UNIT 9 CARBENES, NITRENES AND BENZYNES

Structure

9.1 INTRODUCTION

In the earlier units in this course, you have learnt that certain organic reactions proceed *via* electron-deficient intermediates (carbocations) while in others, electron-rich intermediates (carbanions) are involved. In this unit, we will study some other types of intermediates which are commonly encountered in molecular rearrangements, namely the carbenes, nitrenes and benzynes. Carbenes and nitrenes are electron-poor species having a sextet of electrons on carbon or nitrogen. The simplest benzyne, benzyne (C_6H_4) is dehydrobenzene which is postulated as an intermediate in nucleophilic substitution of aryl halides. These are all highly reactive intermediates. Their reactions are often markedly selective and interesting from the mechanistic view. Still another type of reaction intermediates, the free radicals will be taken up in the next unit.

Objectives

After studying this unit, you should be able to:

- outline different methods for generation of carbenes, nitrenes and benzynes,
- discuss the structures and stabilities of carbenes, nitrenes and benzynes, and
- explain the reactivity of these reaction intermediates and discuss their important reactions.

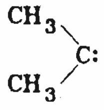
9.2 CARBENES

Carbenes are neutral divalent carbon intermediates with only a sextet on carbon. The simplest carbene is methylene ($:CH_2$), in which the carbon atom has only six electrons, two each in the two carbon-hydrogen covalent bonds and two unshared. As such, methylene is electrically neutral as there is no formal charge on carbon (compare with carbocations and carbanions). However, with only a sextet on the carbon, of which two are unshared electrons, carbenes are expected to be intensely reactive.

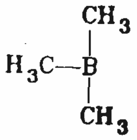
$$CH_2N_2 \xrightarrow{-N_2} :CH_2$$

$$:CH_2 + CH_2N_2 \xrightarrow{-N_2} CH_2{=}CH_2$$

One or both hydrogen atoms in methylene may be replaced by halogen, alkyl, phenyl or acyl groups. The reactions of dichlorocarbene (dichloromethylene) are quite common and would be described later in this unit. The species $(CH_3)_2C$: is known as dimethylcarbene or isopropylidene. Dimethylcarbene is isoelectronic with boron trimethyl. The central carbon and boron atom in each is electron-deficient with only a sextet. Therefore both of them act as electrophiles.



dimethyl
carbene



boron
trimethyl

9.2.1 Generation

Since carbenes are highly reactive, they are generated *in situ*, i.e. in the reaction itself. The following methods for their generation are common:

i) Photolysis or thermolysis of diazomethane or ketene:

$$[\overset{-}{C}H_2-\overset{+}{N}\equiv N \longleftrightarrow CH_2{=}\overset{+}{N}{=}\overset{-}{N}] \xrightarrow{h\nu \text{ or } \Delta} :CH_2 + N_2$$

diazomethane **methylene**

$$CH_2{=}C{=}O \xrightarrow{h\nu \text{ or } \Delta} :CH_2 + CO$$

ketene **methylene**

You would notice that diazomethane and ketene are isoelectronic as are N_2 and CO.

ii) Elimination or 1,1-elimination from haloalkanes: This happens when a haloalkane is treated with a very strong base like potassium *tert*-butoxide (2-methyl propoxide) or *n*-butyl lithium.

$$CHCl_3 + tert\text{-}Bu\overset{-}{O}\overset{+}{K} \xrightarrow{DMSO} :CCl_2 + tert\text{-}BuOH + KCl$$

potassium *tert*-butoxide **dichlorocarbene**

$$CH_2Cl_2 + n\text{-}Bu\,\overset{-}{}\overset{+}{Li} \longrightarrow :CHCl + n\text{-}BuH + LiCl$$

butyl lithium **chlorocarbene** **butane**

In the above reactions, both a proton and a chloride ion are lost from the same carbon atom. Hence such reactions are called as α-elimination or 1,1-elimination, (compare with β-elimination or 1,2-elimination described in Unit 7).

iii) Treatment of (methylene iodide) with zinc, in the presence of copper or silver, in ether solution:

$$CH_2I_2 + Zn \xrightarrow[(C_2H_5)_2O]{Cu \text{ or } Ag} I-CH_2-Zn-I \longrightarrow :CH_2 + ZnI_2$$

(iodomethyl)zinc iodide **methylene**

This is Known as **Simmons - Smith reaction.** The organic compound CH_2ZnI_2 having a masked carbene is called a carbenoid, i.e., carbene like.

iv) Thermal decomposition of sodium trichloroacetate:

$$CCl_3CO\overset{-}{O}\,\overset{+}{Na} \longrightarrow CO_2 + \overset{+}{Na}\;\overset{-}{C}Cl_3 \xrightarrow[-\,NaCl]{} :CCl_2$$

dichlorocarbene

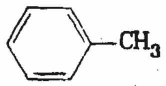
v) Thermal or photochemical decomposition of alkali metal salts of *p*-toluene sulphonylhydrazones of aldehydes and ketones.

$$R_2C=\overset{+}{N}-\overset{-}{N}ArSO_2^{-}\overset{+}{Na} \xrightarrow{h\nu \text{ or } \Delta} R_2C: + N_2 + ArSO_2^{-}\overset{+}{Na}$$

sodium salt of
p-toluene sulphonyl
hydrazone

sodium benzene
sulphonate

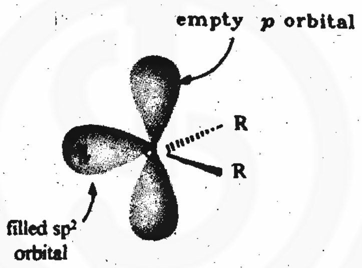
Ar =



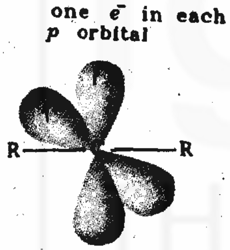
9.2.2 Structure and Stability

Singlet carbene is also indicated as $>C^{\uparrow\downarrow}$ or $>C:$ or $>C^{\uparrow\downarrow}$ whereas triplet carbene is indicated as $>C^{\uparrow\uparrow}$ or $>\overset{\cdot}{\underset{\cdot}{C}}$ or $>\overset{\uparrow}{\underset{\uparrow}{C}}$

The electronic spectra of carbenes show that there are two forms of carbenes-the singlet and the triplet. Let us see how we can account for this. As you know carbon has four low-energy orbitals, one 2*s*, and three 2*p*. In a carbene, two of these are used for bonding. Therefore, there are two low-energy orbitals available to accommodate the unshared electrons. If both these electrons go into one orbital, the spins must pair. If these two electrons go into different orbitals they will have parallel or unpaired spins. A carbene in the latter state would have a permanent magnetic moment and would exist in three closely grouped energy states, if it were placed in a magnetic field. Such a state is called the triplet state. The state, in which the electrons are paired, has no magnetic moment and exists in a single energy state when placed in a magnetic field. Hence it is called the singlet state. Singlet carbene is generated initially in photolysis of diazomethane, as in the preparation (i) above. It is usually formed in the liquid phase. Singlet carbene is less stable of the two. It has higher energy than the triplet carbene due to electron repulsion arising from pairing the two electrons in a single orbital. Singlet carbene is supposed to have a bent shape with RCR bond angle around 103-110°. Here the carbon is sp^2 hybridized.



singlet carbene, : CR_2
(C is sp^2)



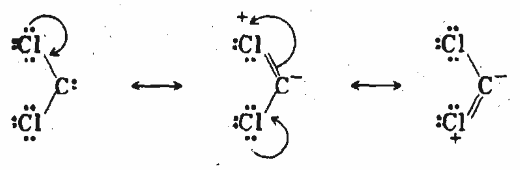
triplet carbene, RCR
(C is *sp*)

Changeover from singlet to triplet state is called inter system crossing.

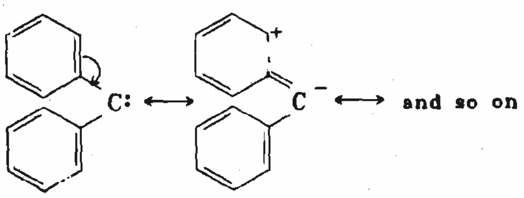
$$>C: \rightsquigarrow \overset{\cdot}{\underset{\cdot}{C}}-$$

Triplet carbene is formed in gas phase photolysis in the presence of an inert gas like nitrogen or argon. Since in triplet carbene, the unshared electron pair is not spin-paired, the two electrons with parallel spins are in separate *p*-orbitals. So triplet carbene behaves as a diradical. It is nearly linear in shape, with RCR bond angle around 136-180°, and the carbon atom is *sp* hybridised.

Atoms with unshared pairs of electrons like halogen atoms stabilise carbenes. We can visualise the following type of resonance, which would stabilise a carbene.



Phenyl groups can, similarly stabilise a carbene through resonance.



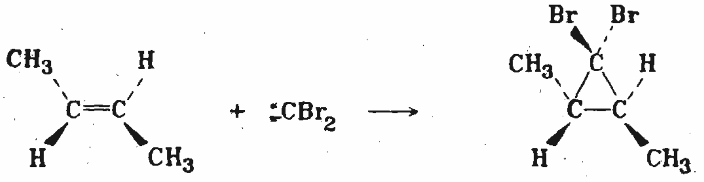
9.2.3 Reactions

Carbenes usually undergo two types of reactions. These are cycloadditions and insertions.

Cycloaddition-Formation of a Ring

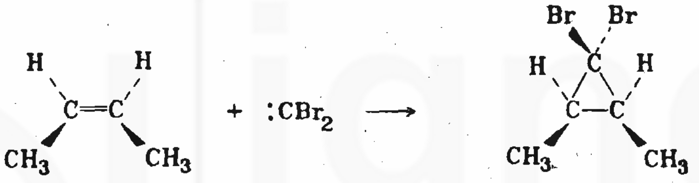
Reactions in which a reagent adds across a multiple bond to give a cyclic product are called cycloadditions. Thus, the reaction of bromoform with potassium *tert*-butoxide in the presence of *trans* 2-butene forms *trans*-dimethyldibromocyclopropane. *cis*-2-Butene affords the corresponding *cis*-cyclopropane derivative under the same conditions. Here dibromocarbene is generated by the reaction of bromoform with *tert*-butoxide which then adds at the C=C bond of the alkenes.

$$CHBr_3 + tert\text{-}Bu\bar{O}\ \overset{+}{K} \longrightarrow :CBr_2 + tert\text{-}BuOH + KBr$$



trans -2-butene

trans -dimethyl-dibromo-cyclopropane



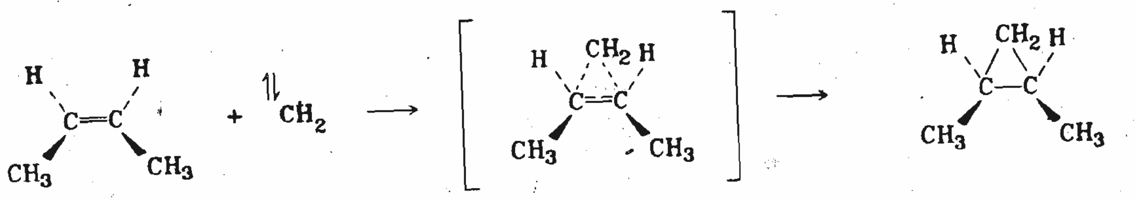
cis -2-butene

cis -dimethyl-dibromo-cyclopropane

The cycloaddition reactions also support the existence of two forms of carbene. For instance, it has been observed that photolysis of diazomethane in the presence of *cis*-2 butene gives only the *cis*-1,2-dimethylcyclopropane. It is presumed that in this reaction, the singlet methylene which is generated, attacks simultaneously both the double-bonded carbon atoms of the alkene in a concerted or nearly concerted manner. The overlap of the π-cloud of alkene with empty *p* orbital of methylene results in the formation of the cyclic intermediate (I). This results in a stereospecific addition, i.e. the cyclopropane formed has the same stereochemistry as the alkene. In this case both have *cis*-geometry. This reaction is an example of *cis* or *syn* addition, meaning that both the new bonds are formed on the same side or face of the alkene.

$$CH_2N_2 \xrightarrow[-N_2]{h\nu} {}^{\uparrow\downarrow}CH_2$$

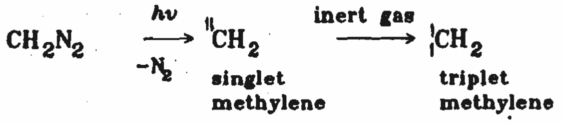
singlet methylene



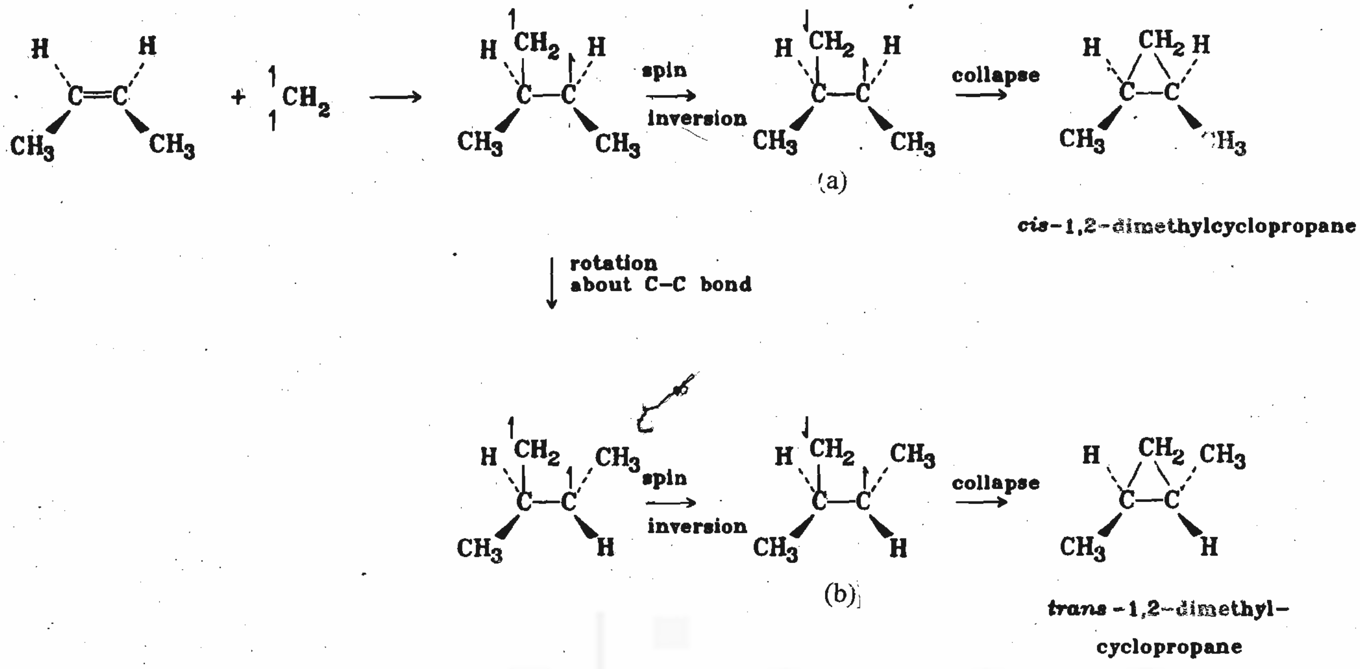
(I)

[*cis* -1,2-dimethylcyclopropane]

If the above reaction is carried out in the presence of an inert gas, the singlet methylene generated initially gets converted to the triplet state. This occurs due to intermolecular collisions. Triplet carbene acts as a diradical and adds to the alkene in two steps. The initial addition of the triplet carbene to one of the carbon atoms of the alkene gives an intermediate diradical. The latter has a life-time long enough to permit rotation about the central carbon-carbon bond. Collapse of the two types of intermediates *a* and *b* would give a mixture of *cis* and *trans*-1,2-dimethylcyclopropanes. It is clear that in this case stereospecificity would be lost. Compare this with stereospecific addition of singlet methylene which occurs in one step, in a concerted manner as described above.



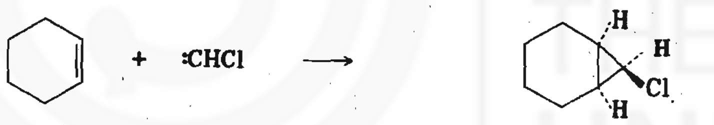
$CH_2N_2 \xrightarrow[-N_2]{h\nu} {}^{\uparrow\downarrow}CH_2 \xrightarrow{\text{inert gas}} {}^{\uparrow}_{\uparrow}CH_2$



The *syn* addition of a carbene to a cyclic alkene gives a bicyclic product having *cis* stereochemistry at the bridge-head. An illustrative example is the addition of chlorocarbene to cyclohexene.

$CH_2Cl_2 + n\text{-BuLi} \longrightarrow :CHCl_2$

dichloromethane chlorocarbene

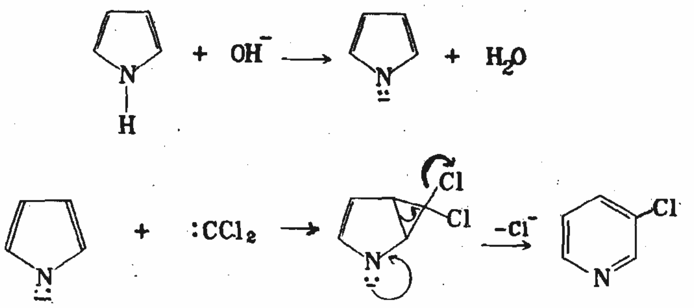


cis-bicyclo-7-chloro-[4.1.0]heptane
(7-chloronorcarnane)

Polycyclic compounds, in which or more carbon atoms are common to two or more rings, take the name of the open-chain compound having the same number of carbon atoms. Suffixes such as bicyclo- or tricyclo- indicate the number of rings. The points of fusion of the rings are indicated by listing numbers of carbon atoms in each of the bridges, i.e., the number of atoms between the fusion points or bridge heads. The atoms in larger ring are numbered first and then in the smaller one. The bridges are listed within brackets in order of decreasing length. Check the name given to 7-chloronorcarnane and convince yourself that it is correct.

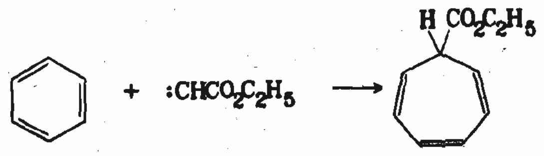
In some cases, the initial cycloaddition of carbene to cyclic molecules is followed by a ring opening process. The bond common to both rings of the bicyclic addition product gets cleaved. This process, thus, leads to ring expansion. A common example is the reaction of pyrrole with trichloromethane (chloroform) and caustic potash to give 3-chloropyridine, where a five membered ring gets expanded to a six-membered one.

$$CHCl_3 + KOH \longrightarrow :CCl_2 + KCl + H_2O$$



The conversion of a six-membered ring to a seven-membered ring product occurs in the formation of cycloheptatriene carboxylate from the photolysis of diazoacetic ester in the presence of benzene.

$$N_2CHCO_2C_2H_5 \xrightarrow[-N_2]{h\nu} :CHCO_2C_2H_5$$



SAQ 1

It is interesting to note that when photolysis of diazomethane is carried out in liquid *cis* or *trans* 2-butene, the addition is stereoselective and stereospecific. On the other hand when photolysis is carried out in gaseous 2-bufene, the addition is non-stereoselective and non-stereospecific. Explain.

....

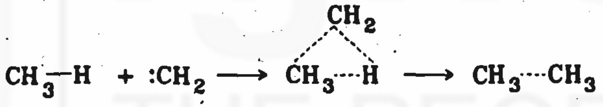
....

....

Insertions

It has been observed that the activated carbenes generated by photolysis of diazomethane or ketene undergo insertion reactions with alkanes. Methylene, for example, gets inserted into the carbon-hydrogen bond of methane to give ethane.

$$CH_2N_2 \xrightarrow[-N_2]{h\nu} :CH_2$$



$$CH_3{-}H + :CH_2 \longrightarrow \overset{CH_2}{CH_3 \cdots H} \longrightarrow CH_3 \cdots CH_3$$

With propane, a mixture of butane and 2-methylpropane is formed. Carbene, in this case, may be generated by photolysis of ketene,

$$CH_2{=}C{=}O \xrightarrow[-CO]{h\nu} :CH_2$$

$$:CH_2 \quad + \quad CH_3{-}CH_2{-}CH_2{-}H \quad \longrightarrow \quad CH_3{-}CH_2{-}CH_2{-}CH_3$$

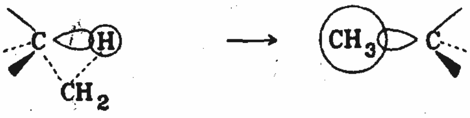
63%

$$:CH_2 \quad + \quad CH_3{-}\underset{\displaystyle H}{\underset{|}{CH}}{-}CH_3 \quad \longrightarrow \quad CH_3{-}\underset{\displaystyle CH_3}{\underset{|}{CH}}{-}CH_3$$

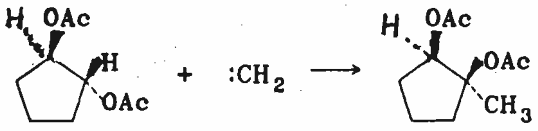
37%

Such insertion reactions with higher alkanes lead to a complex mixture of isomeric products.

