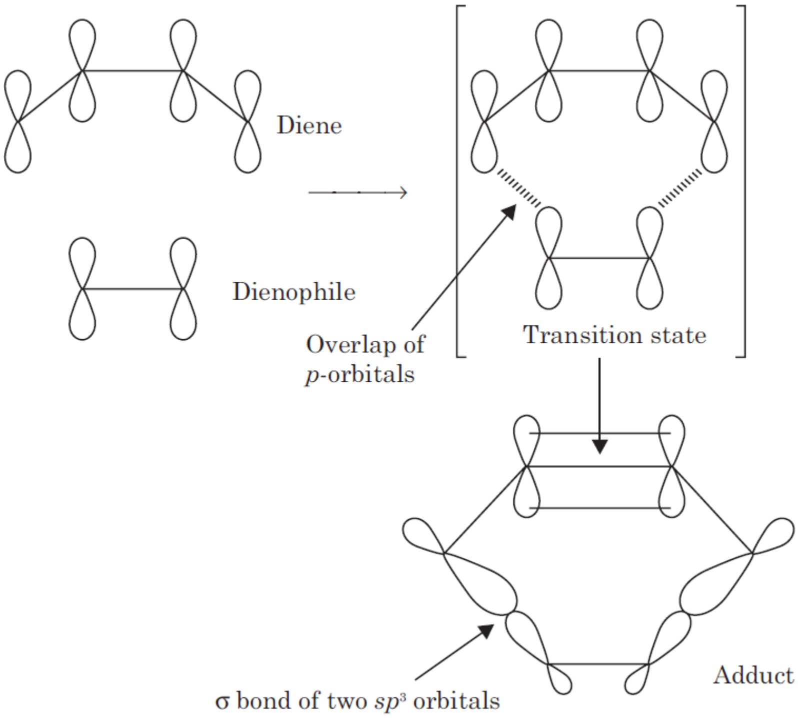
The mechanism of the Diels-Alder reaction is a simultaneous cyclic movement of six electrons: four in the diene and two in the dienophile. The simple representation of the mechanism shown below is fairly accurate. This is called a concerted reaction because all the bond making and bond breaking occurs simultaneously. For these three pairs of electrons to move simultaneously, however, the transition state must have a geometry that allows overlap of the two end *p*-orbitals of the diene with those of the dienophile.



There are three major **stereochemical** features of the Diels-Alder reaction that are controlled by the requirements of the T.S.

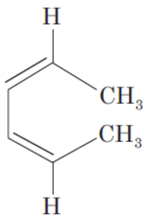
(*i*) ***s-cis* conformation of the diene:** This mechanism explain why the **diene** should be in *s-cis* conformation.

Diels-Alder reaction is a one step reaction that proceeds through a cyclic transition state. Bond formation occurs at both ends of the diene system, and the Diels-Alder transition state involves a cyclic array of six carbons and six π electrons. For this the diene adopts the *s-cis* conformation in the transition state.

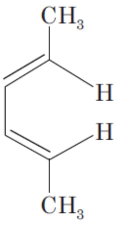


When the diene is in the *s-trans* conformation, the end *p*-orbitals are too far apart to overlap with the *p*-orbitals of the dienophile.

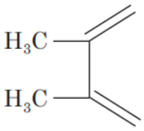
Structural feature that aid or hinder the diene in achieving the *s-cis* conformation affect its ability to participate in the Diels-Alder reaction. Thus the diene with functional groups that hinder the *s-cis* conformation react slower than butadiene. Dienes with functional groups that hinder the *s-trans* conformation react faster than butadiene.



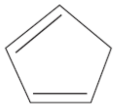
Much slower than butadiene



Similar to butadiene



Faster than butadiene

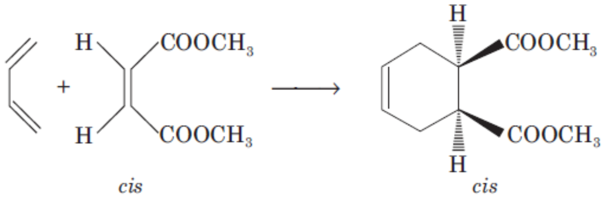


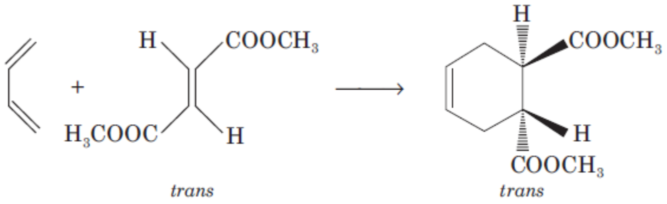
Much faster than butadiene

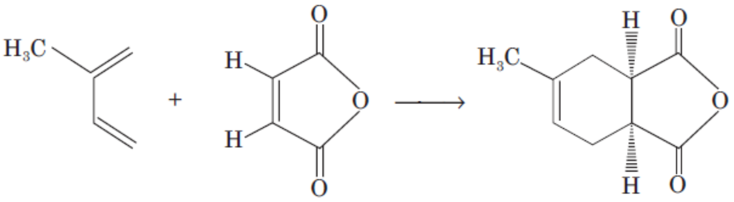
(*ii*) *syn* **stereochemistry:** The Diels-Alder reaction is a *syn* addition with respect to both the diene and dienophile. The dienophile adds to one face of the diene, and the diene adds to one face of the dienophile. As you can see from the transition state, there is no opportunity for any of the substituents that are on the same side of the diene or dienophile will be *cis* on the newly formed ring. Thus, the stereochemistry of the diene and dienophile are preserved during the adduct formation.

(a) Stereochemistry of the adduct due to stereochemistry of the dienophile

The Diels-Alder reaction is stereospecific. Substituents that are *cis* in the dienophile remain *cis* in the product; substituents that are *trans* in the dienophile remain *trans* in the product.





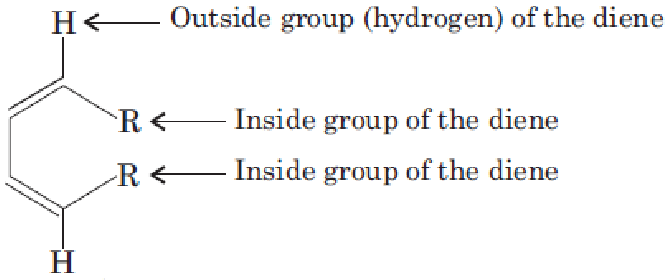


(b) Stereochemistry of the product due to the stereochemistry in the diene

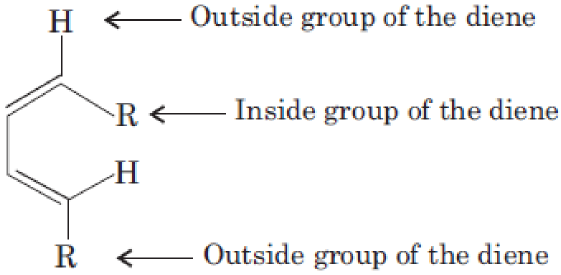
The product stereochemistry is controlled by the geometry of the diene.

This is slightly more complicated as the diene can be *cis, cis*; *trans, trans* or *cis, trans.*

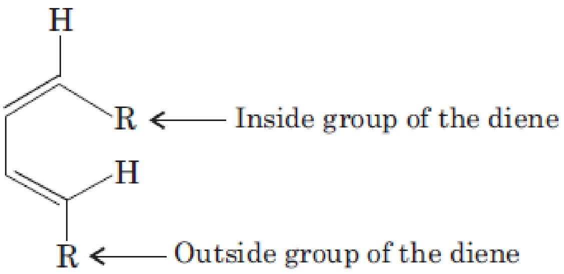
Terminal vinylic carbons (1 and 4 in butadiene) of the *s-cis* diene contain two substituents. One is designated as outside group and other is designated as inside group of the diene. For example,