It is supposed that the back lobe of the C—H bond is involved in insertion reactions leading to an inversion of configuration.

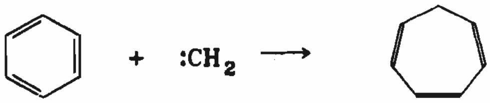


This is elegantly illustrated by photolysis of diazomethane in the diacetate of *trans*-1,2-cyclopentanediol. In the product, the two acetate groups have a *cis* configuration. Obviously inversion of configuration has taken place during the insertion reaction.



diacetate of *cis*-2-methyl-1,2-cyclopentanediol

Methylene also inserts into benzene to form cycloheptatriene.



cycloheptatriene

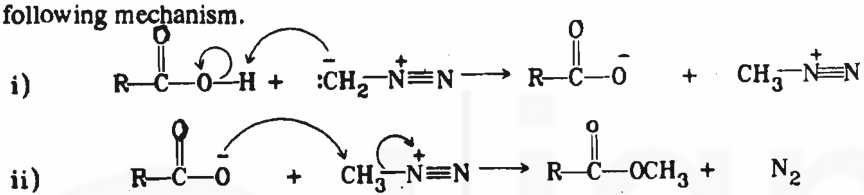
Insertion of carbenes also occurs into oxygen-hydrogen bonds of alcohols and acids. In fact this is one of the most convenient methods for preparing methyl ethers or esters. The alcohol or acid has just to be treated with an ethereal solution of diazomethane.

$$CH_2N_2 \longrightarrow :CH_2 + N_2$$

$$RCH_2{-}O{-}H \quad + \quad :CH_2 \longrightarrow RCH_2{-}O{-}CH_3$$

$$RCH_2{-}COOH \quad + \quad :CH_2 \longrightarrow RCH_2{-}COOCH_3$$

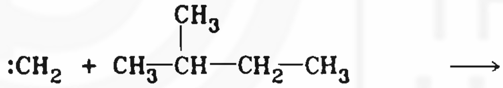
Unlike the C—H bond O—H bond is a polar bond and the reaction is supposed to proceed by the following mechanism.



Similar insertion products are formed from alkyl halides. However, insertion reactions of dichlorocarbene and methylene obtained by **Simmons-Smith** reaction have not been observed.

SAQ 2

Predict the products in the following reactions.

i)


$$:CH_2 + CH_3{-}\overset{\overset{\displaystyle CH_3}{|}}{CH}{-}CH_2{-}CH_3 \longrightarrow$$

ii)

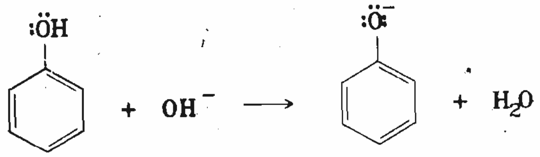

$$C_6H_5\overset{\overset{\displaystyle O}{\|}}{C}C_6H_5 + CH_3OH \longrightarrow$$

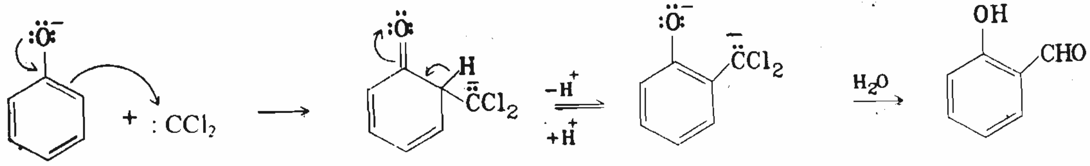
iii)


Some of the common and synthetically useful reactions occurring through carbene intermediates are described below:

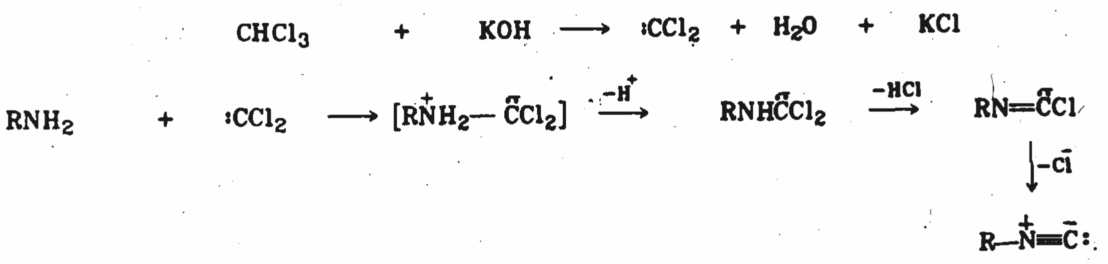
Reimer - Tiemann Reaction : **Involves heating a phenol with chloroform and aqueous sodium hydroxide to give a hydroxyaldehyde. Thus phenol reacts with chloroform and aqueous sodium hydroxide to give *o*-hydroxybenzaldehyde.**

$$CHCl_3 \quad + \quad KOH \longrightarrow :CCl_2 + H_2O + KCl$$





Carbylamine Reaction: On heating a mixture of a primary amine, chloroform and caustic potash, an isocyanide or nitrile, having a bad smell is formed. This is one of the tests for the presence of a *p*-amino group in a compound.



$$CHCl_3 + KOH \longrightarrow :CCl_2 + H_2O + KCl$$

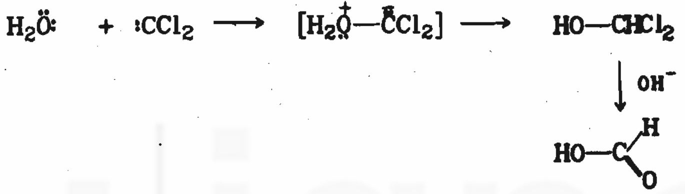
$$RNH_2 + :CCl_2 \longrightarrow [R\overset{+}{N}H_2-\overset{-}{C}Cl_2] \xrightarrow{-H^+} RNH\overset{-}{C}Cl_2 \xrightarrow{-HCl} RN{=}\overset{-}{C}Cl \xrightarrow{-\bar{Cl}} R-\overset{+}{N}{\equiv}\overset{-}{C}:$$

Ylides are compounds in which two adjacent atoms bear opposite formal charges, but the negative atom cannot donate its unshared pair to the bond between them since the positive atom already has its octet full. The name ylide is a combination of suffix 'yl' and 'ide'. N and S-ylides are also known.

Dichlorocarbene (generated as above) reacts with ethanol to give ethyl orthoformate. This reaction is used in industrial preparation of orthoformate ester.

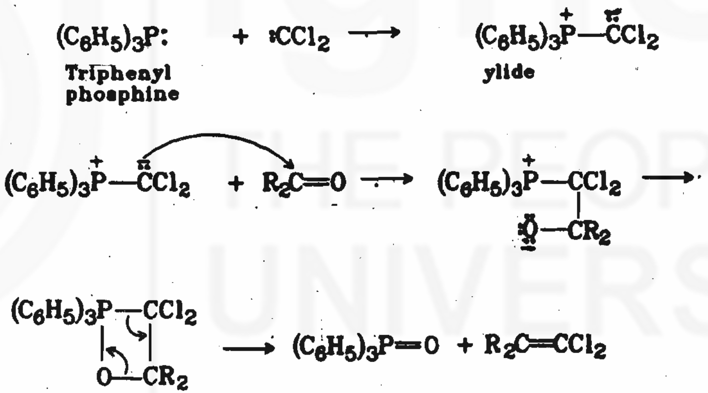
$$:CCl_2 + C_2H_5OH \longrightarrow C_2H_5OCHCl_2 \xrightarrow{2C_2H_5\bar{O}} (C_2H_5O)_3CH + 2\bar{Cl}$$

Dichlorocarbene is hydrolysed readily to form formate ion.



$$H_2\ddot{O}: + :CCl_2 \longrightarrow [H_2\overset{+}{O}-\overset{-}{C}Cl_2] \longrightarrow HO-CHCl_2 \xrightarrow{OH^-} HO-C(H){=}O$$

Wittig Reaction: Dichlorocarbene reacts with triphenylphosphine to give an ylide intermediate which on treatment with ketones gives 1,1-dichloroalkenes.

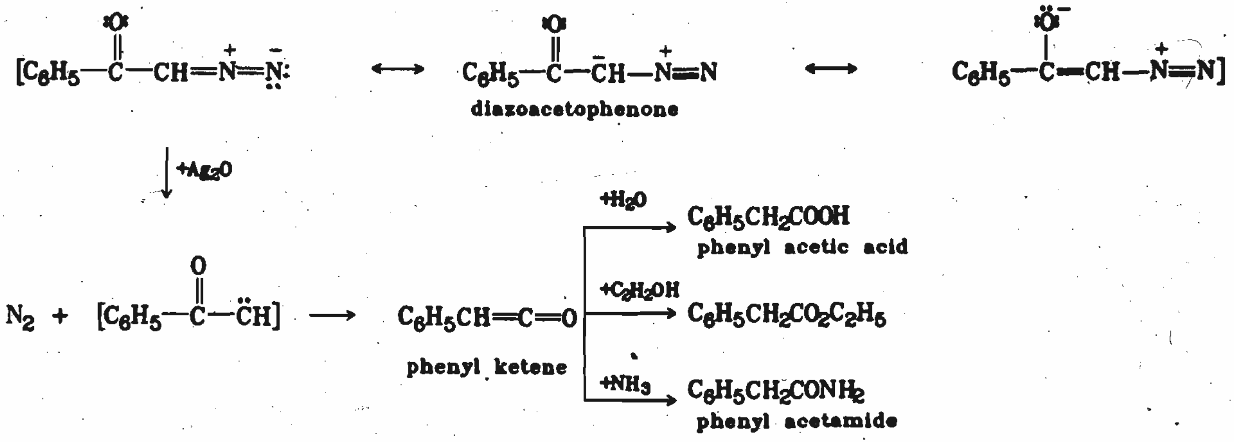


$$\underset{\text{Triphenyl phosphine}}{(C_6H_5)_3P:} + :CCl_2 \longrightarrow \underset{\text{ylide}}{(C_6H_5)_3\overset{+}{P}-\overset{-}{C}Cl_2}$$

$$(C_6H_5)_3\overset{+}{P}-\overset{-}{C}Cl_2 + R_2C{=}O \longrightarrow (C_6H_5)_3\overset{+}{P}-CCl_2(-CR_2-\ddot{O}:^-) \longrightarrow$$

$$(C_6H_5)_3P-CCl_2(O-CR_2) \longrightarrow (C_6H_5)_3P{=}O + R_2C{=}CCl_2$$

Wolff Rearrangement: A carbene intermediate is formed when α-diazoketones are either treated with silver oxide or irradiated with light. Migration of a group, attached to the carbonyl function, to the electron-deficient carbon gives rise to a ketene. This isomerisation is known as the Wolff rearrangement. The ketene rapidly reacts with protic solvents to form addition products. Carboxylic acids, esters or acid amides are the final products formed with water, ethanol or ammonia, respectively.



$$[C_6H_5-C(=\ddot{O})-CH{=}\overset{+}{N}{=}\overset{-}{\ddot{N}}: \longleftrightarrow \underset{\text{diazoacetophenone}}{C_6H_5-C(=\ddot{O})-\overset{-}{C}H-\overset{+}{N}{\equiv}N} \longleftrightarrow C_6H_5-C(-\ddot{O}^-){=}CH-\overset{+}{N}{\equiv}N]$$

$$\xrightarrow{+Ag_2O} N_2 + [C_6H_5-C(=O)-\ddot{C}H] \longrightarrow \underset{\text{phenyl ketene}}{C_6H_5CH{=}C{=}O}$$

$$C_6H_5CH{=}C{=}O \xrightarrow{+H_2O} \underset{\text{phenyl acetic acid}}{C_6H_5CH_2COOH}$$

$$C_6H_5CH{=}C{=}O \xrightarrow{+C_2H_5OH} C_6H_5CH_2CO_2C_2H_5$$

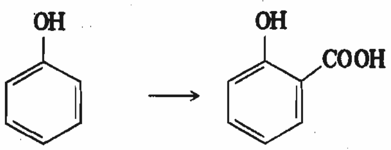
$$C_6H_5CH{=}C{=}O \xrightarrow{+NH_3} \underset{\text{phenyl acetamide}}{C_6H_5CH_2CONH_2}$$

The above reaction is used to convert carboxylic acids, via acid chlorides, , to their higher homologues in Arndt-Eistert synthesis.

SAQ 3

How will you affect the following conversions?

i)



ii)

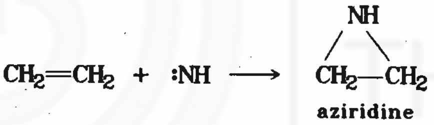
iii) $C_6H_5COOH \longrightarrow C_6H_5CH_2COOH$

9.3 NITRENES

Nitrenes, like carbenes, are neutral species in which the nitrogen atom has only a sextet of valence electrons and thus, like the carbon atom in carbenes, it is electron-deficient. Nitrenes are highly unstable intermediates with a very short life time, of the order of a few microseconds. They are either trapped with suitable reagents or may form stable molecules by rearrangement.

The parent species, :NH, is known as imidogen or azene or imene. It is formed when hydrazoic acid is irradiated with UV light. Cycloaddition occurs in the presence of ethene to give ethene imine or aziridine.

$$HN_3 \xrightarrow{-N_2} {:}NH$$



In the absence of a reagent, dimerisation of imidogen to diimide takes place.

$$2{:}NH \xrightarrow{\text{dimerisation}} HN{=}NH$$

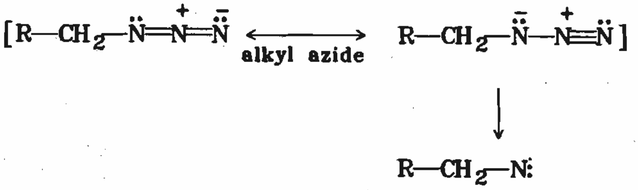
9.3.1 Generation

The common method for generation of nitrenes is thermolysis or photolysis of azides.

$$R{-}\overset{-}{N}{-}\overset{+}{N}{\equiv}N \xrightarrow{h\nu \text{ or } \Delta} R{-}N{:} + N_2$$

Nitrene intermediates are formed in thermal or photochemical decomposition reactions of most alkyl, aryl or sulphonyl azides and azido formates with loss of nitrogen.

Alkyl nitrenes are highly reactive and either immediately isomerise to imines by 1, 2-H migration or form primary amines by intermolecular hydrogen abstraction.



$$R{-}CH_2{-}N: \xrightarrow{\text{isomerisation}} RCH{=}NH$$

$$R{-}CH_2{-}N: \xrightarrow[+2H]{\text{hydrogen abstraction}} RCH_2NH_2$$

Alkenyl nitrenes generally rearrange to imines which are tautomeric with nitriles.

$$R{-}CH{=}CH{-}N: \longrightarrow R{-}CH{=}C{=}NH \rightleftharpoons RCH_2{-}C{\equiv}N$$

Alkynyl nitrenes have not yet been prepared. However the analogous cyanonitrene has been well characterised during the decomposition of cyanogen azide;

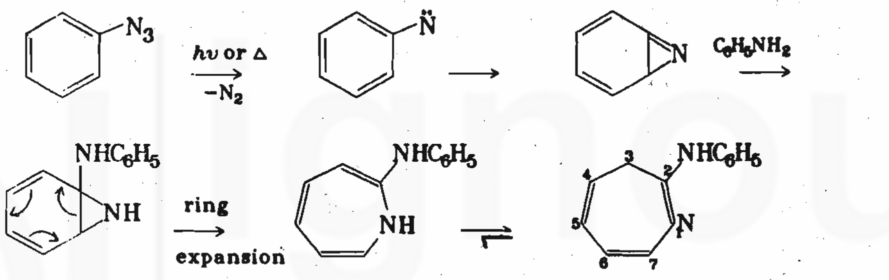
$$NCN_3 \longrightarrow NC{-}N: + N_2$$

$$\text{Or } [N{\equiv}C{-}N{=}\overset{+}{N}{=}\overset{-}{N} \longleftrightarrow N{\equiv}C{-}\overset{-}{N}{-}\overset{+}{N}{\equiv}N] \longrightarrow N{\equiv}C{-}N:$$

Notice the name, 2-phenylamino-3H-azepine. Azepine is the name for the seven membered ring compound containing one nitrogen. The number of the ring starts from N; 3-H indicates that there is >CH_2 group in position 3.

Decomposition of aryl azides in a variety of solvents has been studied. In inert solvents like hydrocarbons the main products are azo compounds and amines. The amines, as we will discuss later, are formed from azo compounds by hydrogen abstraction.

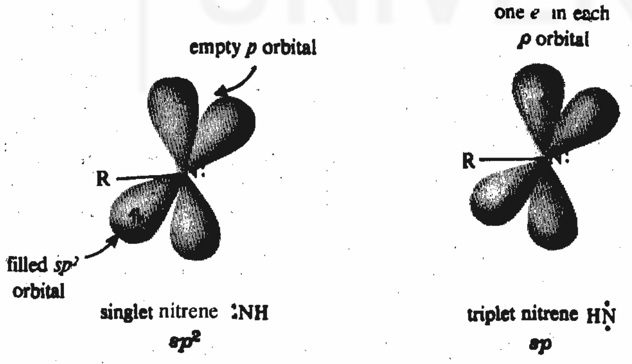
Thermolysis or photolysis of a phenyl azide in aniline solution can be a good route to derivatives of 2-phenylamino-3H-azepine. It has been proposed that the reaction involves generation of a nitrene in the initial step followed by the sequences given below:



2-phenylamine-3H-azepine

9.3.2 Structure and Stability

Nitrenes, like methylenes, can exist either in a singlet or triplet state. In the singlet state, there are two pairs of electrons and a low lying empty p_x orbital, while in the triplet state, there is one electron pair and two unpaired electrons with parallel spins.



As said earlier, the unshared lone pair on nitrene is generally not shown

Electron spin resonance studies have shown that in nitrenes, like in methylenes, the triplet state is the ground state. Experimental evidence from a variety of reactions indicates that nitrenes are initially formed in singlet state. However, this may change to the lower energy triplet state by collisional deactivation with inert gas or solvent molecules.

The two forms differ in their chemical reactions. As would be expected, the singlet species adds to multiple bonds in a stereospecific manner, whereas in the case of the triplet species which behaves more like a diradical, the addition would be non-stereospecific. Further, the singlet nitrene inserts into C—H bonds while the triplet species abstracts hydrogen. These reactions are described in the following subsection.

9.3.3 Reactions

The highly reactive nitrenes formed in any reaction stabilise themselves in a number of ways. Some of these are:

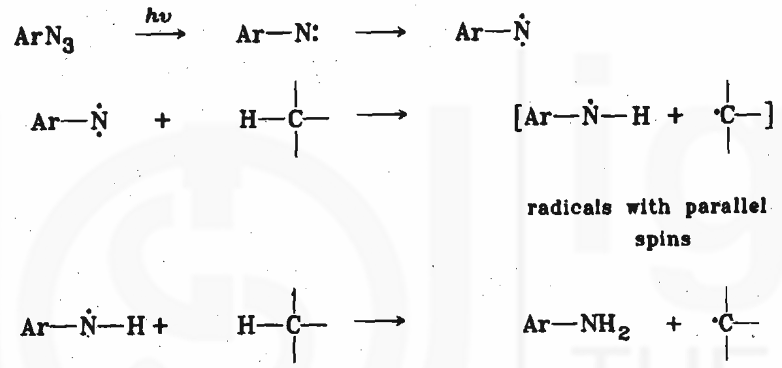
Coupling: Two nitrene species may unite to form an azo compound. This reaction is observed only in flash photolysis in inert solvents where a high nitrene concentration is produced.

$$2[R—\ddot{N}] \longrightarrow R—N{=}N—R$$

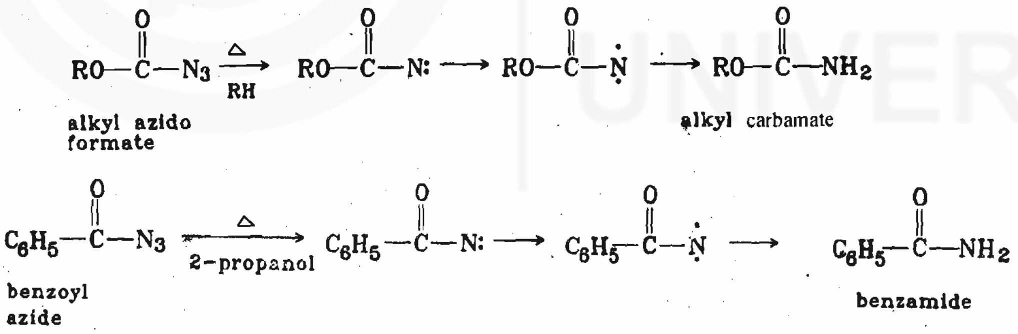
In flash photolysis, a large doze of radiant energy is introduced over a very short period. This technique helps in obtaining a high concentration of reactive intermediates or excited states.