cis-cis Diene



cis-trans Diene

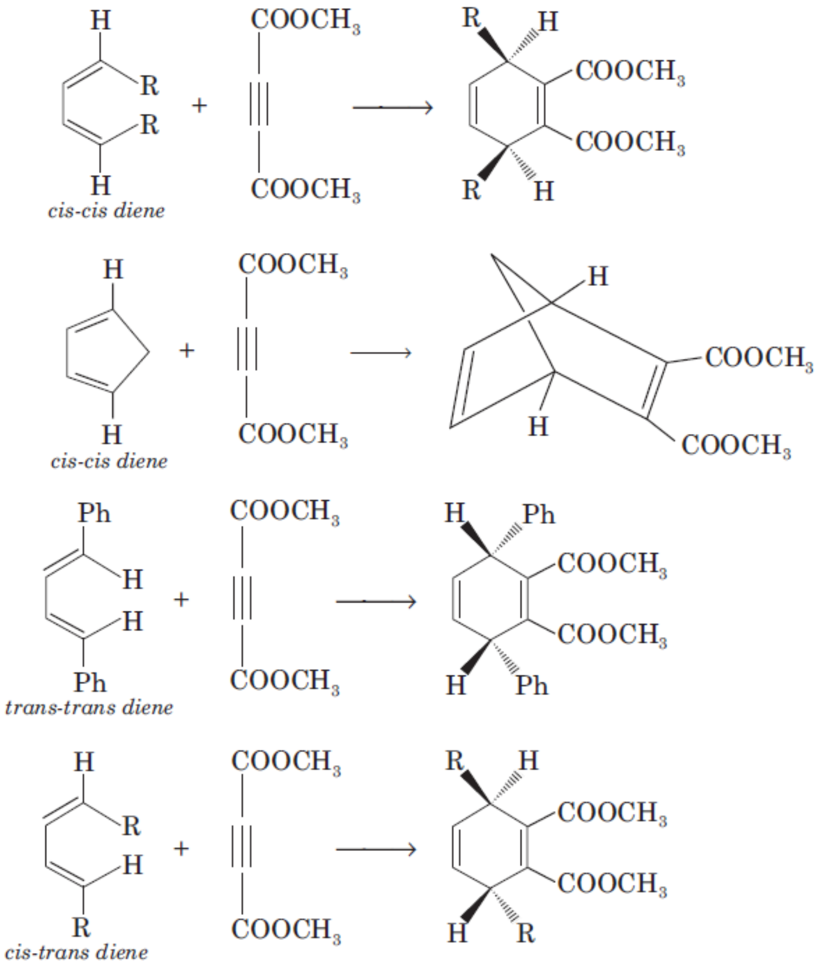


cis-trans Diene

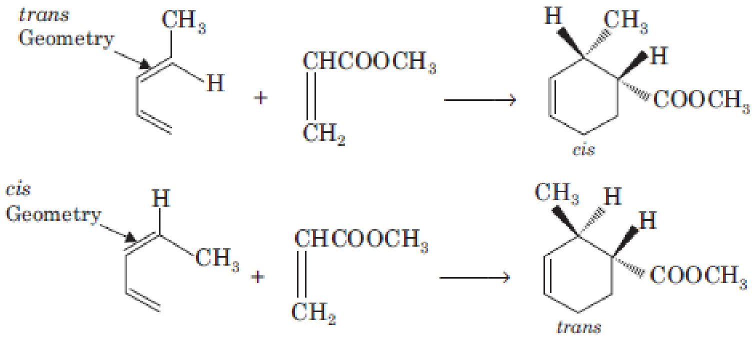
Outside groups at C-1 and C-4 are always *trans* to each other. Similarly, two inside groups at C-1 and C-4 are *cis* to each other.

As mentioned earlier that the Diels-Alder reaction is stereospecific. According to the structure of the transition state of the Diels-Alder reaction the *outside substituents of the diene are always below the plane of the new six-membered ring of the adduct.*

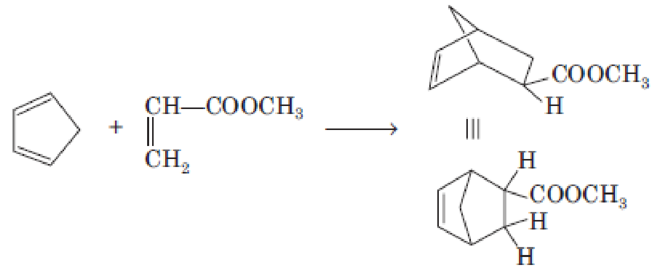
Thus the inside substituents of the diene should always be above the plane of the new six-membered ring of the adduct.



We also need to consider the stereochemistry in the product of the substituents on the diene relative to those on the dienophile. If *trans* 1, 3-pentadiene reacts with methyl propenoate we know that in the product the methyl and ester groups could be either *cis* or *trans*. It is found, in fact, that the *cis* product is formed from *trans* diene and the *trans* product is formed from *cis* diene.

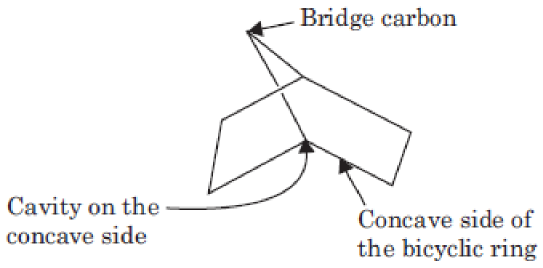


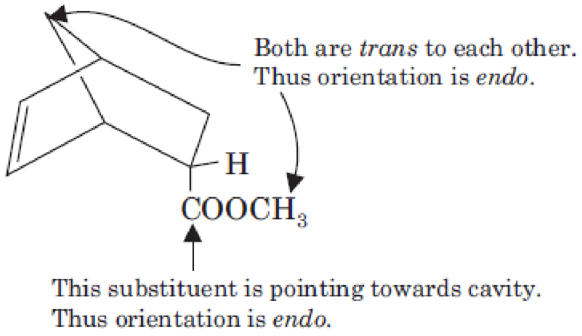
(*iii*) ***Endo* and *Exo* stereochemistry:** The Diels-Alder reaction will produce a bicyclic ring system if the diene is monocyclic. Cyclic dienes are particularly reactive in Diels-Alder reaction because the two double bonds are held in an *s-cis* conformation in five or six-membered rings. This can be seen in the reaction of 1, 3-cyclopentadiene with methyl propenoate.



An orientation is said to be *endo* meaning that the substituent is *trans* to the bridge carbon or substituent projects into the cavity on the concave side of the bicyclic ring. Similarly, an orientation is said to be *exo*

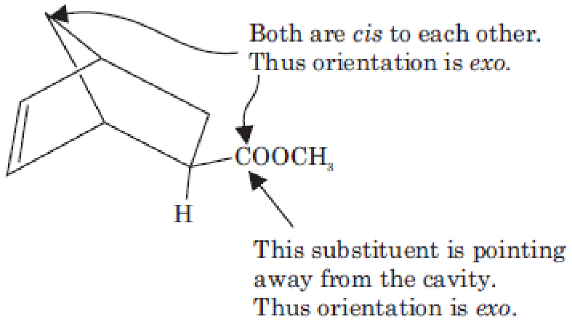
meaning that the substituent is *cis* to the bridge carbon or substituent projects out of the cavity on the concave side of the bicyclic ring.





Both are *trans* to each other. Thus orientation is *endo*.

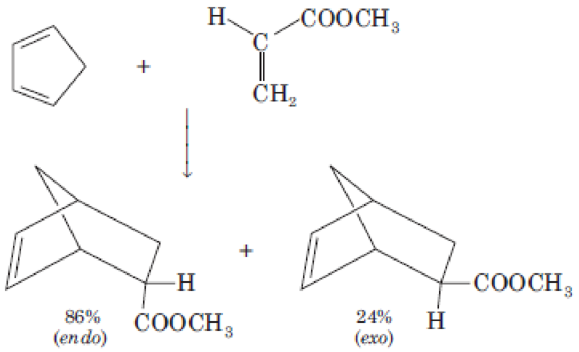
This substituent is pointing towards cavity. Thus orientation is *endo*.



Both are *cis* to each other. Thus orientation is *exo*.

This substituent is pointing away from the cavity. Thus orientation is *exo*.

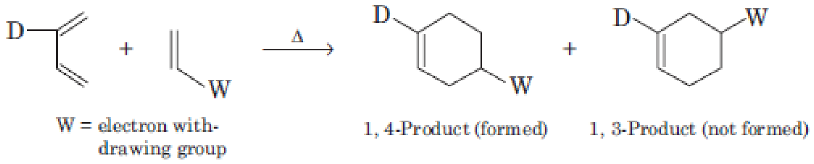
The *exo* product is expected to be more stable than the *endo* product for steric reasons. In *exo* product the *exo* substituent points away from the more congested part, *i.e.*, bicyclic ring but in *endo* product the *endo* substituent points towards the more congested part. Thus steric repulsion in *endo* is more than the *exo*. Due to this reason *exo* is expected to be more stable than the *endo*. But in practice it has been found that if the diene has a π bond in its electron-withdrawing group then the *endo* product is more stable than the expected *exo* product. This stereochemical preference for the *endo* position is often called the *endo rule*. The reaction of 1, 3-butadiene with methyl propenoate produces three times as much as *endo* as *exo* product. Endo product is major product due to the secondary interactions.



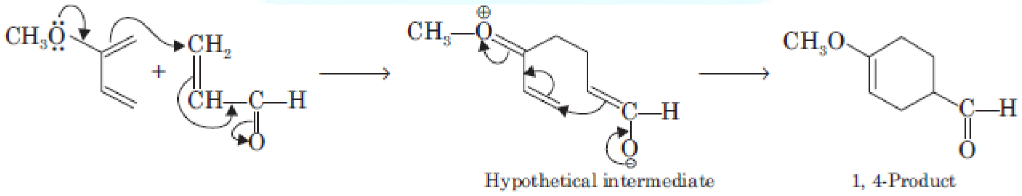
(D) Orientation Effects in Diels-Alder Reaction

Even when the diene and dienophile are both unsymmetrically substituted, the Diels- Alder product is usually a single isomer rather than a mixture. The product is the isomer that results from orienting the diene and dienophile so that we can imagine a hypothetical reaction intermediate with a “push-pull” flow of electrons from the electron-donating group to the electron-withdrawing group.