Hydrogen abstraction: It has been postulated that hydrogen abstraction probably involves triplet nitrene. Abstraction rections of nitrenes, in a way, can be taken as a indication of the presence of triplet species.

Triplet nitrenes abstract hydrogen from a C—H bond to produce primary amines. The first step of the reaction is supposed to be abstraction of hydrogen by triplet nitrene from the substrate to form an amino and a carbon radical. The two radicals produced would have parallel spins and, therefore, cannot couple unless their spins are reversed. The time required for this reversal is enough to allow the radicals to drift apart. The amino radical, meanwhile, would abstract another hydroen to form a primary amine.

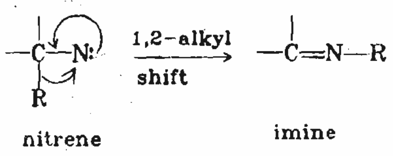


Following are some examples illustrating hydrogen abstraction by nitrenes.

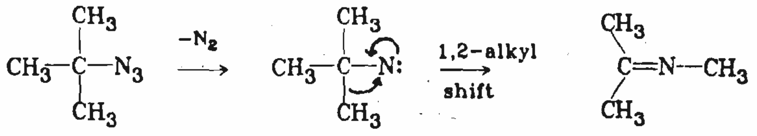


Rearrangement

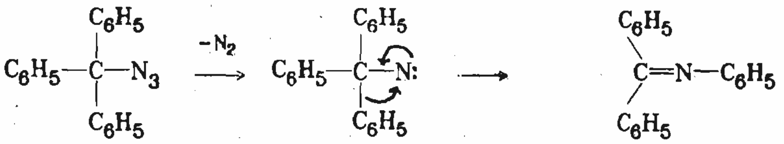
Nitrenes frequently undergo a rearrangement in which an alkyl, aryl or H migrates from α-carbon to the nitrogen, in a 1,2-shift. The group migrates with its electron pair from carbon to the electron-deficient nitrogen. The mechanism of this rearrangement is very similar to that of carbocations which you will study later in this block.



Gas phase pyrolysis of *tert*-butyl azide and photosensitized decomposition of triphenylmethyl azide given below illustrate this type of rearrangement.



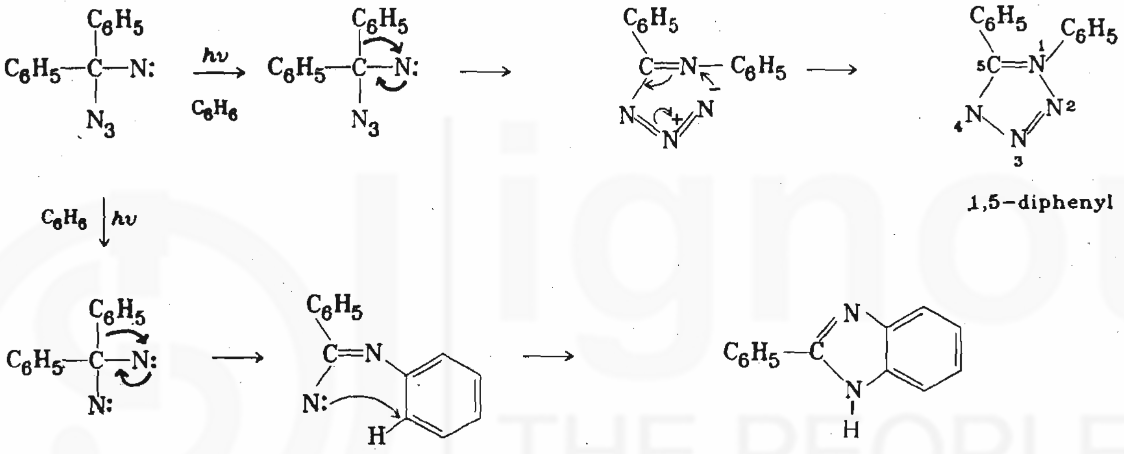
tert- butyl azide



triphenyl methyl azide

The name tetrazole indicates a five membered ring with four nitrogen atoms. Benzimidazole indicates a five membered ring containing two nitrogen atoms fused to a benzene ring. Notice the numbering starts with the saturated hetero atom going round the ring as shown.

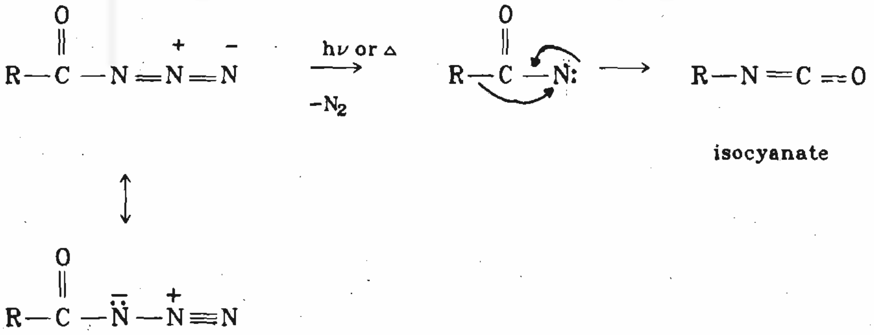
Such 1,2 shifts of nitrenes are of great synthetic utility in heterocyclic chemistry. For example, benzophenone diazide on photolysis gives a tetrazole and a benzimidazole on rearrangement of the nitrene intermediates.



1,5-diphenyl tetrazole

2-phenyl benzimidazole

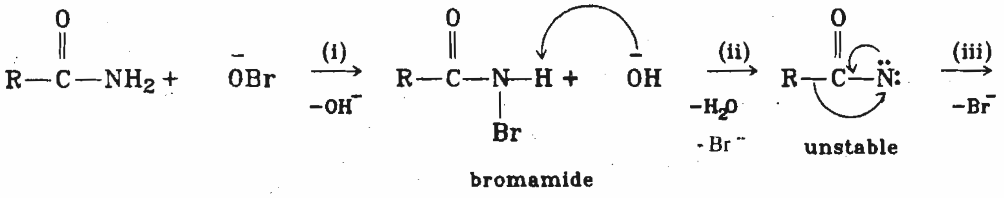
Acyl nitrenes, formed during photolysis or thermolysis of dilute solutions of acyl azides, undergo rearrangement to give isocyanates:



isocyanate

An important example of the above is **Hofmann rearrangement** in which an acid amide is reacted with bromine and aqueous sodium hydroxide to give a primary amine. In this reaction an acyl nitrene intermediate is formed through N-bromamide, which immediately rearranges to an isocyanate. Hydrolysis of the isocyanate gives the primary amine with loss of carbon dioxide. The amine would therefore have one carbon atom less than the acid. We will take up details of this reaction in Unit 11.

$2NaOH + Br_2 \longrightarrow NaBr + NaOBr + H_2O$

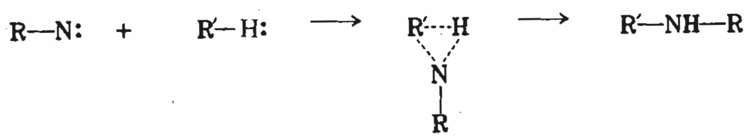


$$\underset{\text{isocynate}}{R-\ddot{N}=C=O} + H_2O \xrightarrow[OH^-]{(iv)} RNH_2 + CO_2$$

As you will study later, there is a similarity in Hofmann, Schmidt and Curtius rearrangements. Mechanistically, in each of these an acyl nitrene seems to be involved.

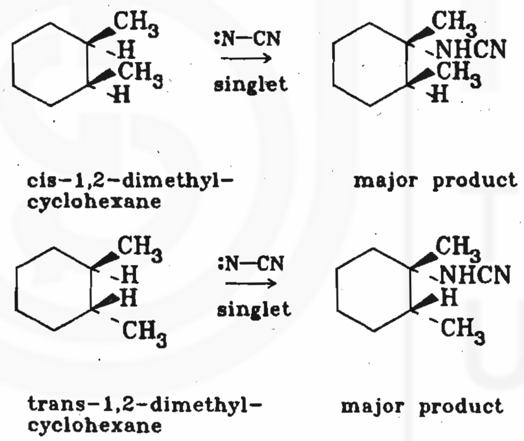
Insertion:

Nitrenes insert into various C—H bonds:



Thermolysis of cyanogen azide at temperatures, 586-600K, proceeds with conservation of spin to yield singlet nitrene, which inserts stereo — specifically into tertiary C—H bonds of *cis* and *trans* 1,2-dimethylcyclohexane.

$$N_3CN \xrightarrow[-N_2]{} N—CN$$

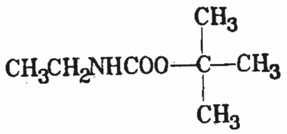


SAQ 4

Write down various steps involved in the following conversions. Give the mechanism where possible.

i) $CH_3CH_2COOH \longrightarrow CH_3CH_2NH_2$

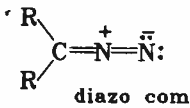
ii) $CH_3CH_2COOH \longrightarrow$



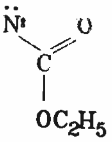
$$CH_3CH_2NHCOO-\underset{CH_3}{\overset{CH_3}{\underset{|}{\overset{|}{C}}}}-CH_3$$

1,3-Diploar cyclo-additions

You are familiar with 1,2-dipolar additions across multiple bonds like the addition of Br_2 to a >C=C<. In 1,3-dipolar cycloadditions a neutral three-atom 4π electron unit (addendum) adds to a mulltiple bond. The term dipolar refers to the necessary formal charges in the Lewis structure of the 4-π component. Examples of such system are:



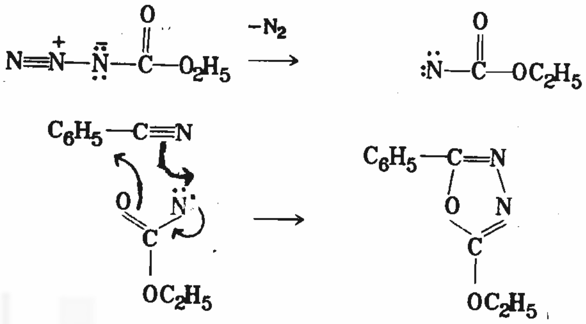
diazo compounds



acyl nitrenes

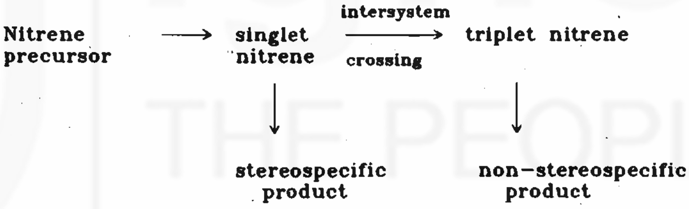
The products of such reactions are five member ring systems. You may recall ozonolysis of alkenes which starts with addition of ozone to the >C=C<

Photolysis of ethyl azidoformate in benzonitrile giving 1,3,4-oxadiazole is an example of a 1,3-dipolar addition in which the carboethoxy nitrene formed as a intermediate adds across the $-C\equiv N$.



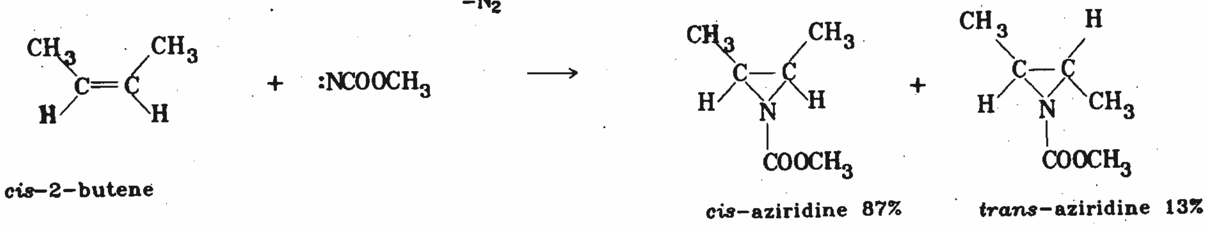
Additions to alkenes

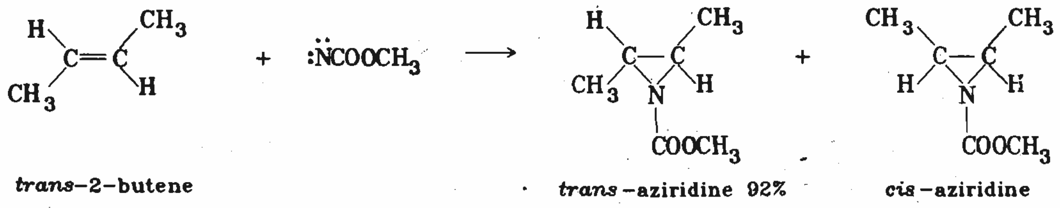
Nitrenes add to alkenes to form aziridines. As in the insertion reaction singlet nitrenes add stereospecifically while the triplet ones non-stereospecifically. Nitrene initially formed as singlet species may slowly decay into the triplet one:



Thus photolysis of methyl azidoformate, N_3COOCH_3 in *cis*- and *trans*-2-butene gives 87% *cis* and 13% *trans* aziridine in the former case and 8% *cis* and 92% *trans* aziridine in the latter.

$$N_3COOCH_3 \xrightarrow[-N_2]{h\nu} :\ddot{N}COOCH_3$$

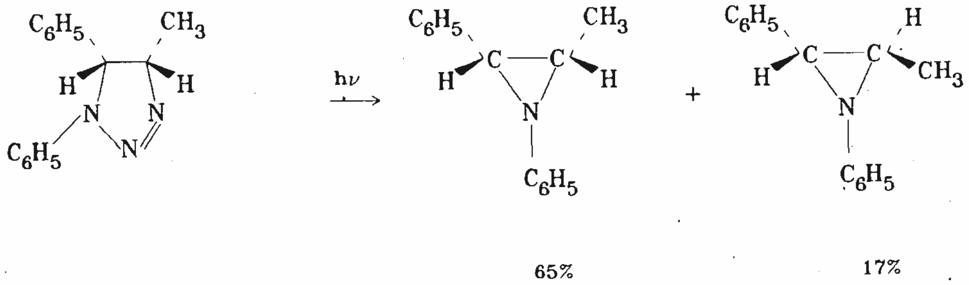




As you can see the addition is stereospecific, which implies that the singlet nitrene formed adds to the double bond before it has time to change to the triplet state

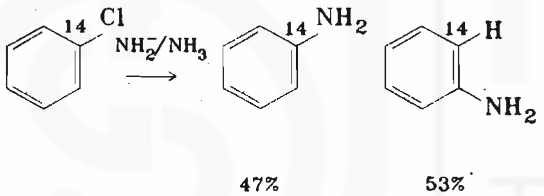
SAQ 5

Photo decomposition of *cis*-triazoline gave the *cis*- and *trans*- aziridines in the following proportion. How do you explain this?

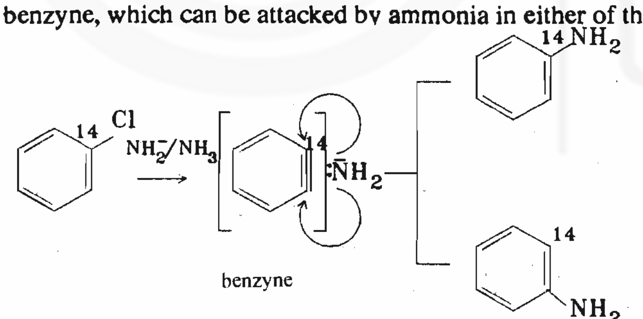


9.4 BENZYNES

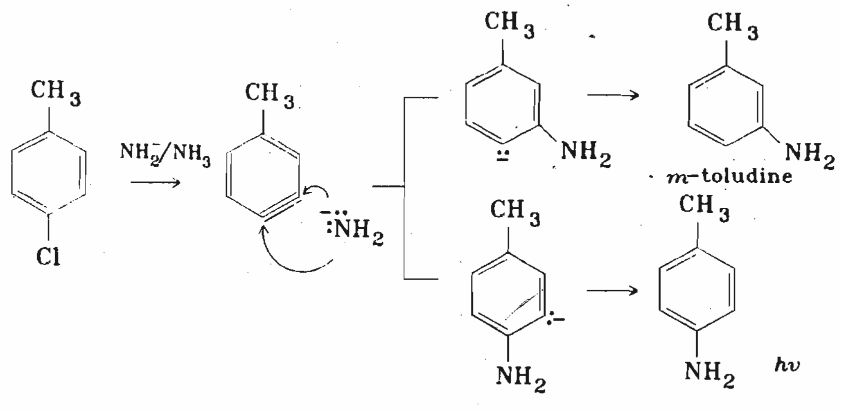
Another type of intensely reactive reaction intermediates are benzynes, or the 1,2-dehydrobenzenes. Benzynes or arynes have been postulated as intermediates in nucleophilic substitutions of aryl halides which have no activating groups. In such reactions, the bases required are stronger than those normally used. The most interesting aspect of the these reactions is that the incoming group does not always take the position vacated by the leaving group. That the latter statement is true was elegantly demonstrated by the reaction of 1-^{14}C-chlorobenzene with potassium amide in liquid ammonia.



The product consisted of aniline, half of which was labelled in 1-position and the other half in 2-position. This is possible only if there is a symmetrical intermediate, like benzyne, which can be attacked by ammonia in either of the two positions.

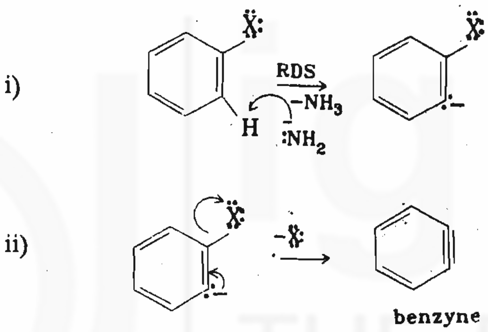


Other strong bases like *tert*-butoxide ion can be used in place of amide ion. Evidence for the formation of benzyne as an intermediate also comes from the reaction of *p*-chlorotoluene with potassium amide and liquid ammonia. The product is a mixture of *m*- and *p*-toluidines. This can only be explained on the basis of 3:4-benzyne as an intermediate, since direct replacement of the halogen would give only *p*-toluidine. Addition of an amide ion to a 3,4 benzyne intermediate and subsequent abstraction of a proton from ammonia by the anions can account for the formation of two products:



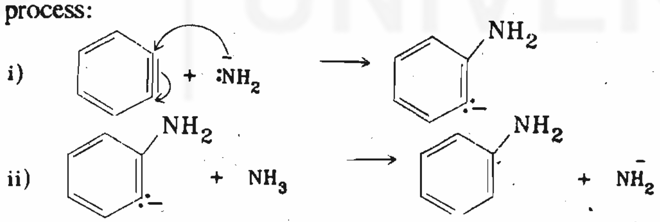
Let us look into the mechanistic details of a substitution reaction involving benzyne as an intermediate. We can take the reaction of chlorobenzene with potassium amide in liquid ammonia as an example. In such replacements mechanistic route is supposed to involve two stages, elimination followed by addition of the nucleophile. The elimination stage, in which benzyne is formed, is again presumed to involve two steps: abstraction of proton by the amide ion to form a carbanion which then loses the halide ion to form benzyne. The first step in this reaction, the loss of proton is the slow, rate determining step.

Thus elimination can be shown as:

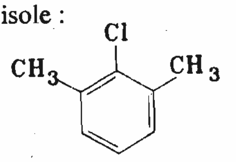


As you can see, the geometry of benzene ring would permit only a *cis* coplanar elimination (though not concerted).