Case I: *When electron-donating group (D) is present on the middle carbon of the diene.*

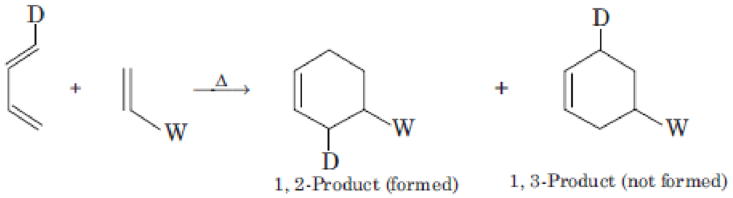


Imaginary flow of electrons:

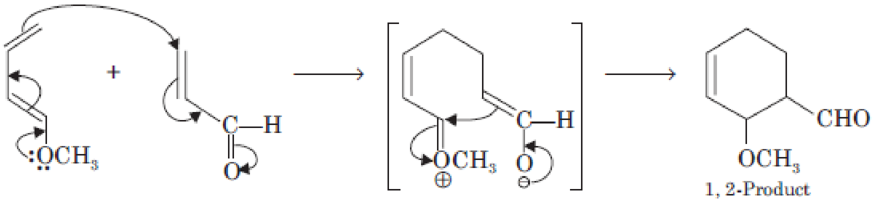


Thus, if electron-donating group is present either at C-2 or at C-3 then in this case product is always 1, 4 and not 1, 3.

Case II: *When an electron-donating group is present at terminal carbon of the diene.*



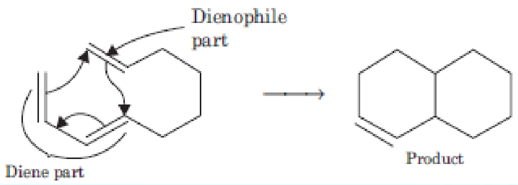
Imaginary flow of electrons :



Thus, if electron-donating group is present either at C-1 or C-4 then in this case the product is always 1, 2 and not 1, 3.

(E) Intramolecular Diels-Alder Reactions

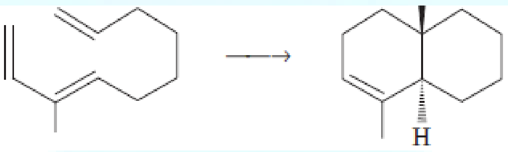
When diene and the dienophile are part of the same molecule then such type of molecule gives Diels-Alder reaction known as intramolecular Diels-Alder reaction.



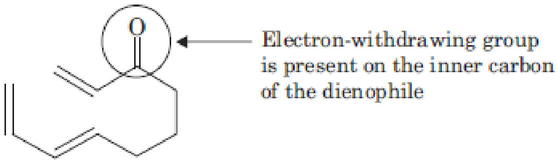
Example is an intramolecular Diels-Alder reaction.

In intramolecular Diels-Alder reaction the stereochemistry at fused ring carbons depends on the nature of the substituent on the dienophile part of the molecule.

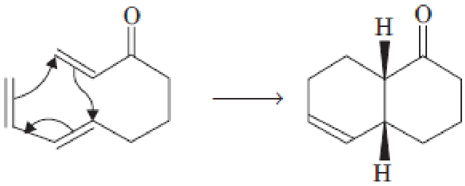
Case I: *When electron-withdrawing group is not present on dienophile*
In this case both ring junctions are *trans* to each other. Thus the substituents (*i.e.*,hydrogens) on both fused carbons are always *trans* to each other.



Case II: *When dienophilic part has electron-withdrawing group which is present on inner carbon of the dienophile*

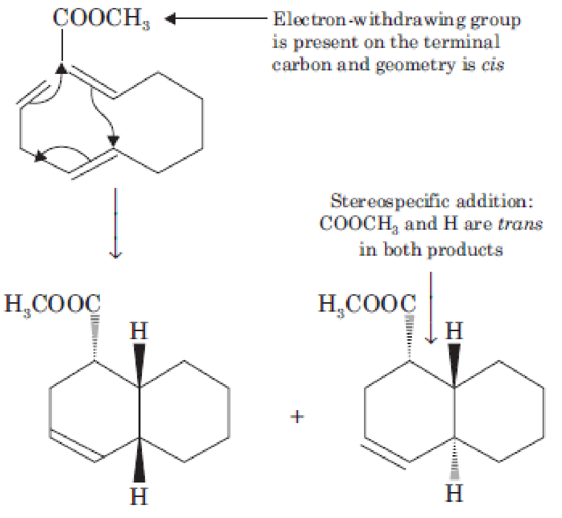


In this case both bridge hydrogens are *cis* to each other and perpendicular to the plane of the ring.



Case III: *When electron-withdrawing group is present on terminal carbon of the diene and geometry is cis*

In this case a mixture of two products are formed. In one product both hydrogens of the fused ring carbons are *cis*. In other product both hydrogens are *trans*. Electron-withdrawing group is always below the plane of the ring and *trans* to the bridge hydrogen.

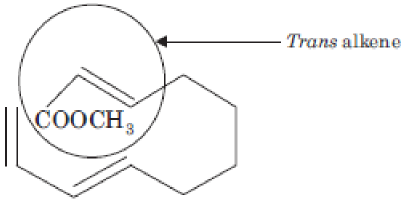


Electron-withdrawing group is present on the terminal carbon and geometry is *cis*

Stereospecific addition: $COOCH_3$ and H are *trans* in both products

(Both hydrogens are *cis*)　(Both hydrogens are *trans*)

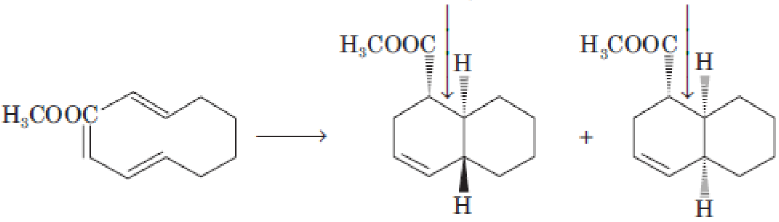
Case IV: *When electron-withdrawing group is present on terminal carbon of the dienophile and geometry is trans*



Trans alkene

In this case also mixture of two products are formed. In one product both hydrogens of the bridge carbons are *cis* and in other product both are *trans*.

Electron-withdrawing group is always below the plane of the ring and *cis* to adjacent hydrogen of the bridge carbon.



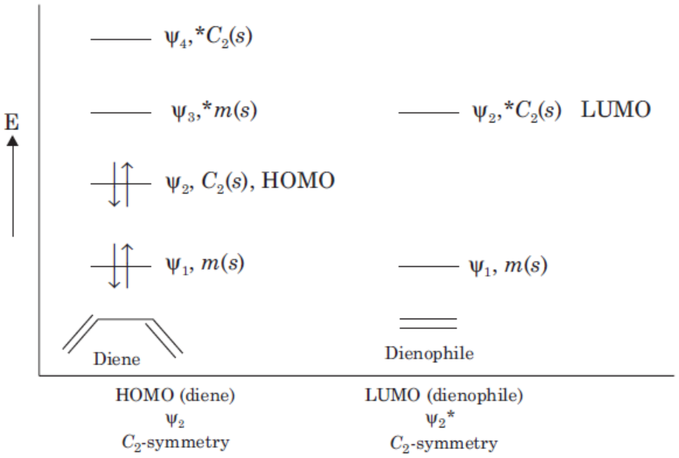
Stereospecific addition: $COOCH_3$ and H are *cis* in both products

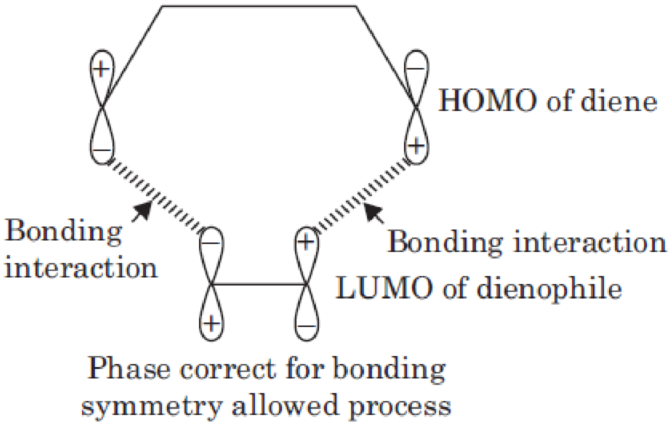
(F) The Frontier Orbital Description of [4 + 2] Cycloadditions

The reaction condition of [4 + 2] cycloaddition reactions are different from [2 + 2] cycloaddition reactions. [4 + 2] cycloaddition reaction is thermally allowed whereas [2 + 2] cycloaddition reaction is photochemically allowed. To see why this is so, we will examine the HOMO-LUMO interactions of only the *p*-orbital components that will form the new σ (*sigma*) bonds in a [4 + 2] cycloaddition. We will compare the HOMO-LUMO interactions for the ground state (for a thermal induced reaction) and those for the excited state (for photo induced reaction).

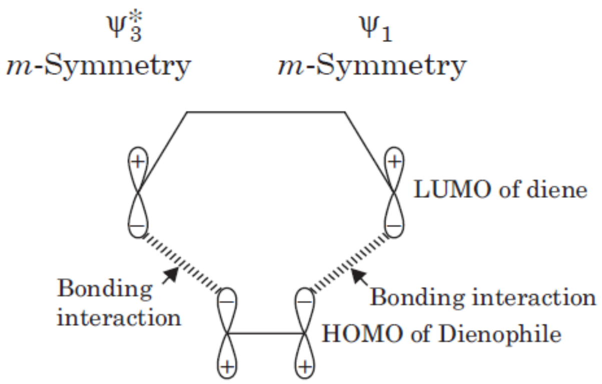
(i) **Thermal induced reaction:** There are two possible interactions, HOMO (diene)-LUMO (dienophile) and HOMO (dienophile)-LUMO (diene).