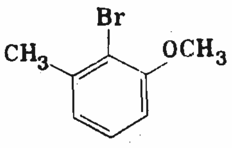
The addition stage, in which benzyne reacts with the nucleophile, may again be a two step process:



Such elimination-addition reactions proceeding through a benzyne intermediate are also called **"Cine Substitution"**. Further confirmation of this mechanism comes from the observation that 2,6-disubstituted aryl halides which do not have hydrogens *ortho* to the halogen do not react with amide ion in liquid ammonia, e.g., 2-chloro-*m*-xylene and 2-bromo-3-methyl-anisole :



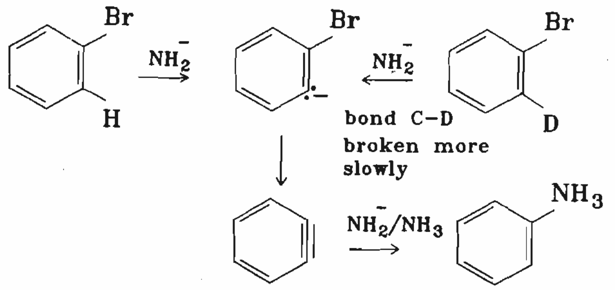
2-chloro-*m*-xylene



2-bromo-3-methyl-anisole

Another interesting observation is that *o*-deuterobromobenzene reacts more slowly than bromobenzene with amide ion in liquid ammonia. It is known that carbon-deuterium bond is stronger than carbon hydrogen bond. Since, as said above, loss of proton is the rate-determining step in this reaction, the slower rate in case of *o*-deutero bromo-benzene can be explained on the basis of isotope effect.

When hydrogen in a reactant molecule is replaced by deuterium, there is often a change in the rate of the reaction involving this bond. Such changes are called deuterium isotope effects.



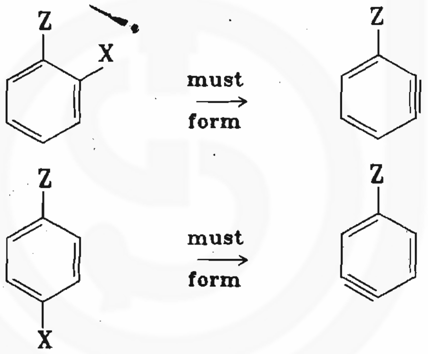
You can now differentiate cine substitution from an ordinary nucleophilic substitution. In an ordinary nucleophilic substitution, the incoming group is expected to occupy the position vacated by the leaving group. Further, whether or not an *ortho* hydrogen is present would make no difference.

Orientation

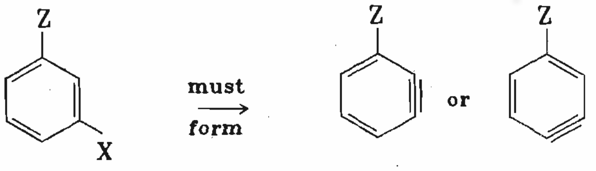
However, in reactions involving benzyne intermediates, there are two factors which affect the position of the incoming group. One of these is related to the acidity of the hydrogen which is removed, and the other to the stability of the carbanion formed on addition of the nucleophile. Both these are briefly discussed below:

i) Acidity of hydrogen being removed

When there are groups *ortho* or *para* to the leaving group, X, there is no choice and benzyne is formed only in one way e.g.,



But when a *meta* group is present, the benzyne may form in two different ways:



In such cases, the more acidic hydrogen is removed. Since acidity is related to the inductive effect of Z, it may be stated that the electron attracting Z favours removal of the *ortho* hydrogen while an ellectron donating Z favours removal of the *para* hydrogen.

Since the electron pair in the carbanions involved in both the stages is out of the plane of the π – cloud, there is no resonance interaction between these electrons and the π-cloud. Only inductive effect working along bonds or through space is operative. This would be stronger in *ortho* than in *para* position.

ii) Stability of carbanion formed

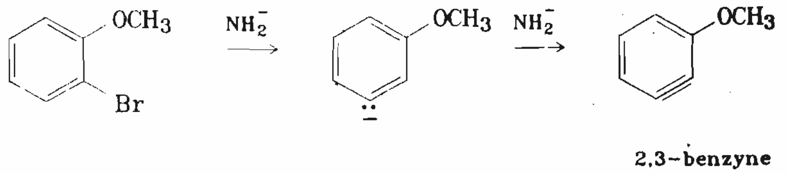
The benzyne, once formed, may be attacked at two positions. The favoured position for nucleophilic attack is the one which leads to the more stable carbanion intermediate, and this in turn is also dependent on the inductive effect of Z.

For–I groups the more stable carbanion is the one in which the negative charge is closer to the substituent.

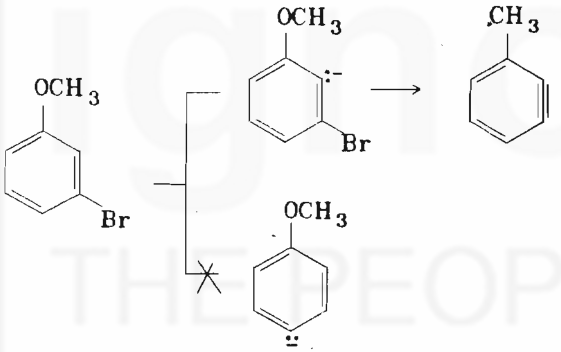
The above principles are illustrated by the reaction of *o*-bromoanisole and *m*-bromoanisole with sodamide. Both yield the same product, namely, *m*-aminoanisole (*m*-anisidine).

It is obvious that for both of them to yield the same product, the benzyne intermediate would have to be the same in both the cases. Let us go into the orientation in the elimination as well as in the addition stage and see if we can justify these experimental observations. Remember, methoxy group has an electron-withdrawing, –I, inductive effect.

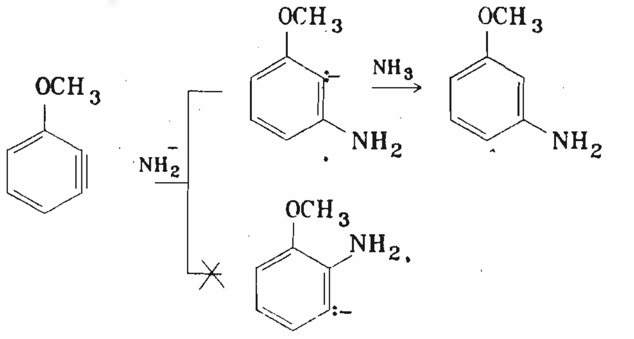
o-Bromoanisole would yield, 2,3-benzyne as shown because there is only one option.



In the case of *m*-bromoanisole, the more acidic *ortho* hydrogen is removed, leading to the same benzyne. The carbanion formed would obviously be also the more stable one, due to –I effect of both *ortho* OCH_3 and Br. The *para* hydrogen is less acidic, the carbanion formed would be stabilised only by the –I effect of *ortho* bromine, and so it is not formed. The *ortho* carbanion loses Br to give 2,3-benzyne as shown.



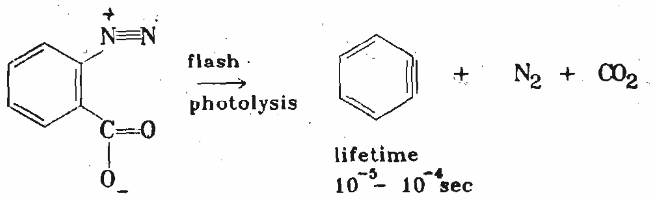
In the second stage, addition of NH_2 to the benzyne, carbanion *ortho* to the methoxy group would be stabilised by the —I effect, whereas the one at the *meta* position is not. So you can see why *m*-anisidine would be the predominant product.



9.4.1 Generation

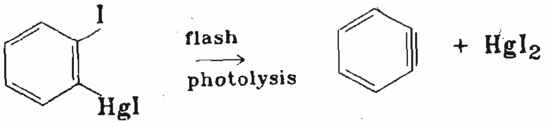
You have studied above aromatic substitution reactions in which benzynes have been postulated as intermediates. There is spectroscopic and other evidence for the formation of benzynes in the following reactions.

i)



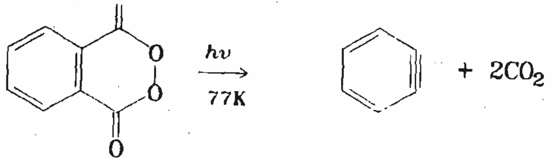
benzene diazonium-
o-carboxylate

ii)



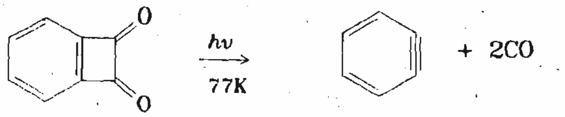
iodophenyl mercuric iodide

iii)



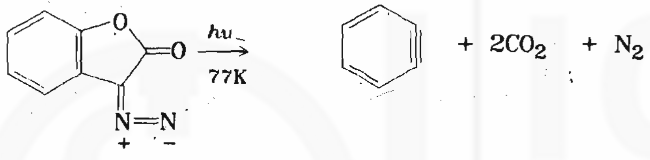
phthaloylperoxide

iv)



benzocyclobuta-
dione

v)

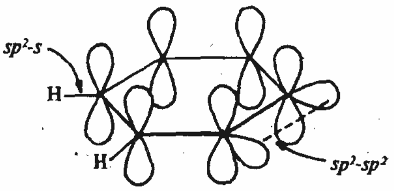


3-diabenzo fluranone

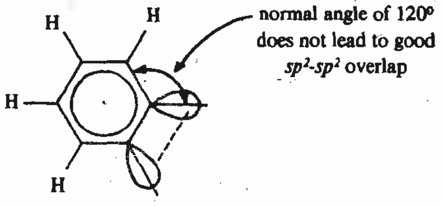
Benzyne generated as above can be trapped by suitable reagents like furan or anthracene as discussed in section 9.4.3. In the absence of a reagent they dimerise

9.4.2 Structure and Stability

Althouth no benzynes have been isolated, spectroscopic evidence for the transient existence of benzynes has been obtained. It is generally agreed that the aromatic character of the cyclic system in the benzyne intermediate is undisturbed. On this presumption two alternate structures can be written. One structure of benzyne has been postulated as:



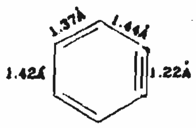
side view



top view

This involves sideways overlap of sp^2 orbitals of the two carbon atoms, one originally holding the helogen and the other hydrogen, to form an additional π-bond which is out of the plane of the aromotic π-cloud. This new bond orbital lies along the side of the ring and has little interaction with the π-cloud lying above and below the ring. However, the additional bond involves considerable deformation of the bond angles concerned, from 180° to 120°, and is therefore weak. Try to visualise this structure. It is like the formation of a triple bond between C_1 and C_2. If it were an open chain compound, the two *sp* orbitals would be linear with an angle of 180°. However, in this six-membered ring structure, these *sp* carbons have to be bonded on either side with sp^2 carbon atoms, reducing the bond anglel to nearer 120°. This would imply that this bond would have to be bent, setting in severe strain, something like in cyclopropene. The unstable nature of benzyne and its high reactivity can be easily explained on the basis of this structure.

In the dipolar structures, which can be considered as resonance structures of the above, the benzene ring is again essentialy undisturbed except for the removal of two hydrogens. There would be a partial overlap between adjacent sp^2 orbitals with the formation of a weak bond, which is consistent with observed reactivity.



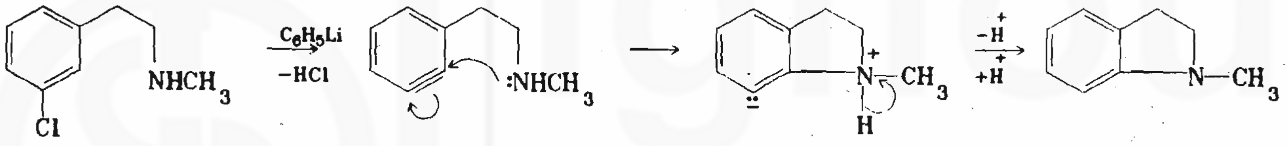
It is argued that if this were the case, C_1— C_2 distance should be less; as this would provide a better overlap of weakly interacting sp^2 orbitals. As a resultl C_2— C_3 and C_1— C_6 bond lengths are consistent with this stipulation as you can see in the above diagram.

9.4.3 Reactions

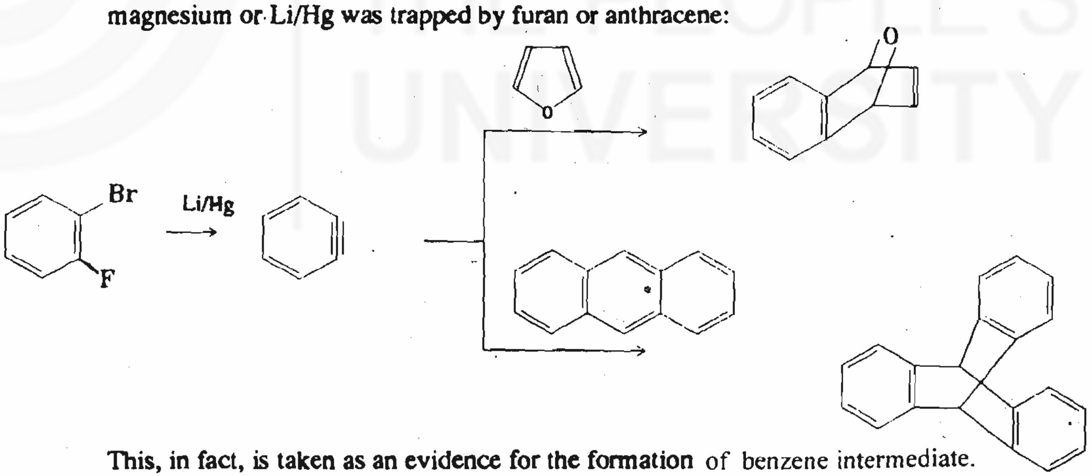
In addition to amination and hydrolysis of halobenzenes about which you have studied above, benzyne intermediates have also been postulated in the following reactions:

Ring closure reactions: Benzyne is an electron-deficient species and, therefore, we may expect it to behave as an electrophile. In case an atom, which can donate a pair of electrons is suitably placed, intramolecular addition leading to cyclisation can occur.

This provides a new general method for the synthesis of cyclic systems. N-Methyl 1-2-(*m*-chlorophenyl)-ethylamine, for example, gives N-methyl-indoline on treatment with phenyl lithium:

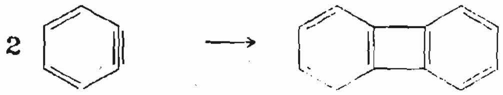


Addition Reactions: As powerful dienophiles, benzynes react with conjugated systems to give Diels-Alder adducts. For example,*o*-bromofluorobenzene on treatment with magnesium or Li/Hg was trapped by furan or anthracene:



This, in fact, is taken as an evidence for the formation of benzene intermediate.

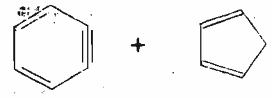
In the absence of a reagent, the benzyne formed undergoes dimerisation to give diphenylene.



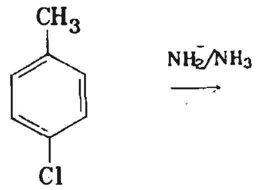
SAQ 6

Give the Products in the following cases·

i)



ii)



9.5 SUMMARY

Carbenes, nitrenes and benzynes are intensely reactive reaction intermediates. They are unstable species and have not been isolated. Their existence has been shown either by spectroscopic studies or by chemical reactions. While carbenes and nitrenes have been postulated as intermediates in molecular rearrangements, nucleophilic substitution of aryl halides which do not have any activating groups is supposed to proceed via benzyne mechanism.

In this unit various methods for the generation of these transient reaction intermediates have been described and their structure and stability discussed. Carbenes and nitrenes are electron-deficient species. They act as electrophiles in chemical reactions. Their typical reactions are insertion, cycloadditions, and rearrangement. Carbenes and nitrenes react with alkenes to give three-membered ring products. Rearrangement reactions of carbenes and nitrenes lead to a variety of products. Benzyne acts as dienophiles and participate in Diels-Alder reaction.

9.6 TERMINAL QUESTIONS

1) Predict the product(s) in the following and give mechanism.

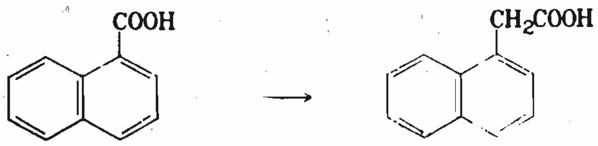
Cyclohexene + $CH_2I_2 \xrightarrow[(C_2H_5)_2O]{Zn-Cu}$

Z-2-pentene + $CHCl_3$ + *tert*-BuO$^-$K$^+ \longrightarrow$

Fluorobenzene with
with labelled
α-carbon $\xrightarrow[(C_2H_5)_2O]{C_6H_5Li}$

2) Give the steps involved in the following conversions:

a)



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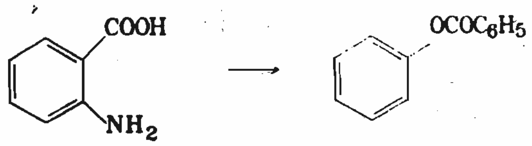
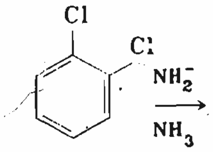


c) $C_6H_5COCH_3 \longrightarrow C_6H_5—NH—COCH_3$

3) Write down the predicted product and the corresponding intermediate in each of the following cases:

a)



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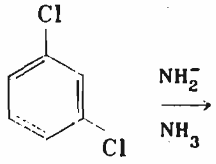
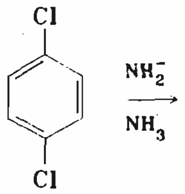


c)



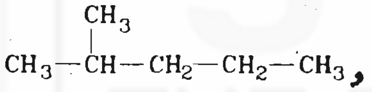
9.7 ANSWERS

Self-Assessment Questions

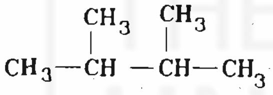
1) In the liquid phase, singlet carbene produced adds stereospecifically to the alkenes. In the gaseous phase, singlet carbene first produced changes to triplet state, which adds in a non-stereospecific mode.

2)

i)

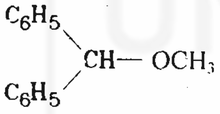


$CH_3-\overset{\displaystyle CH_3}{\overset{|}{C}H}-CH_2-CH_2-CH_3$,



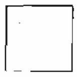
$CH_3-\overset{\displaystyle CH_3}{\overset{|}{C}H}-\overset{\displaystyle CH_3}{\overset{|}{C}H}-CH_3$

ii)



$(C_6H_5)_2CH-OCH_3$

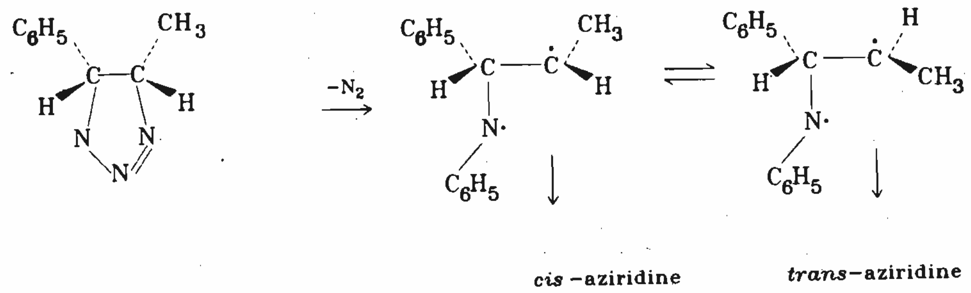
iii)



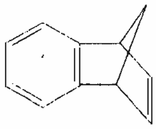
3) i) Reimer-Tiemann reaction on phenol with CCl_4/KOH.
ii) Wittig reaction with $(C_6H_5)_3PCCl_2$
iii) Conversion of diazoacetophenone and Wolff rearrangement.

4) i) Conversion to azide and then rearrangement of acyl nitrene in the presence of water.
ii) Rearrangement of acylnitrene in the present of *tert*-butylalcohol.

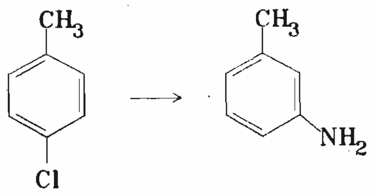
5) Triazoline undergoes photodecomposition to give the intermediate singlet diradical which undergoes ring closure to aziridine more rapidly than bond rotation.



6) i)



ii)



Terminal Questions

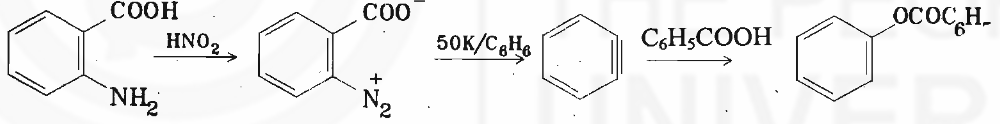
1) a) Cycloaddition of methylene to give norcarane. No insertion of methylene occurs.

b) *Syn* addition of dichlorocarbene on the alkene. No insertion product is observed.