Case I: *HOMO of diene and LUMO of dienophile*





Case II: *LUMO of diene and HOMO of dienophile* LUMO (diene)—HOMO (dienophile)



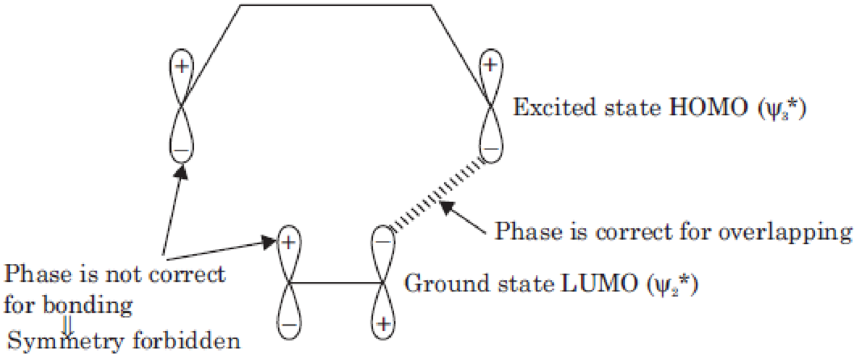
Phase correct for bonding
symmetry allowed process

The stronger of these two interactions will control the reaction. In this case, the stronger interaction is between the HOMO and LUMO pair closer in energy. The strength of the orbital overlap and the magnitude of the resulting stabilisation, depends on the relative energies of the two orbitals. The closer the two are in energy, the stronger the interaction.
In the Diels-Alder reaction of ethylene and butadiene, the two HOMO-LUMO interactions are of equal energy and orbital symmetry is same in both reactions. Both interactions involve bonding overlap at the point of formation of the two new σ (*sigma*) bonds. Accordingly this reaction is symmetry allowed reaction.

(ii) **Photo induced reaction:** In photo-induced cycloaddition reaction, interaction always takes place between excited state HOMO(HOMO*) of diene and ground state LUMO of dienophile and *vice-versa*. Thus, there are two possible interactions.

(*i*) Excited state HOMO (diene) and ground state LUMO (dienophile), and
(*ii*) Excited state HOMO (dienophile) and ground state LUMO (diene).

Let us take the example of excited state HOMO of diene and ground state LUMO of dienophile. When butadiene is excited by light its HOMO becomes ψ_3* which has *m*-symmetry. This MO cannot overlap with ground state LUMO of the ethylene which has C_2-symmetry.



Phase is not correct for overlapping symmetry forbidden process

Thus, photochemical cycloaddition of [4 + 2] system is symmetry forbidden reaction. On the basis of the results we can obtain the following selection rules for the cycloaddition reactions.

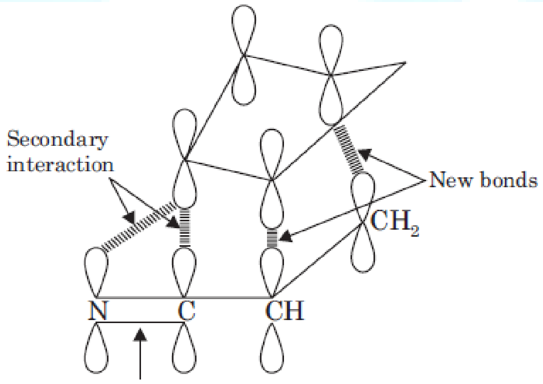
Selection rules for cycloaddition reactions

Number of electrons	*Mode of activation*	*Allowed stereochemistry*
$(4n)\pi$	Photochemical	Supra-Supra
$(4n + 2)\pi$	Thermal	Supra-Supra

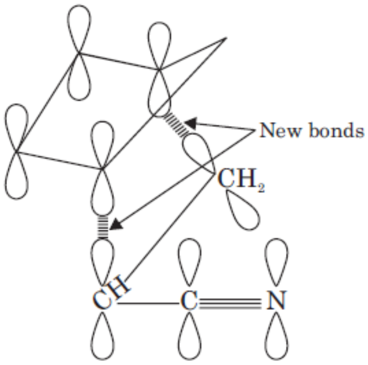
(*iii*) **Endo orientation in bicyclic compounds:** As mentioned earlier that the *exo* product is more stable (*i.e.*, it is thermodynamic product) than the *endo* product (*i.e.*, it is kinetically controlled product) in Diels-Alder reaction. Diels-Alder reaction always gives *endo* product as a major product when dienophile has a π bond in its electron-withdrawing group.

This clearly confirms that transition state of *endo* product in this case is more stable than the transition state of *exo* product due to some other factor, which overwhelms steric considerations.

In *endo* orientation the electron-withdrawing group having a π bond of a dienophile is directed to the inside of the cyclic ring, *i.e.*, electron-withdrawing group is nearer to the conjugated system of diene in the formation of transition state. In this orientation the *p*-orbital of the electron-withdrawing group approach the central carbon atoms (*C*-2 and *C*-3) of the diene. This proximity results in a weak secondary overlap: An overlap of the *p*-orbitals of the electron-withdrawing group with the *p*-orbitals of *C*-2 and *C*-3 of the diene. This fancy-phrase simply means that there can be interaction between the *back* diene orbitals and orbitals on the substituent only in the *endo* transition state. In *exo* orientation the electron-withdrawing group of the dienophile is directed away from the cyclic diene conjugated system.



Group is near to the conjugated system of diene *endo* transition state



Exo transition state has no possible secondary interactions

The Woodward – Hoffmann rule for Cycloaddition reaction

Thermal Reactions

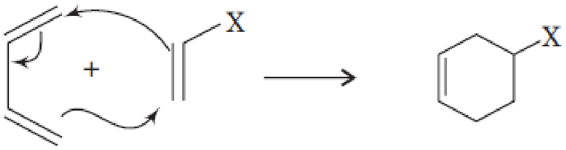
A thermal (ground state) pericyclic change is symmetry-allowed when the total number of (4*q* + 2)*s* and (4*r*) *a* components is odd.

Photo Chemical Reactions

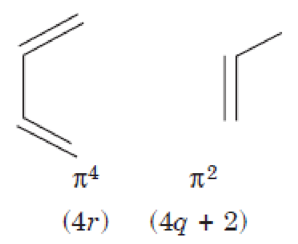
A pericyclic change in the first electronically excited state is symmetry-allowed when the total number of (4*q* + 2) *s* and (4*r*) *a* component is even.

The Woodward-Hoffmann Rule in | 4 + 2 | Cycloadditions

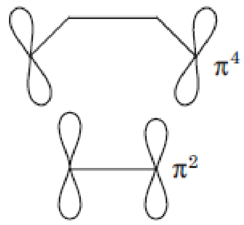
1. Draw the general mechanism of the reaction



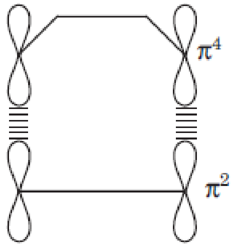
2. Choose the components. All the bonds taking part in the mechanism must be included and ignore all substituents which are not directly involved.



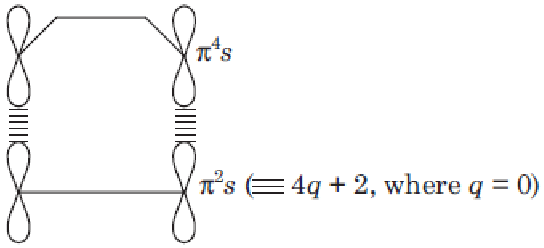
3. Make a three-dimensional drawing of the way the components come together for the reaction putting the orbitals at the ends of the components.



4. Join the components where new bonds are to be formed.



5. Label each component *s* or *a* depending on whether new bonds are formed on the same side or opposite sides.

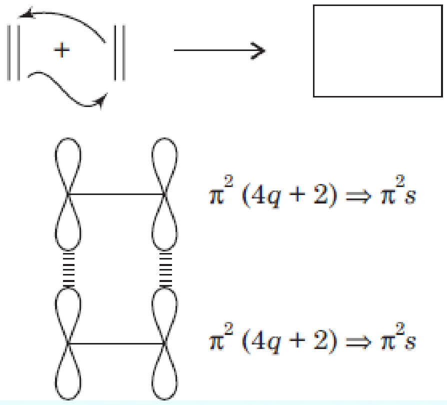


6. Count the number of $(4q + 2)$ *s* and $(4r)$ *a* components.

Number of $(4q + 2)$ *s* component = 1
Number of $(4r)$ *a* component = $\frac{0}{Total=1(odd)}$

Thermally allowed.