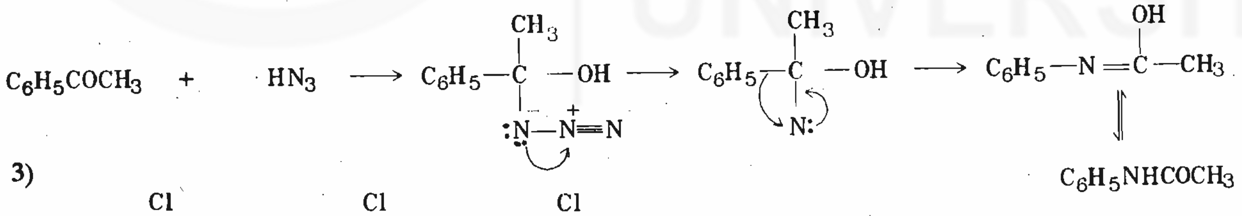
c) Two types of biphenyl. One in which the α- carbon and other in which the β-carbon is labelled.

2) a) Arndt-Eistert synthesis $-COOH \longrightarrow -COCHN_2 \longrightarrow -CH_2COOH$

b)

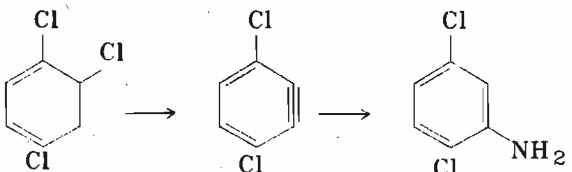


c)



3)

a)



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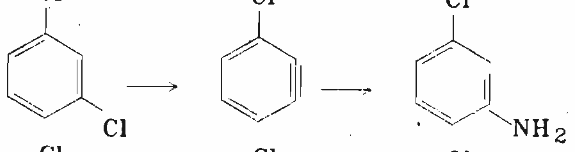
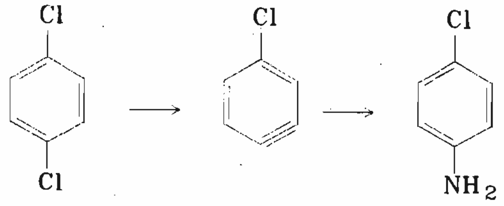


c)



This can be justified on the basic of the –I effect of Cl in determining the orientation at elimination and addition stage.

UNIT 10 FREE RADICALS

Structure

10.1 INTRODUCTION

In the previous unit, reaction intermediates like carbenes, nitrenes and benzynes were described. In this unit, we will describe another group of reaction intermediates, the free radicals. Free radicals are formed by homolytic fission of covalent bonds. Homolysis can be induced thermally or by irradiation. It generally takes place in the gaseous phase or in solution in non-polar solvents. Free Radicals are characterised by one or more unpaired electrons as reflected in their paramagnetic nature and the fact that they are coloured. They vary in their stability from the transient to the stable ones which can even be crystallised from a solvent. Free radicals have been postulated as intermediates in photochemical substitution and in certain addition reactions. Autoxidation of organic compounds as well as arylations like in Sandmeyer reaction are also supposed to involve free radical intermediates. One of the most important aspect of their chemistry is as intermediates in vinyl polymerisation. Radical reactions are also of biological importance. Living organism utilise atmospheric oxygen by a sequence of reactions that begins with radical oxidation-reduction. Fats become rancid partly by radical reactions with oxygen from the air.

Objectives

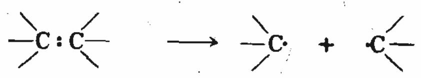
After studying this unit you should be able to:

- describe the nature of free radicals,
- trace the discovery of free radicals,
- describe various methods for generation and detection of free radicals,
- relate the stability of free radicals to their structure and
- discuss various types of free radical reactions.

10.2 FREE RADICALS —THEIR NATURE

Free radicals are reactive intermediates with one or more unpaired electrons. As you have studied in Unit 1 they are generated by homolytic fission of a covalent bond.

$$X:Y \longrightarrow X\cdot + \cdot Y$$



Reactions involving free radicals generally take place in the gaseous phase, but they also occur in solution, particularly if the reaction is carried out in non-polar solvents. Free radical reactions are catalysed by light or by substances like peroxides which undergo decomposition easily to produce free radicals.

A characteristic of free radical reactions is that once a radical reaction has been started, it usually proceeds at a great rapidity due to the establishment of fast chain reactions. These chain reactions arise as a result of the reaction of the first formed radical to generate another radical on reaction with a molecule. The new radical being able to repeat the process, the reaction is carried on. The reaction is terminated when the radicals start reacting with each other to form neutral molecules. This happens when most of the reactants have been consumed. Thus, there are three distinct phases of a radical reaction; initiation, propagation and termination. In the specific case of photochemical-chlorination of methane; these three phases can be described as:

i) **Initiation** $Cl_2 \xrightarrow{h\nu} Cl\cdot + Cl\cdot$

ii) **Propagation**

a) $Cl\cdot + H{-}CH_3 \longrightarrow HCl + \cdot CH_3$

b) $\cdot CH_3 + Cl{-}Cl \longrightarrow CH_3Cl$

iii) **Termination**

$\cdot CH_3 + \cdot CH_3 \longrightarrow CH_3{-}CH_3$

$Cl\cdot + \cdot CH_3 \longrightarrow CH_3Cl + \cdot CH_3$

$Cl\cdot + Cl\cdot \longrightarrow Cl_2$

It may also be mentioned here that in addition to chloromethane, di, tri and tetrachloromethanes are also formed resulting from replacement of two, three or all the four hydrogen atoms.

$CH_4 + Cl_2 \longrightarrow$
CH_3Cl: Choromethane (methyl chloride)
CH_2Cl_2: dichloromethane (methylene chloride)
$CHCl_3$: trichloromethane (chloroform)
CCl_4: tetrachloromethane (Carbon tetrachloride)

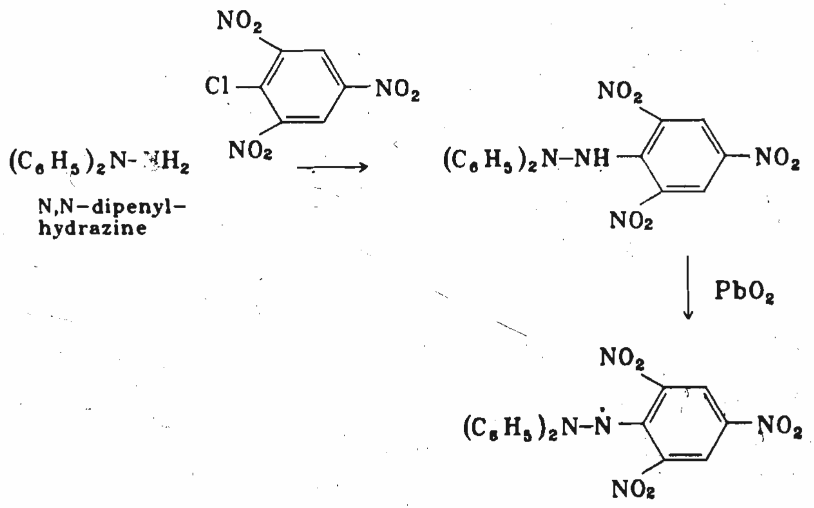
In fact direct halogenation generally yields a mixture of products. We will study the detailed mechanism of free radical reactions later in Section 10.7. Here it may be mentioned that in addition to the above, the two other characteristics of free radical reactions are their initiation by substances known to produce radicals, called initiators, and their inhibition or termination by substances which react readily with radicals, called inhibitors.

In addition to carbon radicals, a large number of hetero-radicals are also known. Thus N,N,N', N'-tetraphenyl hydrazine formed by oxidation of diphenylamine on warming in non-polar solvents imparts green colour to the solution due to the formation of radicals as depicted below:

$$(C_6H_5)_2NH \xrightarrow{MnO_4^-} (C_6H_5)_2N{-}N(C_6H_5)_2 \rightleftharpoons (C_6H_5)_2N\cdot + \cdot N(C_6H_5)_2$$

diphenyl amine — N,N,N',N' tetra phenyl hydrazine — diphenyl amino radicals

Another important nitrogen radical is 1,1-diphenyl-2-picryl hydrazyl which is quite stable and can be crystallised from various solvents:



1,1-diphenyl-2-picryl-hydrazyl radical

It is possibe to monitor the progress of a reaction by measuring the intensity of a coloured species taking part in the reaction.

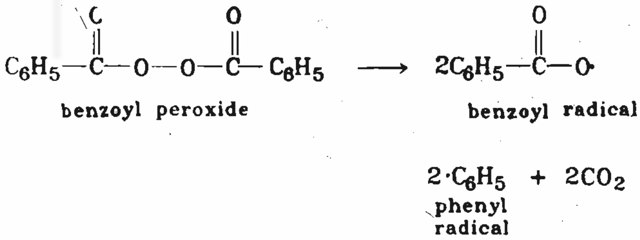
This radical traps other radicals forming stable products and thus helps in their detection. A solution of the radical is highly coloured. On reaction with other radicals, the solution becomes cololess. Thus the trapping reaction can be followed colorimeterically.

Radicals of sulphur, both aromatic and aliphatic are also known. Diphenyl disulphide on heating gives a yellow solution due to the formation of phenylthiyl radicals. The colour disappears on cooling indicating the equilibrium nature of homolytic fission.

$$C_6H_5S{-}SC_6H_5 \rightleftharpoons C_6H_5S\cdot + \cdot SC_6H_5$$

diphenyl disulphide — phenylthiyl radical

Decomposition of peroxides to give radicals has already been mentioned above.



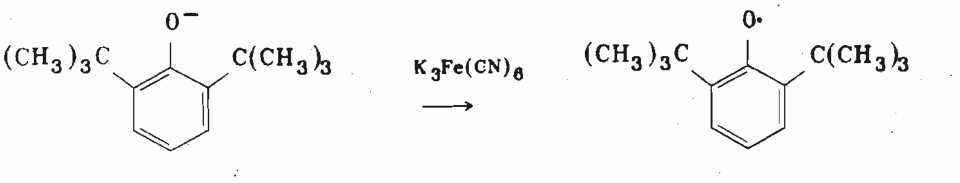
$$C_6H_5{-}\overset{O}{\overset{\|}{C}}{-}O{-}O{-}\overset{O}{\overset{\|}{C}}{-}C_6H_5 \longrightarrow 2C_6H_5{-}\overset{O}{\overset{\|}{C}}{-}O\cdot$$

benzoyl peroxide — benzoyl radical

$$2\cdot C_6H_5 + 2CO_2$$

phenyl radical

Oxygen containing radicals with reasonable stability are also known. Thus, 2,6 - di-tert-butylphenoxy radical exists both in solution and in the solid state as such, and not in the form of dimer. The bulky *tert*-butyl groups at both the *ortho* positions restrict the approach of radicals, leading to their stability.



2,6-di-tetra-butylphenoxy ion — 2,6-di-tetra-butylphenoxy radical

Radicals vary widely in their stability, there are **stable free radicals** as the one above, at one end of the spectrum; on the other end are **short, lived** alkyl radicals like $CH_3\cdot$ The latter, though difficult to handle, are of much greater importance as reaction intermediates. Their short life is indicative of their high reactivity.

SAQ 1

a) Give Lewis formulae for the following:

$HO\cdot$, $CH_3S\cdot$ $CH_3—CH_2\cdot$ $(C_6H_5)_2N\cdot$ $CH_3CH_2O\cdot$

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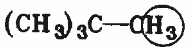
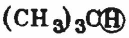
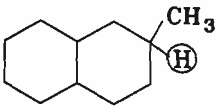
b) Identify the encircled hydrogen in the following as primary, secondary, tertiary, allylic or benzylic.

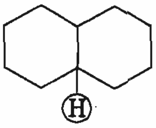


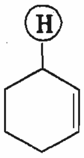
$(CH_3)_3C—CH_3$

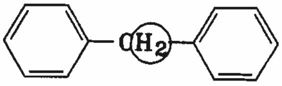


$(CH_3)_3CH$









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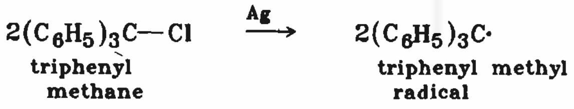
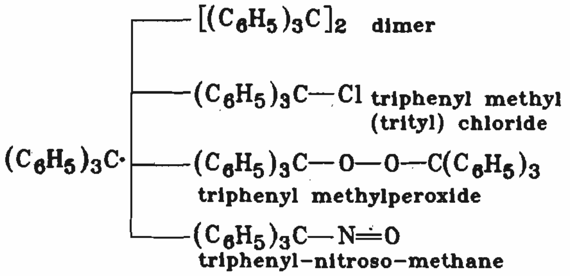
10.3 HISTORICAL BACKGROUND

The concept of free radical reactions owes its development to two important studies done in the past.

The first of these studies was carried out in 1900 by Gomberg. On reacting triphenylmethyl chloride with finely divided silver in benzene solvent, he obtained triphenyl methyl radical. This radical, yellow in colour, was found to reform the triphenyl halide on reacting with halogens. With oxygen from the air it formed the peroxide, and with nitric oxide it formed triphenyl-nitroso-methane.

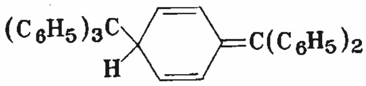


$$2(C_6H_5)_3C—Cl \xrightarrow{Ag} 2(C_6H_5)_3C\cdot$$



In benzene solution, the yellow radical, $(C_6H_5)_3C\cdot$, was in equilibrium with a less reactive molecule presumed to be its dimer, $(C_6H_5)_3C–C(C_6H_5)_3$. The proportion of the radical increased with temperature and dilution.

The dimer was initially assumed to be hexaphenylethane $(C_6H_5)_3C—C(C_6H_5)_3$ but eventually, nearly 70 years later, this was shown to be a cyclohexadiene derivative.



Hexaphenylethane has never been prepared and may not be capable of existing under normal conditions due to the enormous steric crowding that would be present. Study of these radicals was possible primarily due to their low reactivity and hence longer independent existence.

The second set of experiments were carried out in 1929 by Paneth and Hofeditz on simple alkyl radicals that are much more reactive. They carried out thermal decomposition of organometallic compounds, such as tetramethyl lead, and clearly demonstrated the formation and existence of free radicals. Their procedure, often referred to as the 'Paneth technique' consists of passing a stream of nitrogen and vapours of tetramethyl lead through a quartz tube at a pressure of about 2mm. (Fig. 10.1)

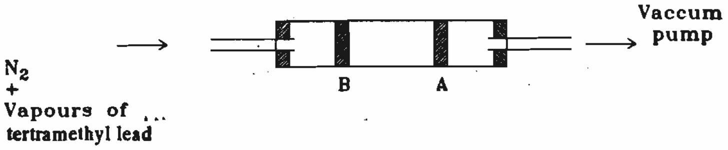


Fig 10.1 Production of radicals by paneth technique

On heating the tube strongly at any point (A), a lead mirror is deposited due to decomposition of tetramethyl lead. The gaseous product of decomposition was found to be ethane. Subsequent heating of the tube at another point (B), on the upstream side, resulted in formation of the mirror at B and its simultaneous disappearance at A, the products now contained tetramethyl lead. These reactions may be depicted as follows:

$$(CH_3)_4Pb(g) \xrightarrow{725K} Pb + 4CH_3\cdot$$

$$4CH_3\cdot + Pb \xrightarrow{375K} Pb(CH_3)_4$$

A great deal of work has been done since then to add information on the existence and properties of free radicals. We will describe some of this in the following sections.

10.4 GENERATION OF FREE RADICALS

As already stated, free radicals are formed from molecules by breaking a covalent bond so that each fragment keeps one electron. There are a number of ways of radicals generation; the most important are:

a) Photolysis

b) Thermolysis

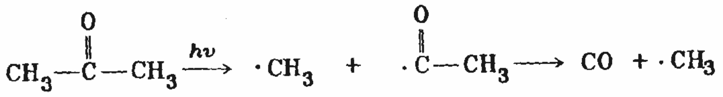
c) Redox reactions

Unimolecular decomposition of diacyl peroxides, peroxy carbonates, peresters, hydroperoxides, dialkyl peroxides, etc. has been carried out using thermal and photochemical means. Following is a brief account.

Photolysis

Photochemical dissociation or cleavage is an important method for the production of radicals. The prerequisite of this method is the ability of the molecule concerned to absorb radiation in the ultra-violet or visible range. The energy of radiation of wavelength 600-300 nm is 200-400 kJ mole^{-1} which is of the order of magnitude of covalent bond energies. Radiation of wavelength corresponding to λ_{max} of a molecule can cause splitting of the latter into radicals.

Many of these molecules also undergo homolysis on heating, but some do not. Chief among the latter group are aliphatic carbonyl compounds which have been studied most extensively in the vapour state. Thus propanone (acetone) in the vapour phase is decomposed by radiation of wavelength of 320 nm.



$$CH_3-\overset{\overset{O}{\|}}{C}-CH_3 \xrightarrow{h\nu} \cdot CH_3 + \cdot\overset{\overset{O}{\|}}{C}-CH_3 \longrightarrow CO + \cdot CH_3$$

Initially, photochemical cleavage of one of the two methyl-carbonyl bonds occurs. This results in two radicals, the methyl and the acetyl. Acetyl radical then breaks down spontaneously to yield another methyl radical and a stable molecule of carbon monoxide. Alkyl hypochlorites and nitrites are also an easy source of radicals. Alkoxyl radicals are obtained as products of their photolysis.

$$RO-Cl \xrightarrow{h\nu} RO\cdot + Cl\cdot$$

$$RO-NO \xrightarrow{h\nu} RO\cdot + NO\cdot$$

Photolysis of chlorine molecule has been mentioned above. This requires 244 kJ mole^{-1} of energy which is supplied by irradiating chlorine at 487.5 nm or heating it to 525K.

$$Cl-Cl \xrightarrow[\text{or } \Delta]{h\nu} 2Cl\cdot$$

Two major advantages of photolysis for generation of radicals are:

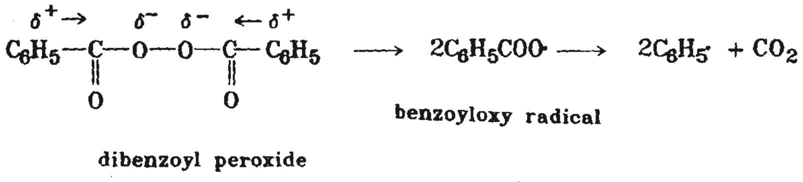
a) Bonds that are difficult to break or do not break at reasonable temperatures can be cleaved by photolysis, e.g. azoalkanes.

$$R-N{=}N-R \xrightarrow{h\nu} R\cdot + N{\equiv}N + R\cdot$$

b) The method is relatively more specific, in that radiation of only a particular wavelength is absorbed by a molecule leading to cleavage of specific bonds. You would study more about such interactions in Unit 14 dealing with Photochemistry.

Thermolysis

Cleavage of organic molecules can occur in the gaseous phase at high temperatures to give free radicals. Clelavage can also occur in the liquid phase if a molecule contains bonds with dissociation energies of less than 165 kJ mole^{-1}. Bonds between atoms other than carbon have bond dissociation energies of this order. Thus peroxides and azo compounds constitute a major source of radicals in solution, where the O — O or C—N bond, respectivelly, cleaves on heating. The oxygen-oxygen bond in peroxides is weak, with bond dissociation energy of about 120kJ mole^{-1}. Diacyl peroxides are a source of alkyl radicals because the acyloxy radicals lose CO_2 very rapidly. In aroyl peroxides, the products may be formed from aroyloxy radicals or from the radicals formed by their decarboxylation. A molecule like dibenzoyl peroxide can be considered as consisting of two dipoles joined at their negative ends. It, therefore, undergoes easy homolytic cleavage due to the repulsion between the two negative charges. Because it can generate radicals easily, dibenzoyl peroxide is used as an **initiator** in many reactions.



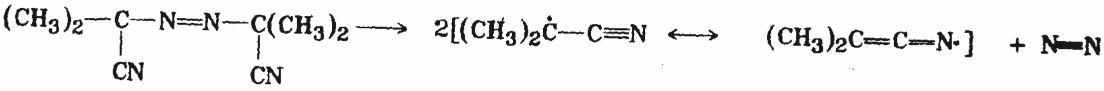
$$\overset{\delta^+\rightarrow}{C_6H_5-\underset{\underset{O}{\|}}{C}}-\overset{\delta^-}{O}-\overset{\delta^-}{O}-\overset{\leftarrow\delta^+}{\underset{\underset{O}{\|}}{C}-C_6H_5} \longrightarrow 2C_6H_5COO\cdot \longrightarrow 2C_6H_5\cdot + CO_2$$

Substituents affect the ease of cleavage of a substance. If a substance contains no substituents capable of promoting its decomposition or stabilising the product radical, then relatively rigorous conditions are required for cleavage. The rate of decomposition generally follows first order kinetics and is dependant on the solvent, temperature, and structure of the compound. For examplle, $(C_6H_5CH_2CH_2COO)_2$ has a half life of 0.5h at 375K while the half life of $(CH_3) CCOO)_2$ is as much as 200h at this temperature. As a consequence, phenyl-propionyl peroxide is so unstable that it cannot be isolated under ordinary conditions, while 2-methylpropyl hydroperoxide is stable for a very long time and gives radicals only slowly on heating even at 375K.

Azo compounds act as facile sourcs of free radicales by releasing N_2. As you have studied in Unit 3, N_2 is a very good leaving group. Simplel alkyl azo compounds are too stable to undergo thermal cleavage, however, suitable substituents can make their cleavage easier. For example, in 2,2-azo-bis-isobutyronitrile (AIBN), the homolytic cleavage is favoured by:

i) stability of N_2 molecule as the leaving group,

ii) delocalisation of the unpaired electron in the radical over the -C—C ≡ N conjugated system.



$$(CH_3)_2\underset{CN}{C}-N{=}N-\underset{CN}{C}(CH_3)_2 \longrightarrow 2[(CH_3)_2\dot{C}-C{\equiv}N \longleftrightarrow (CH_3)_2C{=}C{=}N\cdot] + N{\equiv}N$$

2,2′-azo-bis-isobutyronitrile

$CH_3-N=N-CH_3$ is stable up to 475K, while (AIBN) has a half life of only 5 min at 375K. So, as indicated above, all alkyl azo compounds may not be good sources of radicals.

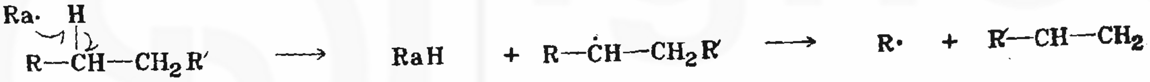
Aryl azo compounds undergo dissociation into radicals relatively more easily.

Remember a primary radical formed at the end of the chain would be more stable than a secondary radical formed anywhere in the middle.

$$(C_6H_5)_3C-N{=}N-C_6H_5 \xrightarrow{325K} (C_6H_5)_3C\cdot + N_2 + \cdot C_6H_5$$

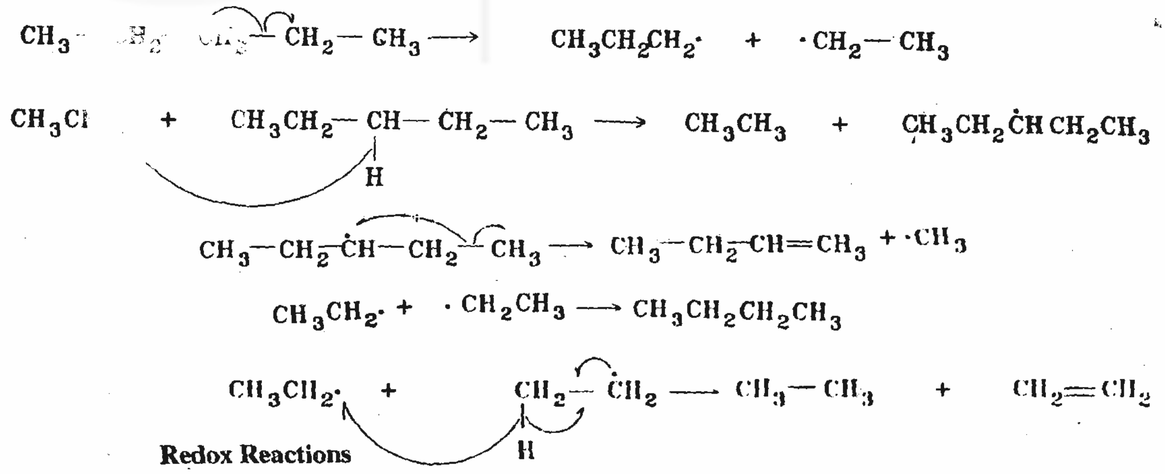
$$(C_6H_5)_3-N{=}N-OH \xrightarrow{300K} (C_6H_5)_3\cdot + N_2 + \cdot OH$$

Pyrolysis or cracking of long chain alkanes at 875K is an exampe of radical generation by C—C bond cleavage. Radicals are introduced into the system initially and they act by abstracting a hydrogen atom from a methylene group in the carbon chain. The resulting radical, obviously not at the end of the chain. undergoes fission β - to the radical C-atom, giving rise to a lower alkene plus another radical that continues the chain reaction.



Since the alkane, in this case, is a long chain hydrocarbon, the likelihood of two radicals coming close enough to terminate the reaction is very little. Hence, termination by radical-radical interaction is insignificant until concentration of the alkane falls to a very low level.

Pyrolysis generally results in a mixture of products. The following equations illustrate some possible pathways pyrolysis of pentane can take.



Redox Reactions

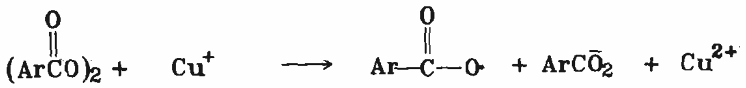
Radicals can be generated by reduction or oxidation of metal ions or by electrolysis of suitable compounds. Redox systems which operate in aqueous media or in organic solvents can be used for generation of radicals. A major advantage of such reactions is that radical production occurs at reasonable rates at very moderate temperatures, 275-325K.

The most familiar redox source of radicals is Fenton's reagent ferrous sulphate and hydrogen peroxide. Free OH radicals are obtained by partial reduction of hydrogen peroxide:

$$Fe^{2+} + HO{:}OH \longrightarrow Fe^{3+} + \cdot OH + OH^-$$

Presence of $\cdot OH$ is confirmed by the ability of Fenton's reagent to initiate vinyl polymerisation.

Cu^+ ions are found to enhance decomposition of aroyl peroxides.



$$(Ar\overset{O}{\overset{\|}{C}}O)_2 + Cu^+ \longrightarrow Ar-\overset{O}{\overset{\|}{C}}-O\cdot + ArC\bar{O}_2 + Cu^{2+}$$

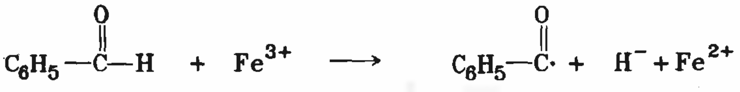
This method of obtaining aroyloxy radicals is more useful than thermolysis. In thermolysis, as you have seen above, there is danger of further decomposition of peroxide radicals to $Ar\cdot + CO_2$.

Cu^+ is also involved in conversion of diazonium salts, ArN_2, to ArCl in Sandmeyer reacton. A radical intermediate is supposed to be involved here:

$$Ar\overset{+}{N_2} + Cl^- + CuCl \longrightarrow Ar\cdot + N_2 + CuCl_2$$

$$Ar\cdot + CuCl_2 \longrightarrow ArCl + CuCl$$

Initiation of auto-oxidation of benzaldehyde is catalysed by a number of heavy metal ions capable of one electron transfer, e.g., Fe^{3+}:



$$C_6H_5-\overset{O}{\overset{\|}{C}}-H + Fe^{3+} \longrightarrow C_6H_5-\overset{O}{\overset{\|}{C}}\cdot + H^- + Fe^{2+}$$

Electrolytic process consists of loss of electrons at the anode and gain of electrons at the cathode. Consequently the process at anode is called 'anodic oxidation' and that at cathode, 'cathodic reduction'.

In some instances, free radicals may be produced by electrolysis. For example, anodic oxidation of salts of carboxylic acids in aqueous solution yield carboxylate radical $RCOO\cdot$ These undergo decarboxylation to alkyl radials $(R\cdot)$ which, in turn, dimerise rapidly. As you have studied in Unit 6 of organic chemistry course, CHE-05, this set of reactions constitutes the Koble electrolytic synthesis of hydrocarbons:

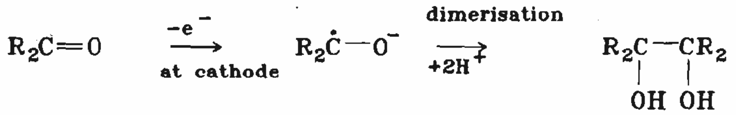
$$RCOO^- \xrightarrow[\text{at anode}]{-e^-} RCOO\cdot \xrightarrow{-CO_2} R\cdot \xrightarrow{\text{dimerisation}} R-R$$

Similarly, alkyl or aryl radicals may be produced by electrolysis of Grignard reagents in ether :

$$RMgBr \xrightarrow{-e^-} R\cdot + \overset{+}{Mg}Br$$

$$R\cdot + R\cdot \xrightarrow{\text{dimerisation}} R-R$$

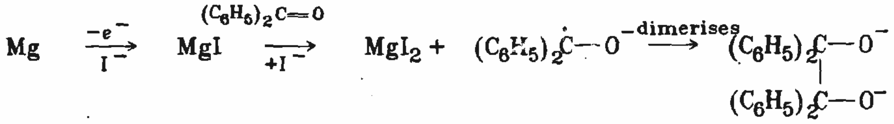
Radicals are produced at the cathode in the electrolysis of ketones in aqueous acid as a result of cathodic reduction.



$$R_2C{=}O \xrightarrow[\text{at cathode}]{-e^-} R_2\dot{C}-O^- \xrightarrow[+2H^+]{\text{dimerisation}} R_2\underset{OH}{\underset{|}{C}}-\underset{OH}{\underset{|}{C}}R_2$$

Species like $R_2\dot{C}-\bar{O}$ which carry both a charge as well as an unpaired electron are called radical ions. You will read more about these later.

The same type of dimeric product is formed when benzophenone is electrolysed in pyridine to which NaI has been added, using magnesium electrodes. The reducing agent is unipositive magnesium formed by oxidation of the magnesium anode. This then reduces benzophenone to the ion-radical which dimerises.

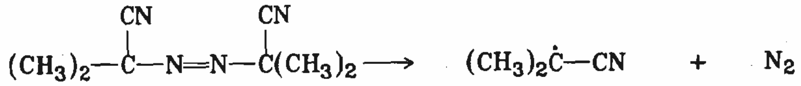


$$Mg \xrightarrow[I^-]{-e^-} MgI \xrightarrow[+I^-]{(C_6H_5)_2C=O} MgI_2 + (C_6H_5)_2\dot{C}-O^- \xrightarrow{\text{dimerises}} \begin{array}{l}(C_6H_5)_2C-O^- \\ \qquad | \\ (C_6H_5)_2C-O^-\end{array}$$

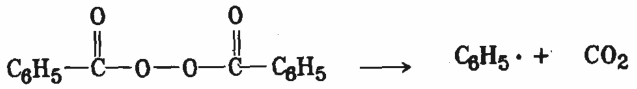
The reduction of ketones to pinacoles with a mixture of magnesium and magnesium oxide probably proceeds in the same way.

SAQ 2

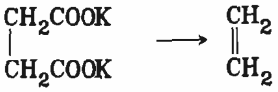
Give the mechanism of the following reactions:

i) 

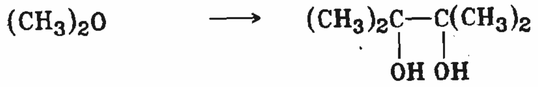
$(CH_3)_2\overset{CN}{\overset{|}{C}}-N=N-\overset{CN}{\overset{|}{C}}(CH_3)_2 \longrightarrow (CH_3)_2\dot{C}-CN + N_2$

ii) 

$C_6H_5-\overset{O}{\overset{\|}{C}}-O-O-\overset{O}{\overset{\|}{C}}-C_6H_5 \longrightarrow C_6H_5\cdot + CO_2$

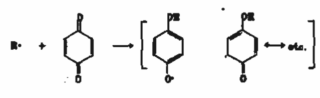
iii) 

$\begin{array}{l}CH_2COOK\\ |\\ CH_2COOK\end{array} \longrightarrow \begin{array}{l}CH_2\\ \|\\ CH_2\end{array}$

iv) 

$(CH_3)_2O \longrightarrow (CH_3)_2\underset{OH}{\underset{|}{C}}-\underset{OH}{\underset{|}{C}}(CH_3)_2$

10.5 DETECTION OF FREE RADICALS



Of the various methods that can be used for the detection of free radicals, two, *viz,* the Paneth technique and trapping by a relatively stable radical like 1,1-diphenyl-2-picrylhydrazyl radical have already been referred to in Section 10.2 and 10.3. A simple method to know whether a reaction proceeds via a radical intermediate or not, is to introduce a small quantity of a radical inhibitor like benzoquinone. If the reaction proceeds via a radical intermediate, it will slow down, otherwise it will remain unaffected. Alternatively, enhancement in the rate of a reaction on addition of an initiator would also indicate that it proceeds via a radical intermediate.

Since radicals have one or more unpaired electrons, they have a net magnetic moment and would thus be paramagnetic. Electron spin reasonance (esr) or electron paramagnetic resonance (epr) spectroscopy takes advantage of this property for their detection. Using this technique radicals can be detected at concentrations as low as $10^{-8} M$. Phenyl radical, for example, can be detected in solutions of benzoyl peroxide at concentration of about 2.5 $\mu g\ l^{-1}$ or $2.5 \times 10^{-6}\ g\ l^{-1}$.

The basic principle of this form of spectroscopy is that an unpaired electron, like a proton, has spin and this spin has an associated magnetic moment. When a free radical is placed in a magnetic field, the magnetic moment generated by the spinning electron can be aligned with or against the external magnetic field. These two orientations define two energy states, the one aligned with the field has less energy and the other one, aligned against the field, has higher energy (see Fig 16.2). So the former is more stable than the latter. With the absorption of energy, the spin state of an electron can change from one in alignment (lower) to the one against the field (higher). This happens when the sample is subjected to radiation in the microwave region.

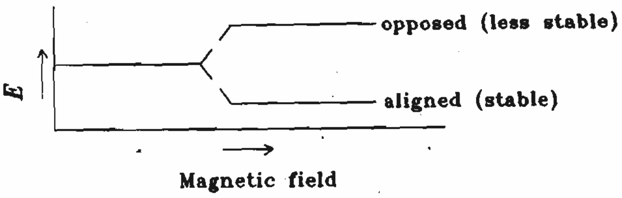


Fig 10.2 : Principle of esr spectroscopy

The transition from stable to the less stable state, or level produces a line in the esr spectrum. At high resolution, this single line is split into several lines due to coupling of the unpaired electron with the protons on the atom which carries this odd electron. If the number of the coupling protons is n, then the number of lines in the esr spectrum would be $n + 1$. Methyl radical, $CH_3^{\bullet}$, for example, shows 3 + 1 = 4 resonance lines (see Fig. 10.3).

Fig 10.3 : Esr spectrum of methyl radical

The esr of cycloheptatrienyl radical, C_7H_7, generated by irradiation of 1,3,5 - cycloheptatriene with X-rays shows eight equally spaced lines, indicating coupling with seven equivalent protons (see Fig. 10.4). This confirms the delocalisation of the unpaired electron around the ring.

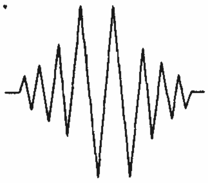
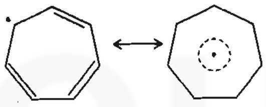


Fig. 10.4: Esr Spectrum of 1, 2, 3-cycloheptatriene



cycloheptatrienyl radical

So, you can see that the usefulness of esr spectroscopy lies not only in its great sensitivity in detecting free radicals at very low concentrations, but also as a tool for studying how the odd electron is placed in the molecular environment.

10.6 STRUCTURE AND STABILITY OF FREE RADICALS

In this section we will disuss the structure and stability of free radicals. We will take up structure first and then stability.

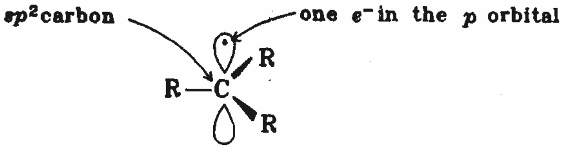
10.6.1 Structure

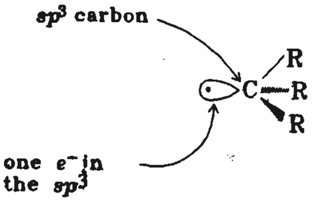
Simple radicals of the type $R_3C\cdot$ may have:

i) planar shape, i.e. the unpaired electron is a p-orbital and the paired electrons in sp^2 orbitals.

ii) pyramidal shape, i.e. the unpaired electron is in an sp^3 orbital

iii) shape some where between (i) and (ii).





A knowledge of the degree of '*s*' character of the orbital occupied by an unpaired electron can give information about the planar or pyramidal configuration of the radical. Electron paramagnetic resonance (epr) spectroscopy can give this information. The epr spectrum of methyl radical shows a negligible '*s*' character, indicating thereby that its structure could be either planar or a very shallow pyramid. The '*s*' character of the half filled corbitals in fluoromethyl radicals increases across the series:

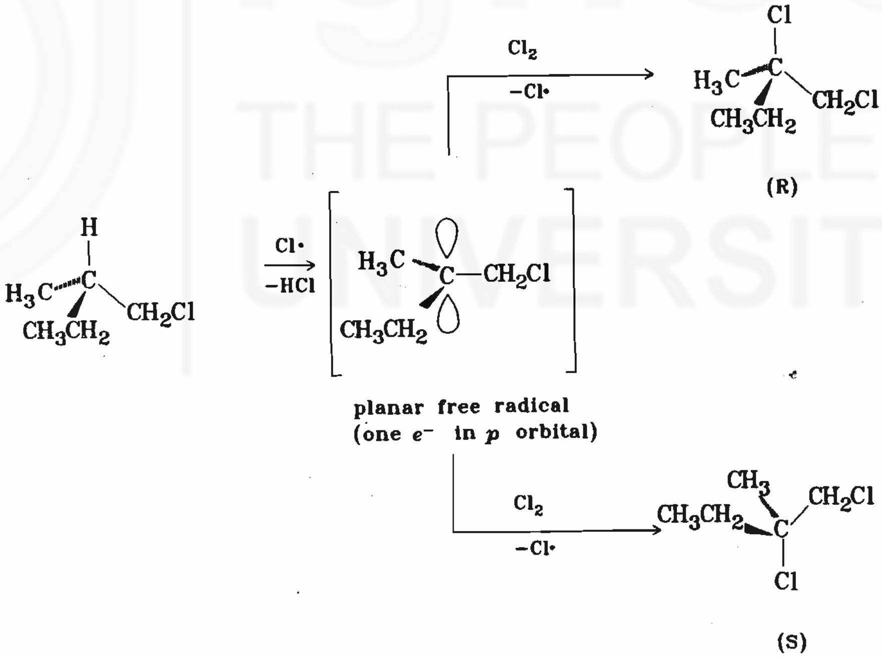
$$\cdot CH_3 \quad < \quad \cdot CH_2F \quad < \quad \cdot CHF_2 \quad < \quad \cdot CF_3$$

As shown by an analysis of the epr spectra of these radicals, there is a progressive distortion from planarity as we go from $\cdot CH_3$ to $\cdot CF_3$; CF_3 radical is esentially pyramidal implying that the unpaired electron is in an sp^3 hybrid orbital. Repulsive interaction beween singly occupied *p*-orbital and the filled orbitals occupied by 'lone pair' electrons on flourine atoms is minimised by adoption of pyramidal geometry. Presence of oxygen containing substituents also favours pyramidal geometry for similar reasons.

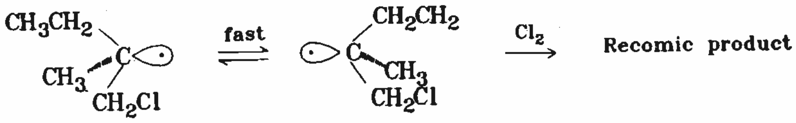
Deductions about radical configuration can also be made by examining the stereochemistry or radical reactions at a carbon that is either a chiral centre of part of a cyclic system. A planar or a rapidly inverting pyramidal radical should lead to a racemic product, while an optically active product will be obtained from a rigid pyramidal radical.

One of the most elegant experiments to determine the configuration of free radicals was done by Brown, Kharasch and Chao, who found that free radical chlorination of (+)-1-chloro-2-methylbutane yields racemic 1,2-dichloro-2-methylbutane. This is possible whether the free radical has a planar configuration or that of a rapidly inverting pyramid. Let us consider both the possibilities:

If the free radical is planar, the carbon atom bearing the odd electron is sp^2 hybridised and the odd electron would be in *p* orbital. Such a planar radical can be attacked equally easily from both the sides, leading to equal possibility of the formation of either isomer; implying racemisation.