Woodward-Hoffmann Rule in |2 + 2| Cycloadditions



Number of $(4q + 2)$ *s* component = 2
Number of $(4r)$ *a* component = $\frac{0}{Total=2(even)}$

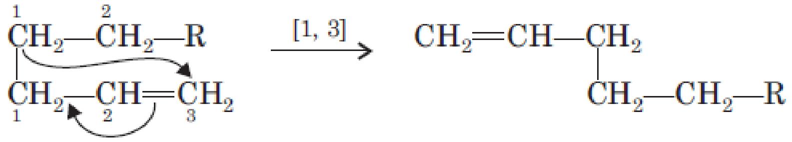
Photochemically allowed.

Sigmatropic rearrangements

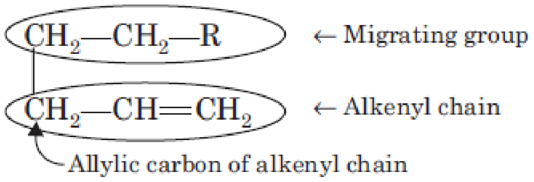
This rearrangement involves a concerted reorganisation of electrons during which a group attached by a σ (*sigma*) bond migrates to the terminus of an adjacent π (*pi*) electron system. The reactions are called sigma tropic rearrangement because a σ (*sigma*) bond appears to move from one place to another during the reaction. There is a simultaneous shift of the π (*pi*) electrons. The number of the π (*pi*) and σ (*sigma*) bonds remain separately unchanged.

Classification of sigmatropic rearrangements

Sigmatropic rearrangements are classified by a double numbering system (*i*, *j* or *m*, *n*) that refers to the relative positions of the atom or group involved in the migration. This method of classification is different from those for cycloaddition or electrocyclic reactions which are classified by the number of π (*pi*) electrons involved in the cyclic transition state. The method used in classifying sigmatropic rearrangement is best explained by the following examples:

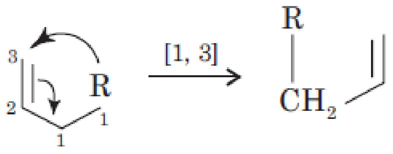


In sigmatropic rearrangement substrate can be divided in two parts: Alkenyl (or polyalkenyl) chain and migrating group. All substrates have at least one allylic carbon in alkenyl chain for sigmatropic rearrangement.

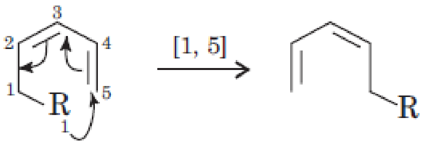


The sigmatropic rearrangements can be divided into *two classes.*

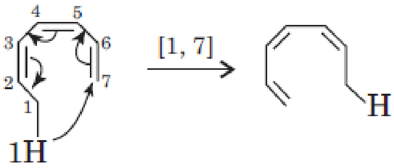
1. Those where the migrating atom or group is bonded through the same atom in both reactant and product.



R is bonded to carbon in reactant as well as in product

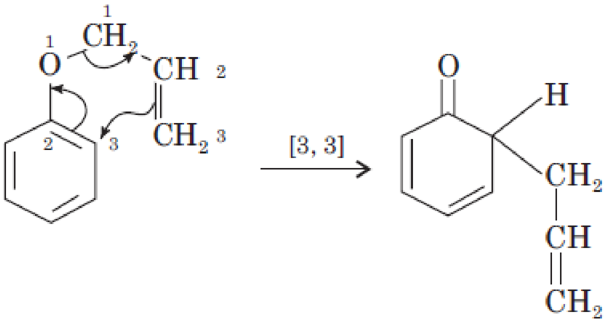


1, 5-shift of alkyl group, R is bonded to carbon in reactant as well as in product

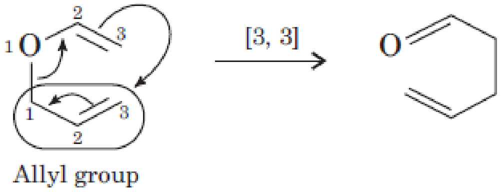


1, 7-shift of hydrogen. H is bonded to carbon in reactant as well as in product

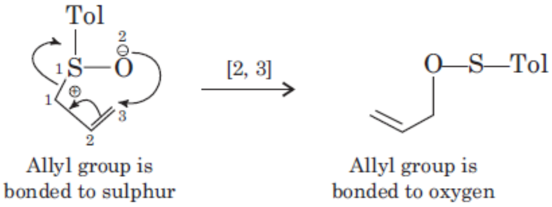
2. Those where the migrating atom or group is bonded through different atoms in reactant and in product.



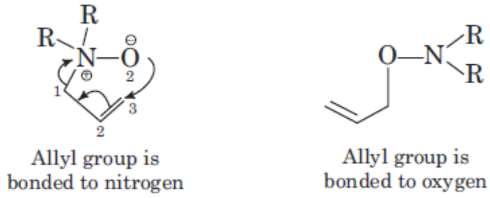
This is [3, 3] sigmatropic rearrangement in which carbon of allyl group is bonded to oxygen in the reactant and carbon in the product.



This is [3, 3] sigmatropic rearrangement of an allyl vinyl ether. Migrating group is bonded to the oxygen in the reactant which is bonded to the carbon in the product.



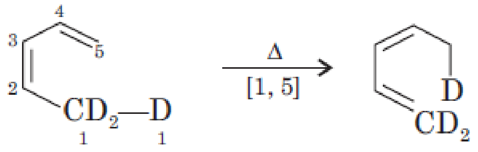
[2, 3] Sigmatropic rearrangement of an allyl sulphoxide



[2, 3] Sigmatropic rearrangement of an amine oxide

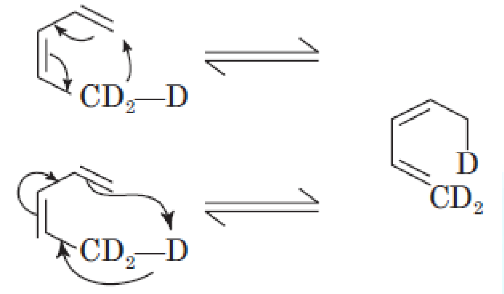
FMO Method

Consider the following reaction:

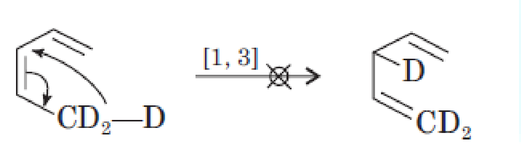


1, 3-Pentadiene

When 1, 3-pentadiene is heated, it gives [1, 5] sigmatropic rearrangement. It is simple to construct an arrow formalism picture of the reaction. The arrow could run in either direction, clockwise or anticlockwise. That is not true for a polar reaction in which the convention is to run the arrow from pair of electrons towards the electron deficient.

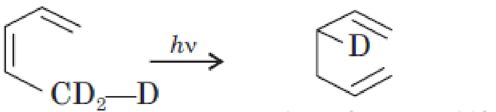


An arrow formalism description of the [1, 5] shift of deuterium in 1, 3-pentadiene. In the given example deuterium of *sp*3 hybrid carbon migrates on to the *sp*2 hybrid carbon (carbon-5). The given compound has also carbon-3 as *sp*2 hybrid carbon. Thus this compound can also give [1, 3] sigmatropic rearrangement on heating, but [1, 3] shift is not observed.



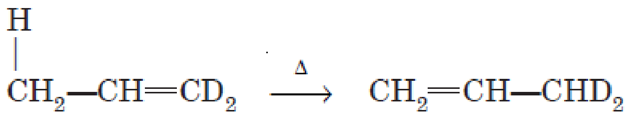
Not observed

An arrow formalism can easily be written and it might be reasonably argued that the [1, 3] shift requiring a shorter path than the [1, 5] shift. A second strange aspect of this reaction comes from photochemical experiments. When 1, 3-pentadienes are irradiated the product of the reaction include the molecules formed through [1, 3] shift but not those of [1, 5] shifts.



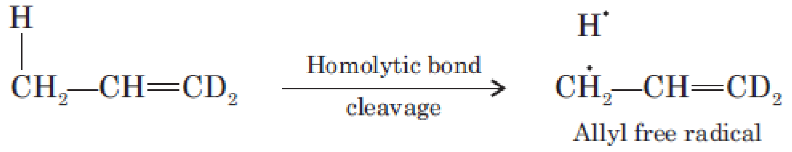
Product of a [1, 3] shift

So any mechanism proposed must include an explanation of why thermal shifts are [1, 5] whereas photochemically induced shifts are [1, 3]. We can use the frontier orbital approach to analyse these reactions and see why this is so. Let us first consider the following thermally induced sigmatropic rearrangement which is a [1, 3] shift.



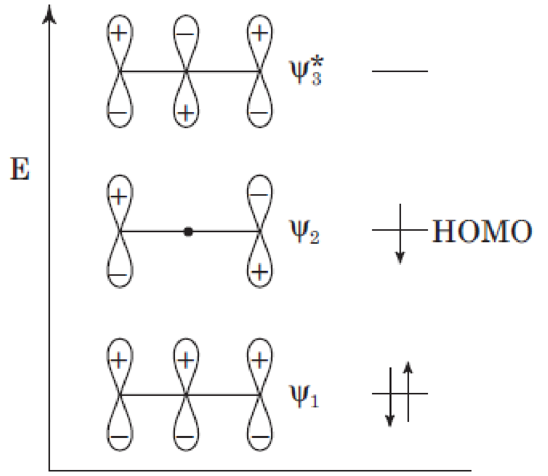
$$\overset{H}{\overset{|}{CH_2}}—CH=CD_2 \xrightarrow{\Delta} CH_2=CH—CHD_2$$

For the purpose of analysing the orbitals, it is assumed that the σ (*sigma*) bond connecting the migrating group to its original position undergoes homolytic cleavage to yield two free radicals. This is not how the reaction takes place because reaction is concerted. But this assumption does allow analysis of the molecular orbitals.



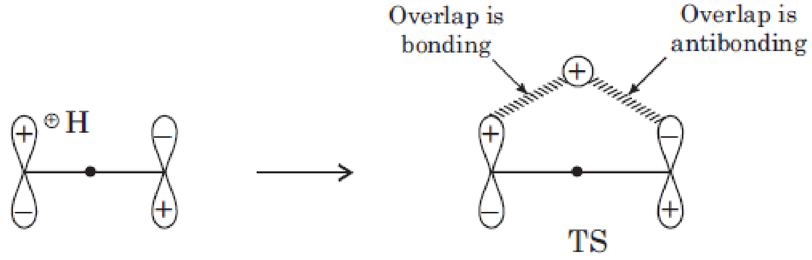
$$\overset{H}{\overset{|}{CH_2}}—CH=CD_2 \xrightarrow[\text{cleavage}]{\text{Homolytic bond}} \overset{H^{\bullet}}{\dot{C}H_2}—CH=CD_2$$

The products of the hypothetical cleavage are a hydrogen atom and an allyl free radical, which contains three *p*-orbitals. The π (*pi*) molecular orbitals of allyl free radical.



Molecular orbitals of allyl free radical

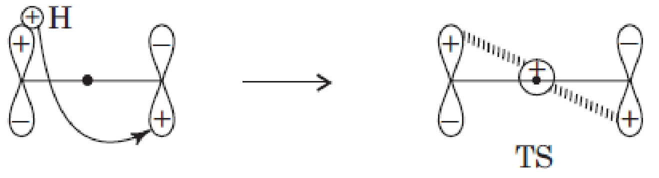
The actual shift of hydrogen could take place in one of the two directions. In the first case, the migrating group could remain on the same side of the π (*pi*) orbital system. Such a migration is known as a *suprafacial process*. In the thermal 1, 3 sigmatropic rearrangement a suprafacial migration is geometrically feasible but symmetry forbidden.



In the C—H bond the overlapping lobes are of the same sign

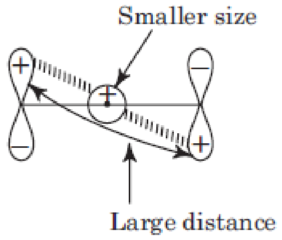
Symmetry forbidden (phase incorrect for overlapping)

Let us consider the second mode of migration for a symmetry allowed [1, 3] sigmatropic shift to occur, the migrating group must shift by an antarafacial process—that is, it must migrate to the *opposite face* of the orbital system.



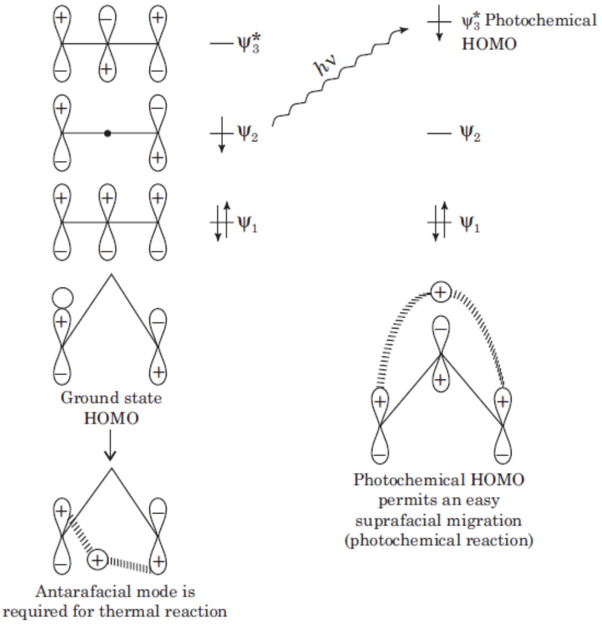
Overlap is bonding, symmetry allowed but geometry difficult

While symmetry-allowed a [1, 3] antarafacial sigmatropic rearrangement of hydrogen is not geometrically favorable. The problem is that the 1*s* orbital is smallest and cannot effectively span the distance required for an antarafacial migration. In other words, size of 1*s* orbital of hydrogen is smallest and distance between two lobes of interacting *p*-orbitals of carbon is maximum hence orbital of 1*s* cannot interact effectively with *p*-orbitals at same time in the formation of transition state.



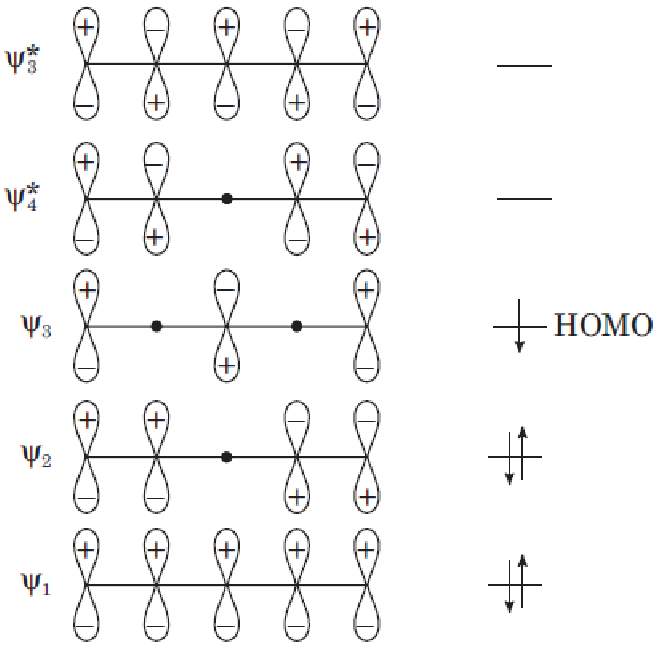
Symmetry allowed but geometrically difficult

[1, 3] sigmatropic shifts take place in the presence of UV light but examples are rare. Consider again what happens when a molecule absorbs a photon. LUMO of ground state will become HOMO of excited state known as photochemical HOMO.



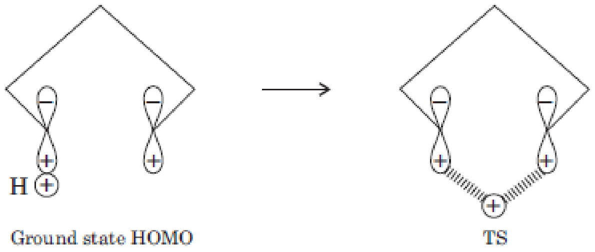
Suprafacial migration is possible in ψ_3^* photochemical HOMO of the reaction

[1, 5] Sigmatropic Rearrangement: The products of hypothetical cleavage in this case are hydrogen free radical and pentadienyl radical. π MOs of pentadienyl radical is given below :



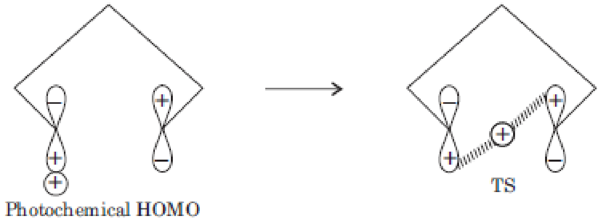
π Molecular orbitals of the pentadienyl radical

[1, 5] Sigmatropic shift is thermally allowed and photochemically forbidden. If we again assume a homolytic bond cleavage for purpose of analysis, we must consider the molecular orbitals of pentadienyl radical.



Suprafacial migration: *The [1, 5] suprafacial shift is symmetry allowed and geometrically feasible.*

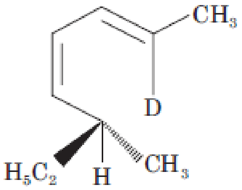
Consider photochemical [1, 5] sigmatropic rearrangement. In this case ψ4* will be photochemical HOMO.



Antarafacial migration, symmetry allowed but geometrically difficult.

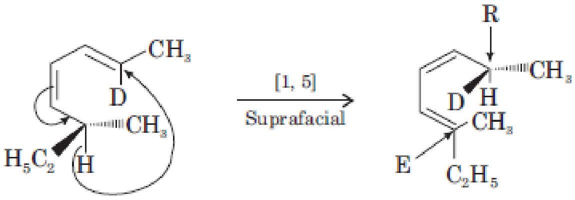
Stereochemistry of [1, 5] sigmatropic Rearrangement

Consider the following compound:



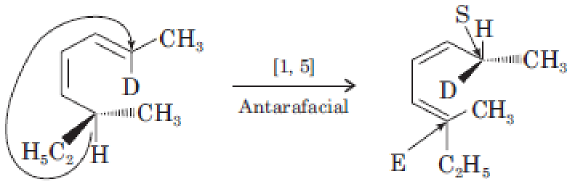
Compound has *S*-configuration at C-6 and *E* configuration at C-2.

Case I: *Suppose migration is suprafacial*



If migration is suprafacial then product has *R*-configuration at C-5 and *E*-configuration at C-1.