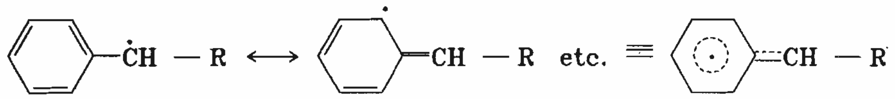


With the free radical having the configuration of a shallow pyramid, if we assume a faster inversion (turning inside out) than attachment of chlorine, we would expect a racemic product.



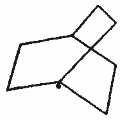
Since the energy barrier between planar configuration and a shallow pyramid is rather small, it is difficult to distinguish between the two in simple radicals. However, where the odd electron is delocalised as in allylic and benzylic radicals, epr, ir and electron diffraction studies have shown the radical to be planar. The delocalisation of π- electrons demand a planar geometry of the conjugated system.

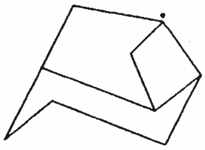
$$R-CH=CH-\dot{C}H_2 \longleftrightarrow R-\dot{C}H-CH=CH_2 \equiv [R-CH \mathrel{\overset{\cdots}{-}} CH \mathrel{\overset{\cdots}{-}} CH_2]^{\bullet}$$

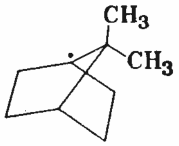


Both these radicals are planar because it is only in this configuration that there is maximum *p* orbital overlap and hence maximum stabilisation of the radical. It is for this reason that these radicals are more stable than simple alkyl radicals.

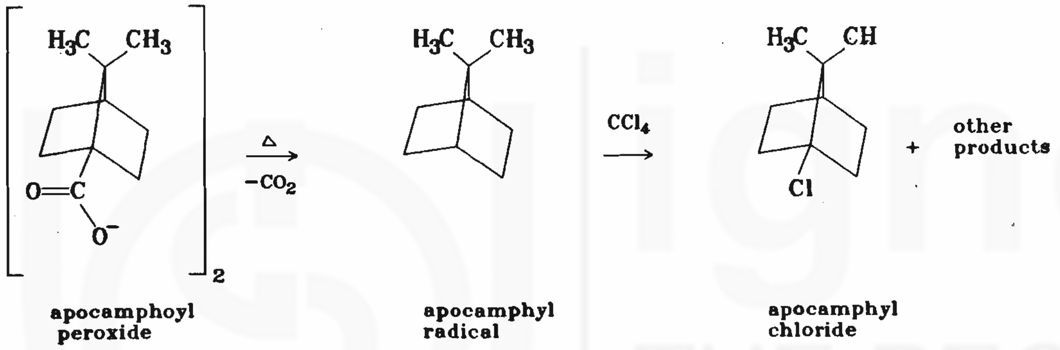
On the other hand, when the unpaired electron is situated on a carbon at the bridgehead of a bicyclic system, planar configuration is prevented by the geometric requirements of the system and the radical is forced to take up pyramidal configuration. The results of epr spectra are consistent with pyramidal geometry in the following radicals:







It may be interesting to mention here that apocamphoyl peroxide readily dissociates in carbon tetrachloride giving apocamphyl radical which on further reaction gives apocamphoyl chloride among other products:



In contrast, formation of a carbocation for which planar geometry is mandatory, is very difficult at such a position, as explained in Section 3.4.

10.6.2 Stability

As mentioned earlier, stability of free radicals varies from the transient short lived radicals like $CH_3\cdot$, with a half-life of the order of a few milliseconds, to what are termed as stable free radicals like 1,1-diphenyl-2-picrylhydrazyl radical which can even be crystallised from various solvents.

Radical stabilisation is reflected in the following two ways:

i) reduction in bond dissociation energies for bonds to the stabilised radical centre.

ii) variaton in rates of radical forming reactions such as thermal decomposition of several peroxides and azo compounds.

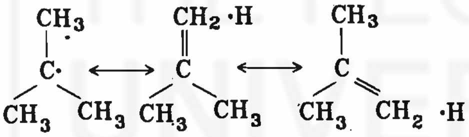
A simple way to compare the stabilities of various radicals is to calculate the bond dissociation energy which may be defined as the energy required for homolytic cleavage of the covalent bond in the particular molecule to form two radicals. In general, the smaller the amount of energy required for bond rupture, the more stable is the radical. Bond dissociation energies of some compounds are given in Table 10.1.

Table 10.1: Bond Dissociation Energies of Some Compounds

Bond	D kJ mole^{-1}	Bond	D kJ mole^{-1}
CH_3-H	426	$Cl-H$	430
C_2H_5-H	410	$Br-H$	364
$CH_3CH_2CH_2-H$	397	$I-H$	297
$CH_3CH_2-CH_2-CH_2-H$	393	$Cl-Cl$	242
$(CH_3)_2CH-H$	372	$Br-Br$	192
$(CH_3)_3C-H$	360	$F-F$	155
$C_6H_5CH_2-H$	326	$I-I$	150
C_6H_5-H	426	$HO-OH$	217
CH_3-CH_3	347	CH_3-Cl	339
$H-H$	435	CH_3-Br	280
CH_3-NH_2	330	CH_3-I	221
H_2N-H	426	CH_3-F	451
$F-H$	564	H_2N-NH_2	250
		CH_3-OH	376

Stability of free radicals can be explained on the basis of electronic as well as steric factors.

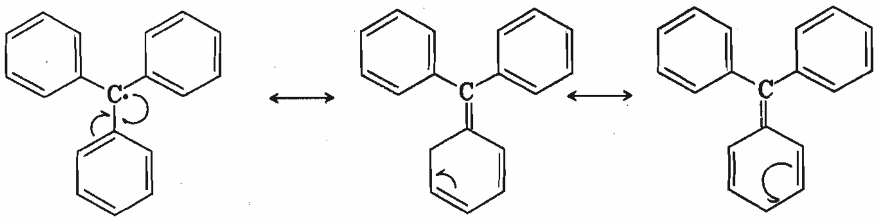
It is clear from the above Table that the stability of radicals increases in the order : primary < secondary < tertiary. In analogy with carbocations, this can be explained on the basis of hyperconjugation. The larger the number of alkyl groups attached to the carbon carrying the unpaired electron the higher would be the stability of the radical, for example the *tert*-butyl radical:



You have already come across allylic and benzylic radicals which are stabilised due to delocalisation of the odd electron.

Another factor responsible for the increased stability of tertiary radicals may be steric. Formation of a *tert*-butyl radical by removal of a hydrogen atom from isobutane is favoured as the steric repulsion between methyl groups is relieved to some extent. Remember there would be an increase in bond angle from about 109° to nearer 120° in the process.

Both electronic as well as steric factors may account for the unusual stability of triphenylmethyl radical. As expected triphenylmethyl radical is resonance stabilised by extensive delocalisation of the odd electron:

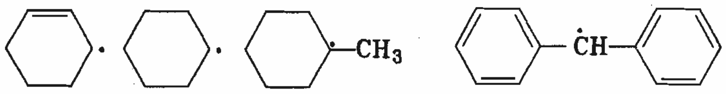


etc.

In addition, the three phenyl groups in this radical occupy a large volume and make it difficult for two radicals to approach each other for bond formation. It has, however, been suggested that the radical is not flat, but is probably more like a three-bladed propeller with angled blades. If this be so, delocalisation of the unpaired electron would be considerably inhibited.

SAQ 3

a) List the following radicals in the order of increasing stability. Justify your answer.



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b) Triphenylmethyl radical is stabilised due to extensive delocalisation. Write at least six resonance structures in addition to the ones given in the text above.

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10.7 FREE RADICAL REACTIONS

Free radicals have been postulated as intermediates in three types of reactions, *viz.*,

i) Substitution reactions
ii) Addition reactions
iii) Rearrangement reactions

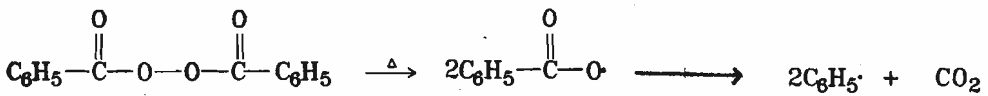
Before we go on to describe these reactions, we would briefly discuss the mechanism of free radical reactions.

10.7.1 Mechanism of Free Radical Reactions

Free radical reactions, in contrast to other types of reaction are generally chain reactions, i.e. they proceed in a cycle of repetitive steps. Such reactions involve three kinetically distinct steps; initiation, propagation and termination. These steps are described below for chlorination of methane.

i) **Initiation:** This step is the radical generation step. Compounds having weak covalent bonds may yield radicals on thermolysis or photolysis and are, hence, used as initiators. Initiation is an energy consuming step and is slow. You have already come across photolysis of chlorine molecules and thermolysis of benzoyl peroxide to produce free radicals.

$$Cl{:}Cl \xrightarrow{h\nu} Cl\cdot + Cl\cdot$$



$$C_6H_5-\overset{O}{\overset{\|}{C}}-O-O-\overset{O}{\overset{\|}{C}}-C_6H_5 \xrightarrow{\Delta} 2C_6H_5-\overset{O}{\overset{\|}{C}}-O\cdot \longrightarrow 2C_6H_5\cdot + CO_2$$

ii) **Propagation:** In this phase, which may involve two or more steps, the radical generated in the initiation step attacks a non-radical species leading to the formation of another radical species and a molecule with an even number of electrons. The radical species formed may follow the same sequence and this is repeated several times. The number of propagation steps that take place per initiation step is called the kinetic chain length. Photochemical halogenation of methane involves the following two propagation steps:

a) $Cl\cdot + H{-}CH_3 \longrightarrow HCl + \cdot CH_3$

b) $CH_3\cdot + Cl{-}Cl \longrightarrow CH_3Cl + \cdot Cl$

A radical like Cl· which helps to propagate the chain is called a **chain carrier.**

iii) **Termination:** The destruction of reactive intermediates neessary for propagation of the reaction chain is called termination. This is an exothermic reaction. Kinetic chain length depends on the frequency of such reactions. The more frequent these reactions, the shorter would be the chain length.

Photochemical chlorination of methane gets terminated when methyl and chlorine radicals start reacting with each other.

$$CH_3\cdot + \cdot Cl \longrightarrow CH_3Cl$$

$$CH_3\cdot + \cdot CH_3 \longrightarrow CH_3{-}CH_3$$

$$Cl\cdot + \cdot Cl \longrightarrow Cl_2$$

These reactions will become more frequent when most of the reactants have been consumed.

The overall rate of a chain reaction depends on the rate of initiation, propagation and termination steps.

10.7.2 Free Radical Substitution Reactions

Halogenation and oxidation by molecular oxygen are examples of free radical substitution reactions. We will briefly discuss them below:

Halogenation

Halogenation of alkanes is a chain reaction consisting of initiation, propagation and termination steps. We will take up halogenation by different halogens separately in order to bring out the similarities as well as differences in these reactions.

i) **Chlorination**

Chlorination of alkanes takes place either thermally or photochemically. It has been shown that the first step is the breaking of a chlorine molecule into two radicals. The process requires 244 kJ mole^{-1} of energy which can be supplied either by heating the reaction mixture up to 525K or irradiating it at 487.5 nm. As an example we will take chlorination of methane. The reaction proceeds at a very rapid rate becoming almost explosive at times.

The following equations show the energy changes involved in theinitiation and propagation steps of this reaction. The figures in parenthesis are the respective bond dissociation energies in kJmole^{-1}.

$$\underset{(244)}{Cl{-}Cl} \longrightarrow 2Cl\cdot \quad (\Delta H{=}{+}244\ KJ\ mole^{-1})$$

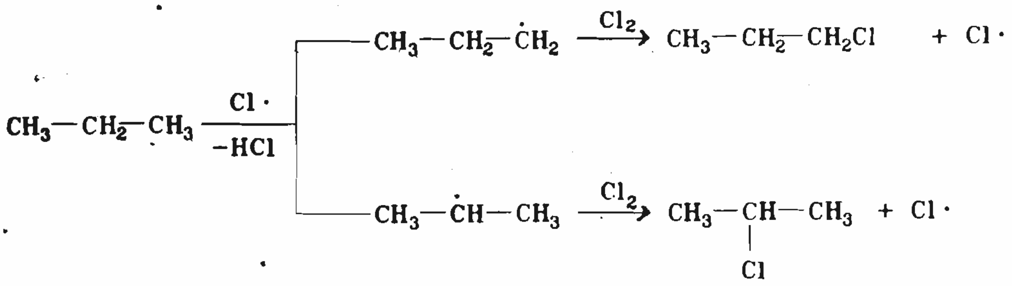
$$Cl\cdot + \underset{(426)}{H{-}CH_3} \longrightarrow \underset{(430)}{HCl} + \cdot CH_3 \quad (\Delta H{=}{-}4.00\ KJ\ mole^{-1})$$

$$CH_3\cdot + \underset{(242)}{Cl{-}Cl} \longrightarrow \underset{(338)}{CH_3Cl} + \cdot Cl \quad (\Delta H{=}{-}96\ KJ\ mole^{-1})$$

The chain is finally terminated when the radicals combine with each other.

A consideration of the bond-dissociation energies would make it clear, that although energy must be supplied for the initiation step, the two chain propagating steps are exothermic and hence proceed readily. Chlorine radical acts as the chain carrier.

In keeping with the stability of the intermediate radical formed, hydrogen atoms in an alkane are substituted in the general order : primary < secondary < tertiary. Chlorination of propane yields *n*-propyl and isopropyl chlorides in the ratio of 1:1.



Since, there are six primary hydrogens against only two secondary hydrogens in a molecule of propane, probability would favour the formation of primary radicals by a ratio of 3:1. The actual composition of the product mixture, however, shows that the ease of formation of a secondary radical is three times more than that of a primary radical.

ii) **Bromination**

Bromination of alkanes has close similarities to chlorination except for the fact that it is slow. As the following equations would show, this difference is mainly due to different bond-dissociation energies of the molecules involved. Again we have taken bromination of methane as an example.

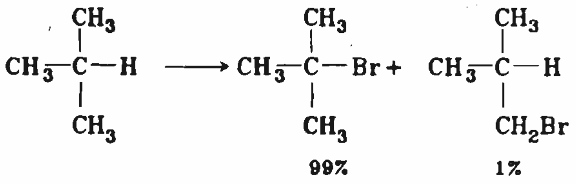
$$\underset{(192)}{Br-Br} \xrightarrow{h\nu} 2Br\cdot \qquad (\Delta H = +192 \text{ KJ mole}^{-1})$$

$$Br\cdot + \underset{(426)}{H-CH_3} \longrightarrow \underset{(363)}{HBr} + \cdot CH_3 \qquad (\Delta H = +63 \text{ KJ mole}^{-1})$$

$$CH_3\cdot + \underset{(192)}{Br-Br} \longrightarrow \underset{(280)}{CH_3Br} + Br\cdot \qquad (\Delta H = -88 \text{ KJ mole}^{-1})$$

Although, the last step of the reaction is exothermic, and therefore takes place readily, the attack of bromine atom on the alkane molecule is endothermic, unlike the analogous step in chlorination. Thus, it is somewhat difficult for a bromine atom to acquire the activation energy required to abstract a hydrogen atom. It becomes all the more difficult in the presence of chain-terminating steps like combination with another bromine atom or an alkyl radical both of which are exothermic reactions. Bromination, therefore, is a slower process than chlorination.

An important consequence of the low reactivity of bromine atom is its high selectivity for tertiary and secondary positions as compared to a chlorine atom. Thus, gaseous bromination of isobutane (2-methylpropane) yields mainly the tertiary bromide in spite of the probability factor favouring the primary bromide by a ratio of 9:1.

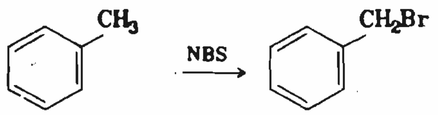


$$CH_3-\overset{CH_3}{\underset{CH_3}{C}}-H \longrightarrow \underset{99\%}{CH_3-\overset{CH_3}{\underset{CH_3}{C}}-Br} + \underset{1\%}{CH_3-\overset{CH_3}{\underset{CH_2Br}{C}}-H}$$

Bromination with N-Bromosuccinimide

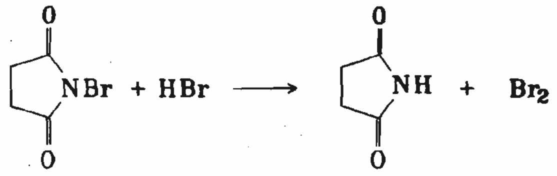
N-Bromosuccinimide (NBS) deserves a special mention because it is a specific reagent for bromination at allylic and benzylic positions.

$$CH_2{=}CH-CH_3 \xrightarrow{NBS} CH_2{=}CH-CH_2Br$$



A mechanism has been proposed for such reactions, in which NBS acts as a bromine reservoir maintaining a low concentration of molecular bromine by reacting with HBr, which is initially formed in a side reaction:

$$RH + Br\cdot \longrightarrow R\cdot + HBr$$



N-bromosuccinimide

Bromine molecule dissociates into bromine atoms in the presence of light or radical initiators. This explains why bromination by NBS is initiated by peroxides or ultraviolet light. Hydrogen abstraction by bromine atom generates an allylic radical which then reacts with molecular bromine to give the product.

$$Br\cdot + CH_2{=}CH{-}CH_3 \longrightarrow CH_2{=}CH{-}CH_2 + HBr$$

$$CH_2{=}CH{-}\dot{C}H_2 + Br_2 \longrightarrow CH_2{=}CH{-}CH_2Br + Br\cdot$$

The chain then continues with the production of HBr and bromine atoms. A low concentration of bromine favours allylic bromination over addition to the double bond. Allylic radical is resonance stabilised whereas the radical formed by addition of bromine reverts back to the alkene, making the latter reaction reversible.

$$\begin{tikzcd}
Br\cdot + CH_2{=}CH{-}CH_3 \arrow[r] & \left[\begin{array}{c} CH_2{=}CH{-}\dot{C}H_2 \\ \updownarrow \\ \dot{C}H_2{-}CH{=}CH_2 \end{array}\right] + HBr \arrow[d, "Br_2"] \\
 & CH_2{=}CH{-}CH_2Br + Br\cdot
\end{tikzcd}$$

iii) **Iodination**

Since iodine atom is very stable, the kinetic chain in iodination is much shorter. The heats of reaction for initiation and propagation steps in the iodination of methane are:

$$\underset{(150)}{I{-}I} \longrightarrow 2I: \quad (\Delta H = +150 \text{ KJ mole}^{-1})$$

$$I\cdot + \underset{(426)}{H{-}CH_3} \longrightarrow \underset{296}{HI} + \cdot CH_3 \quad (\Delta H{=}+130 \text{ KJ mole}^{-1})$$

$$CH_3\cdot + \underset{(155)}{I{-}I} \longrightarrow \underset{(221)}{CH_3I} + I\cdot \quad (\Delta H = -71 \text{ KJ mole}^{-1})$$

It is evident from the above data, that hydrogen abstraction by iodine atom is appreciably endothermic making iodination a very slow process. In actual fact, HI is even used for reduction of alkyl iodides to alkanes.

iv) **Flourination**

Flourination of alkanes is an extremely rapid and exothermic process. Flourinations are, therefore, carried out in the gas phase by diluting fluorine with nitrogen or some other inert gas. Heats of reaction for initiation and propagation steps are as follows:

$$\underset{(155)}{\text{F—F}} \longrightarrow 2\text{F}\cdot \quad (\Delta H = +155 \text{ KJ mole}^{-1})$$

$$\text{F}\cdot + \underset{(426)}{\text{H—CH}_3} \longrightarrow \underset{(561)}{\text{HF}} + \cdot\text{CH}_3 \quad (\Delta H = -138 \text{ KJ mole}^{-1})$$

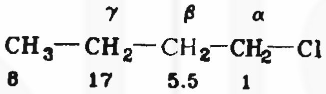
$$\text{CH}_3\cdot + \underset{(155)}{\text{F—F}} \longrightarrow \underset{(451)}{\text{CH}_3\text{F}} + \text{F}\cdot \quad (\Delta H = -296 \text{ KJ mole}^{-1})$$

As you can see both the propagation steps are highly exothermic. In fact, flourination proceeds in the dark, even at 195K, in the absence of chain initiators. Flourine molecule directly attacks an alkane molecule produing a flourine atom and an alkyl radical. Since such a reaction requires only 21kJ mole^{-1} of energy, it can take place at low temperatures.

$$\underset{155}{\text{F—F}} + \underset{426}{\text{H—CH}_3} \longrightarrow \underset{560}{\text{H—F}} + \text{F}\cdot + \text{CH}_3\cdot \quad (\Delta H = +21 \text{ KJ mole}^{-1})$$

Polar Effects in Halogenation

We have seen above that in free radical substitutions, there is always a tendency for the formation of the most stable radical and accordingly the order of reactivity of aliphatic hydrocarbons has been found to be tertiary > secondary > primary. However, there is increasing evidence that in addition to radical stability, polar factors also play a part in deciding which hydrogen of the reactant is to be abstracted. The relative reactivities of various hydrogen atoms of 1-chlorobutane in photochlorination are as follows:

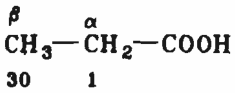


$$\underset{8}{\text{CH}_3}\text{—}\overset{\gamma}{\underset{17}{\text{CH}_2}}\text{—}\overset{\beta}{\underset{5.5}{\text{CH}_2}}\text{—}\overset{\alpha}{\underset{1}{\text{CH}_2}}\text{—Cl}$$

In spite of the fact that α, β, and γ carbons atoms are all secondary in nature, there is a striking difference in the reactivities of hydrogen atoms attached to them. The attacking chlorine radical is relatively electronegative and therefore it prefers to approach hydrogens which are away from the electronegative chlorine substituent.