Case II: *Suppose migration is antarafacial*



If migration is antarafacial then product has *S*-configuration at C-7 and *E*-configuration at C-2.

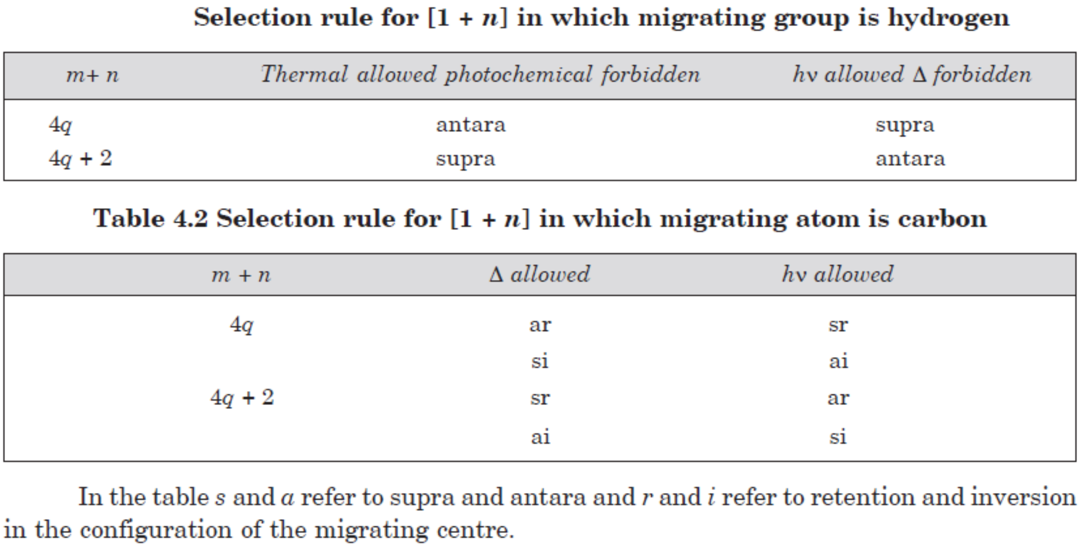
Experimentally it has been found that the product of the reaction is due to suprafacial migration. Thus, the theory is confirmed by this experimental result.

Selection rules for sigmatropic rearrangement

The stereochemistry (*i.e.*, migration of group is suprafacial or antarafacial) of sigmatropic rearrangement is a simply function of number of electrons involved (as with other pericyclic reactions, the number of electrons involved is easily determined from the curved-arrow formalism: Simply count the curved arrow and multiply by two). All suprafacial sigmatropic reactions occurs when there are ($4q + 2$) electrons involved in the reaction—that is an odd number of electron pairs or curved arrows.

Selection rule of [1, *n*] sigmatropic rearrangement when migrating group is hydrogen atom.

If sigmatropic reaction of the order ($m + n$) (for hydrogen $m = 1$) has $m + n = 4q + 2$ then thermal reaction is suprafacial and photochemical reaction will be antarafacial. However, for those cases in which $m + n = 4q$ then thermal reaction is antarafacial and photochemical reaction will be suprafacial.



Selection rule for [1 + *n*] in which migrating group is hydrogen

$m + n$	*Thermal allowed photochemical forbidden*	*hν allowed Δ forbidden*
$4q$	antara	supra
$4q + 2$	supra	antara

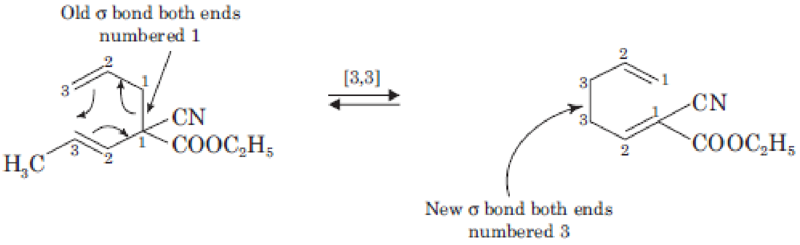
Table 4.2 Selection rule for [1 + *n*] in which migrating atom is carbon

$m + n$	*Δ allowed*	*hν allowed*
$4q$	ar	sr
	si	ai
$4q + 2$	sr	ar
	ai	si

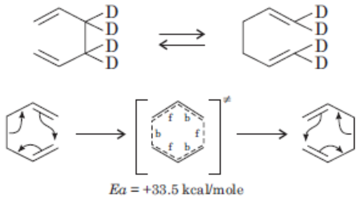
In the table *s* and *a* refer to supra and antara and *r* and *i* refer to retention and inversion in the configuration of the migrating centre.

Cope rearrangement

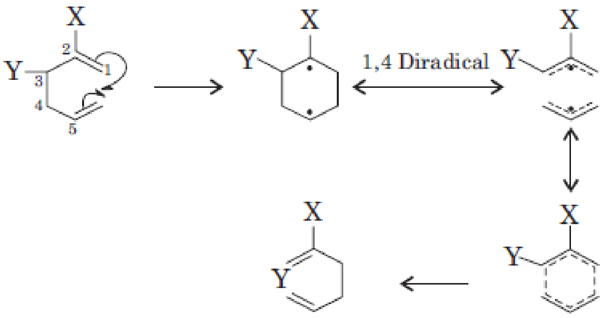
The most important sigmatropic rearrangement are the [3, 3] process involving carbon-carbon bond. The thermal rearrangement of 1, 5-dienes by [3, 3] sigmatropy is called Cope rearrangement. The reaction proceeds in the thermodynamically favoured direction.



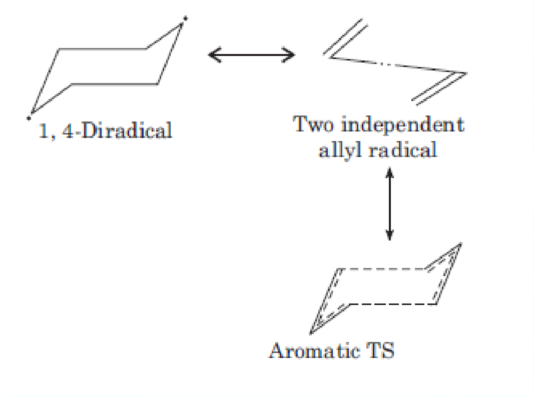
This particular reaction is called a [3, 3] sigmatropic rearrangement because the new *s* bond has a 3, 3 relationship to the old σ (*sigma*) bond. The equilibrium in this case is controlled by the conjugation present in the product. The rearrangement of the simplest possible case, 1, 5-hexadiene, has been studied using deuterium labelling. For this reaction activation energy is 33.5 kcal/mole and the entropy of activation is – 13.8 *eu*. The substantially negative entropy conforms the formation of cyclic transition state.



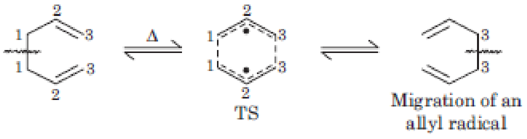
Conjugated substituents at C-2, C-3, C-4 or C-5 accelerate the rearrangement. Donor substituents at C-2 and C-3 have an accelerating effect. The effect of substituents can be rationalised in terms of the stabilisation of the transition state by depicting their different effect on two interacting system.



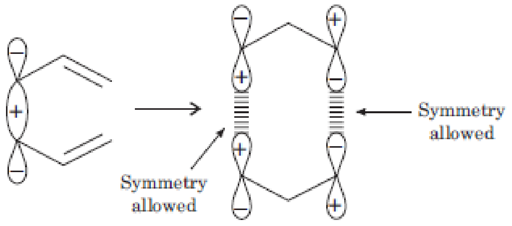
The transition state involves six partially delocalised electrons being transformed from one 1, 5-diene system to another. The transition state could range in character from a 1, 4-diradical to two nearly independent allyl radical, depending on whether bond making or bond breaking is more advanced. The general framework for understanding the substituent effects is that the reaction are concerted with relatively late transition state with well developed C-1-C-6 bonds.



The most advanced molecular orbital calculations support the idea of an aromatic transition state having six partially delocalised electrons. The net effect on reaction rate of any substituent is determined by whether it stabilises the transition state or the ground state more effectively. The aromatic concept of transition state predicts that it could be stabilised by conjugated substituents at all positions. In Cope rearrangement the migrating group is allyl radical. An analysis of the symmetry of the orbitals involved shows why this reaction is a relatively facile thermal process but is not commonly observed on photochemical activation. As we break the C(1)–C(1) bond the phases of the overlaping lobes must be the same. The HOMO of the allyl radical is y2 and that information allows us to fill the symmetries of the two allyl radicals making up of transition state.

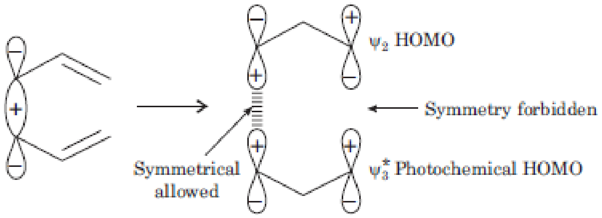


Reattachment at the two C(3) positions is allowed because the interaction of the two lobes on the two C(3) carbons is bonding.



Transition state: Two partially bonded allyl radicals—ψ_2 is the HOMO of each

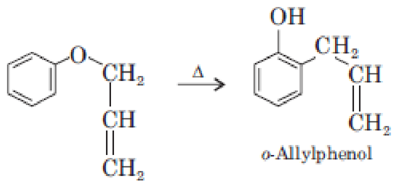
If interaction is carried out in the presence of UV light then one electron is promoted from the HOMO to the LUMO and LUMO will become photochemically HOMO.



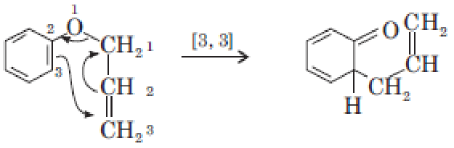
Interaction between HOMO ground and HOMO photochemical symmetry forbidden process

Claisen rearrangement

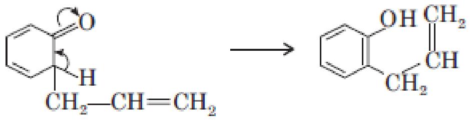
Claisen rearrangement is the first sigmatropic rearrangement which was discovered. The original sigmatropic rearrangement occurs when allyl phenyl ether is heated without solvent. The product of the rearrangement is *o*-allylphenol.



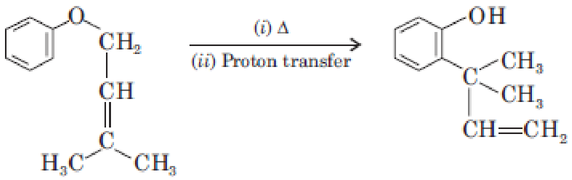
The above Claisen rearrangement is two step reaction. The first step in this reaction is [3, 3] sigmatropic rearrangement.



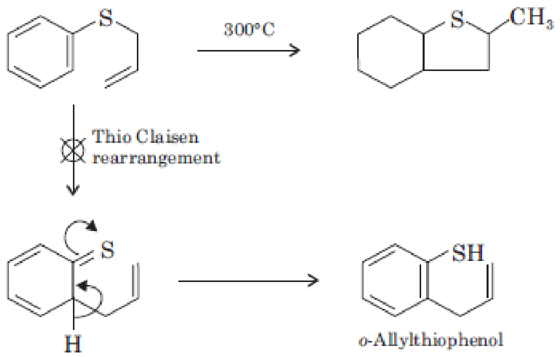
This is one step mechanism without ionic intermediates. In this case numbering start from the heteroatom oxygen having σ (*sigma*) bond and allylic carbon of the allyl group. The second step in the reaction is a simple ionic proton transfer to regenerate aromaticity.



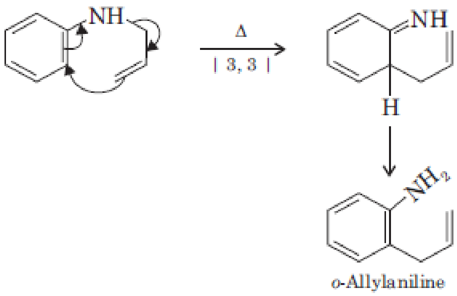
In this reaction allyl group turns inside out which is confirmed by unsymmetrical allyl ether.



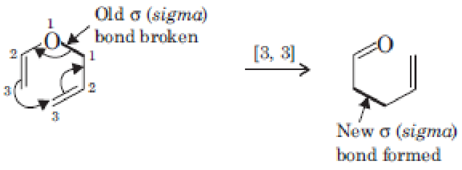
The conversion of allyl phenyl thioethers to *o*-allyl thiophenols, referred to as the thio-Claisen rearrangement, is not possible as the latter compounds are unstable but they instead give bicyclic compound.



But if the oxygen atom in allyl phenyl ether is replaced by nitrogen, then the normal Claisen rearrangement takes place to afford the amino derivatives.



Claisen rearrangement is also given by allyl vinyl ether and in this case rearrangement is known as *aliphatic Claisen rearrangement* or *Claisen-Cope* rearrangement.



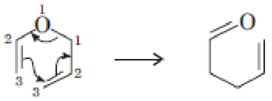
Woodward-Hoffmann rule

According to Woodward-Hoffmann rule a thermal (ground state) sigmatropic rearrangement is symmetry allowed when total number of $(4q + 2)s$ component and $(4r)a$ component is odd. Similarly a sigmatropic change in the first excited state is symmetry allowed when total number of $(4q + 2)s$ and $(4r)a$ component is even.

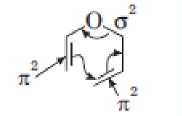
The Woodward-Hoffmann rule for (m,n) sigmatropic rearrangement where migrationg group is not hydrogen

Here we will discuss [3, 3] sigmatropic rearrangement and in this case we will consider the Claisen rearrangement.

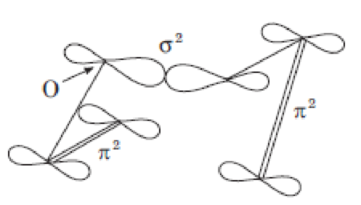
1. Draw the mechanism for the reaction.



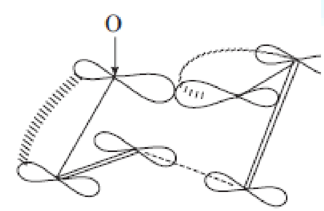
2. Choose the components. Only the bonds taking part in the reaction mechanism must be included.



3. Make a three-dimensional drawing of the way the components come together for the reaction, putting orbitals at the ends of the components.



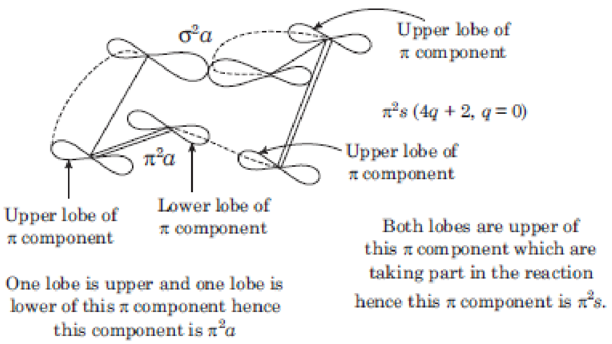
4. Join up the components where new bonds are to be formed. Make sure you join orbitals that are going to form new bonds.



(a) Whether p component is *s* or *a*

If both upper lobes or both lower lobes of the π (*pi*) component are involved in the reaction then the component will be *s* and it is label as $\pi 2s$.

If one upper lobe and other lower lobe of the π (*pi*) component are involved in the reaction then the component will be *a* and it is label as $\pi 2a$.



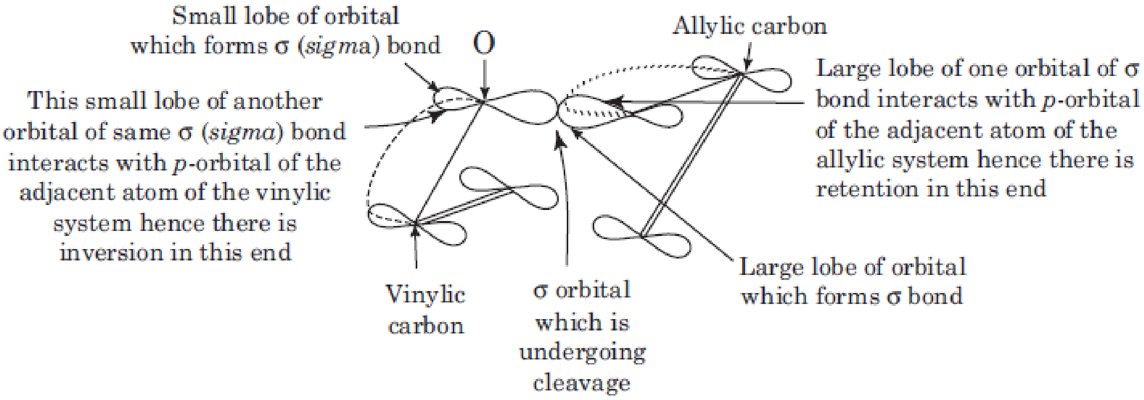
(b) **Whether** s **component is *s* or *a* (when migrating atom is not hydrogen)**

(*i*) If *sp*3-hybrid orbital uses its large lobe for reaction then there will be retention or the small lobe then there will be inversion.
Or

If large lobe of one orbital of the σ bond (which is undergoing cleavage) interacts with *p*-orbital of the adjacent atom (say atom-2 of allyl system) then at this end there will be retention.

If small lobe of the other orbital of the σ bond (which is undergoing cleavage) interacts with *p*-orbital of the adjacent atom (say atom-2 of vinyl system) then at this end there will be inversion.

(*ii*) If there is retention at both ends or inversion at both ends then σ component is σ2*s*.
If there is retention at one end and inversion at other end then σ component is σ2*a*.



Thus, σ component has retention at one end and inversion at another end hence σ component is σ2*a*.

6. Count the number of (4*q* + 2)*s* and (4*r*) *a* components.
Number of (4*q* + 2)*s* component = 1
Number of (4*r*)*a* component = 0
Total = 1 (odd) thermally allowed.

Note: π2 *a* (4*q* + 2)*a* and σ2*a* (4*q* + 2) components have irrelevant symmetry and are not counted.