Where radical stability the only factor, the hydrogens on the α-carbon should be most reactive, as the radical produced by their abstraction is expected to be stabilised by the adjacent chlorine atom. Apparently the polar effect due to electronegative chlorine substitutent overcomes the radical stabilization effect.

A similar polar effect seems to operate in the chlorination of propionic acid where the relative reactivities of hydrogen atoms are:



$$\overset{\beta}{\underset{30}{\text{CH}_3}}\text{—}\overset{\alpha}{\underset{1}{\text{CH}_2}}\text{—COOH}$$

SAQ 4

(a) In the chlorination of 2-methylpropane what product ratio of 1-chloro-2-methylpropane to 2-chloro-2-methylpropane would you expect if all hydrogens were abstracted at equal rates.

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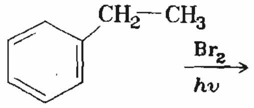
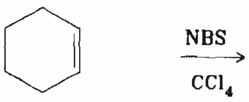
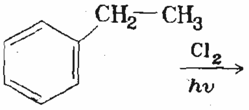
(b) Give the products expected in the following reactions:

(i) 

(ii) 

(iii) 

10.7.3 Addition Reactions

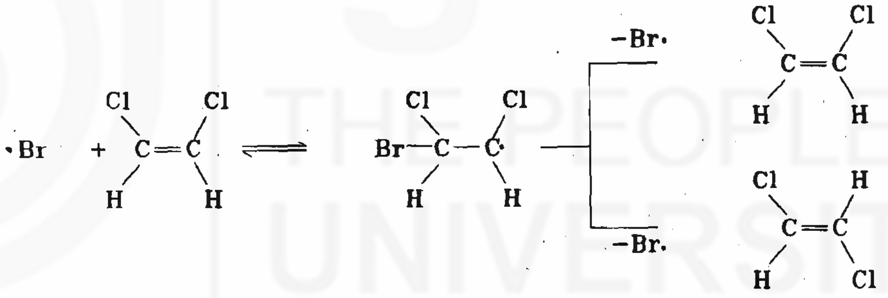
Free radical addition reactions include addition of halogens, halogen acids, polymerisations and autoxidation reactions.

Addition of Halogens

Addition of halogens to carbon-carbon double bond can proceed through free radical mechanism in the vapour phase or in a non-polar solvent like carbon tetrachloride under the catalytic influence of light. Remember, addition is ionic in a polar solvent.

It has been found that the addition of chlorine or bromine to ethene is exothermic and therefore takes place readily. Addition of iodine, on the other hand is endothermic and therefore difficult to achieve.

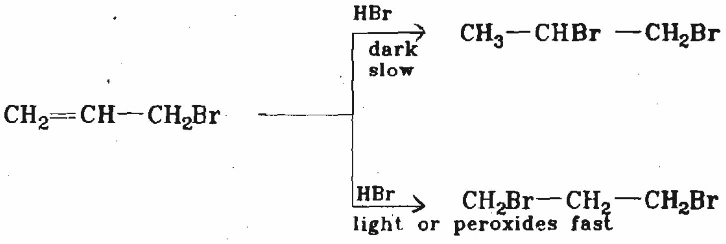
An important consequence of the addition of bromine to olefins, which is a reversible reaction, is their *cis - trans* isomerisation, e.g. bromine catalysed isomerisation of cis - dichloroethene to the *trans* isomer. The latter being more stable predominates in the equilibrium mixture.



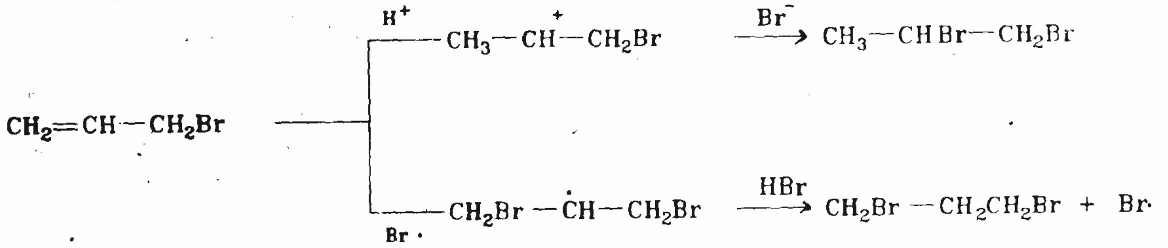
Isomerisation is effected by rotation around the carbon-carbon bond in the intermediate radical.

Addition of halogen acids

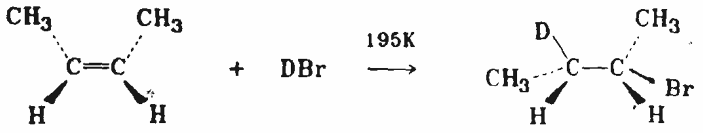
The most well-known example of free radical addition of halogen acids to carbon-carbon double bond is the peroxide catalysed addition of HBr to olefins. Kharasch and Mayo showed that hydrogen bromide can add to olefins either by ionic or by radical mechanism. In the absence of light or radical initiators, the addition of HBr to allyl bromide (3-bromo-propene) proceeds by ionic mechanism giving 1,2- dibromopropane, while in the presence of light or peroxides a rapid radical addition leads to the formation of the 1 : 3-dibromo product.

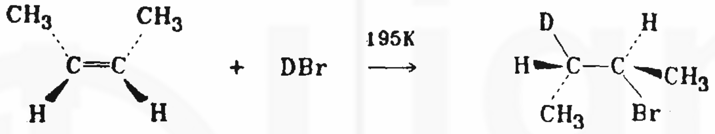


The difference in the nature of the products can be explained on the basis of the stabilities of the intermediate carbocation or radical formed. In the case of ionic addition, the proton adds first, leading to the more stable secondary carbocation whereas in the radical addition, bromine atom adds first giving the more stable secondary radical.



Peroxide catalysed addition of HBr to carbon-carbon double bond is called abnormal because it does not follow Markownikoff's rule. The effect is known as peroxide or Kharasch effect. Radical addition is usually a stereospecific process leading to a trans product. The reaction is done at low temperature to prevent isomerisation. Addition of DBr to butene-2 is given here as an example:





In constrast to addition of HBr, radical addition of HCl and HI to alkenes normally does not take place. A consideration of energy changes associated with each propagating step of the chain-process would make this clear:

$$X\cdot \; + \; CH_2{=}CH_2 \longrightarrow XCH_2{-}\dot{C}H_2 \qquad \left[\begin{array}{l} X{=}Cl \;;\; \Delta H = -109 \text{ KJ mol}^{-1} \\ X{=}Br \;;\; \Delta H = -21 \text{ KJ mol}^{-1} \\ X{=}I \;;\; \Delta H = +29 \text{ KJ mol}^{-1} \end{array}\right]$$

$$XCH_2{-}\dot{C}H_2 \; + \; HX \longrightarrow XCH_2{-}CH_2{-}X \; + \; X\cdot \qquad \left[\begin{array}{l} X{=}Cl \;;\; \Delta H = +21 \text{ KJ mol}^{-1} \\ X{=}Br \;;\; \Delta H = -46 \text{ KJ mol}^{-1} \\ X{=}I \;;\; \Delta H = -113 \text{ KJ mol}^{-1} \end{array}\right]$$

You can see that for the addition of HCl, although the first step is exothermic and so takes place readily, the second step is endothermic, so the initially formed radical is unable to decompose HCl. Polymerisation begins to compete with the addition reaction in this case; addition of HCl to ethene is given below as an example:

$$Cl\cdot \; + \; CH_2{=}CH_2 \longrightarrow Cl{-}CH_2{-}CH_2\cdot$$

$$ClCH_2{-}CH_2\cdot + CH_2{=}CH_2 \longrightarrow ClCH_2{-}CH_2{-}CH_2{-}CH_2\cdot$$

$$ClCH_2{-}CH_2{-}CH_2{-}CH_2\cdot + nCH_2{=}CH_2 \longrightarrow ClCH_2(CH_2CH_2)_{n+1}CH_2\cdot$$

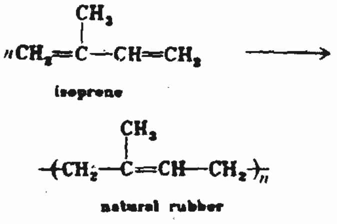
$$ClCH_2(CH_2CH_2)_{n+1}CH_2\cdot + HCl \longrightarrow ClCH_2(CH_2CH_2)_{n+1}CH_3 \; + \; Cl\cdot$$

$$n = 4{-}10$$

These low polymers are known as telemers.

For HBr both the steps are exothermic and so the reaction takes place readily. In HI the first step being endothermic again makes the reaction difficult.

Natural rubber is a linear polymer of isoprene, 2-methy 1-1,3- butadiene



$n\,CH_2{=}\overset{\overset{CH_3}{|}}{C}{-}CH{=}CH_2 \longrightarrow {-}\!\!(CH_2{-}\overset{\overset{CH_3}{|}}{C}{=}CH{-}CH_2)_n\!\!{-}$

isoprene

natural rubber

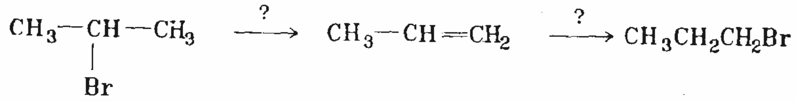
SAQ 5

(a) What products do you expect in the following and why?

$$CH_2{=}CH{-}CH_2Br \;+\; HBr\ (aq) \longrightarrow$$

$$CH_2{=}CH{-}CH_2Br \;+\; HBr \xrightarrow{peroxide}$$

(b) Complete the following sequence:

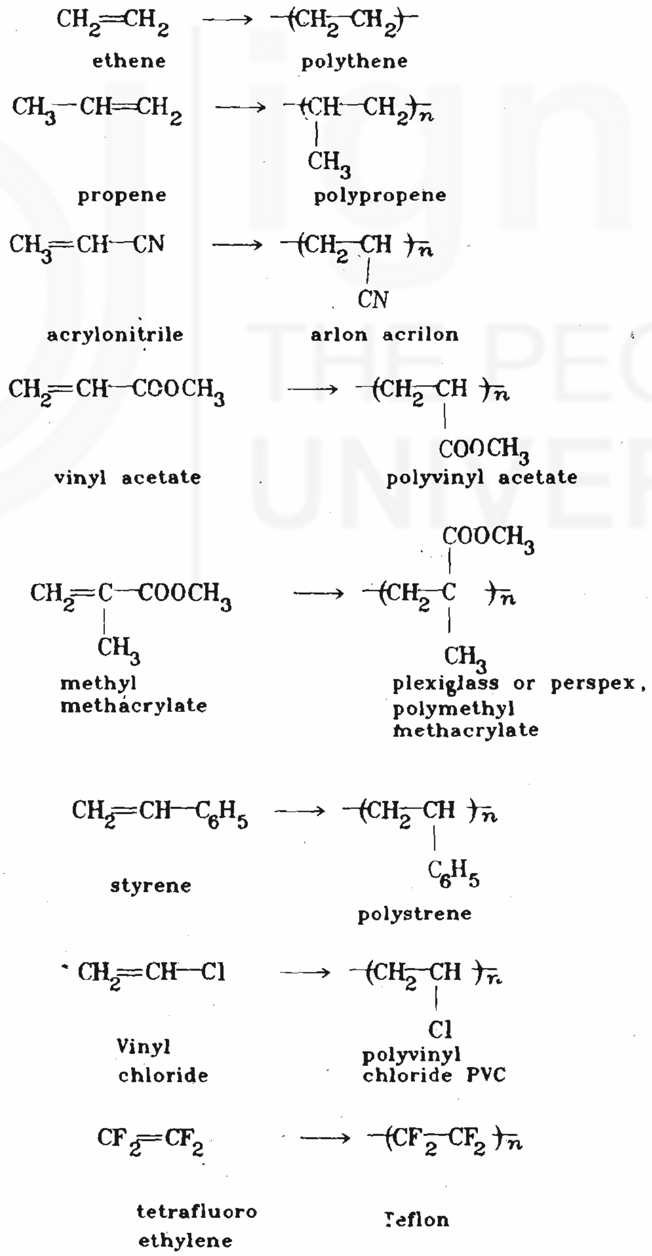


$$CH_3{-}\underset{\underset{Br}{|}}{CH}{-}CH_3 \xrightarrow{?} CH_3{-}CH{=}CH_2 \xrightarrow{?} CH_3CH_2CH_2Br$$

$$CH_3{-}CH_2{-}CH_2Br \xrightarrow{?} CH_3{-}CH_2{-}CH_2OH$$

Vinyl Polymerisations

Vinyl polymers are the most common commercial addition polymers. Familiar products of vinyl polymerisation include synthetic elastomers, Plexiglass, polystyrene, polyethene, Orlon and most of the ion-exchange resins. Natural rubber is a prototype of the class. Some of the common vinyl monomers along with their polymers are listed below:



$$CH_2{=}CH_2 \longrightarrow {-}\!(CH_2{-}CH_2)\!{-}$$

ethene　polythene

$$CH_3{-}CH{=}CH_2 \longrightarrow {-}\!(\underset{\underset{CH_3}{|}}{CH}{-}CH_2)_n$$

propene　polypropene

$$CH_3{=}CH{-}CN \longrightarrow {-}\!(CH_2{-}\underset{\underset{CN}{|}}{CH})_n$$

acrylonitrile　arlon acrilon

$$CH_2{=}CH{-}COOCH_3 \longrightarrow {-}\!(CH_2{-}\underset{\underset{COOCH_3}{|}}{CH})_n$$

vinyl acetate　polyvinyl acetate

$$CH_2{=}\underset{\underset{CH_3}{|}}{C}{-}COOCH_3 \longrightarrow {-}\!(CH_2{-}\overset{\overset{COOCH_3}{|}}{\underset{\underset{CH_3}{|}}{C}})_n$$

methyl methacrylate　plexiglass or perspex, polymethyl methacrylate

$$CH_2{=}CH{-}C_6H_5 \longrightarrow {-}\!(CH_2{-}\underset{\underset{C_6H_5}{|}}{CH})_n$$

styrene　polystrene

$$CH_2{=}CH{-}Cl \longrightarrow {-}\!(CH_2{-}\underset{\underset{Cl}{|}}{CH})_n$$

Vinyl chloride　polyvinyl chloride PVC

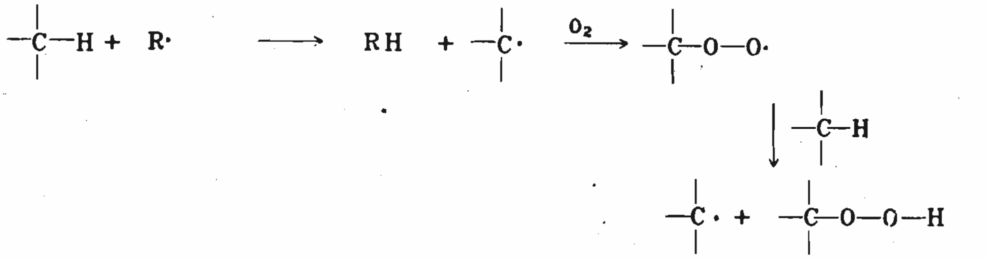
$$CF_2{=}CF_2 \longrightarrow {-}\!(CF_2{-}CF_2)_n$$

tetrafluoro ethylene　Teflon

Polymers of acrylic acid derivatives are glass clear transparent plastics. Due to the commercial importance of vinyl polymers, vinyl polymerisation has been extensively studied. You will read about it in later courses.

Autoxidation

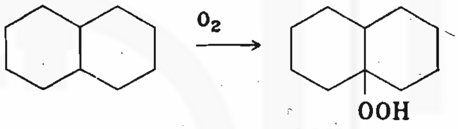
Autoxidation is the reaction of organic compound with oxygen under mild conditions. Decomposition of most organic compound exposed to air and sunlight is due to photosensitised oxidation. Trace metals present as impurities can act as initiators. Hydrocarbons may get converted to hydroperoxides, molecules of oxygen react readily with radicals due to their own diradical nature.

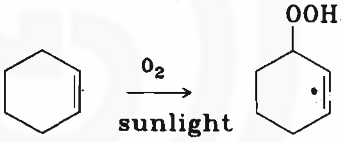


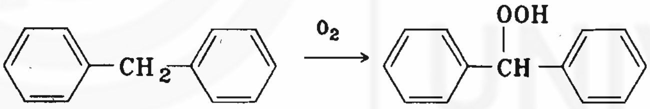
a hydroperoxide

In a number of cases, the hydroperoxide formed can itself act as an initiator, so that the reaction is autocatalysed.

As would be expected, initial abstraction of hydrogen from the hydrocarbon takes place more readily from a tertiary than from a secondary or primary position and especially readily from an allylic or benzylic position as is evident from the following reactions:

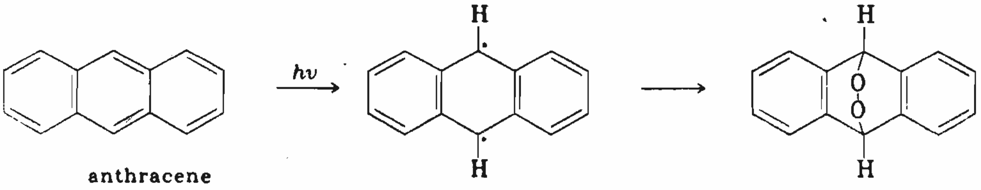




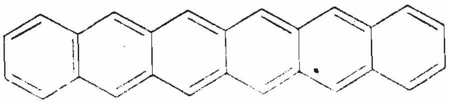


Drying oils like linseed oil which contain a large proportion of unsaturated acids change into hard solids on exposure to air. This 'drying' property has been attributed among other things to oxidation. Metal oxides especially lead monoxide which is mixed with linseed oil in paints catalyse this process.

An interesting case of autoxidation is the photoxidation of hydrocarbons such as anthracene.

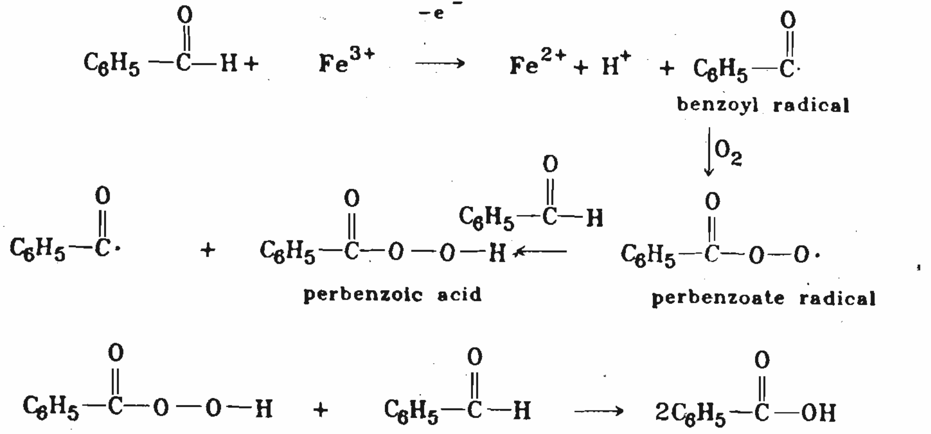


Absorbed light converts anthracene to an excited state, something like a diradical, which then adds a molecule of oxygen to form an end peroxide. Photo oxidation proceeds so readily with some of the higher lin aromatic hydrocarbons, such as, hexacene that it is not possible to work with them in light



hexacene

Aldehydes also undergo autoxidation, thus, benzaldehyde gets easily oxidised to benzoic acid, the reaction is catalysed by light and also by metal ions capable of one electron oxidation/reduction transition, eg., $Fe^{3+} \overset{-e^-}{\rightleftharpoons} Fe^{2+}$



$$C_6H_5-\overset{O}{\overset{\|}{C}}-H + Fe^{3+} \longrightarrow Fe^{2+} + H^+ + C_6H_5-\overset{O}{\overset{\|}{C}}\cdot$$

benzoyl radical

$$\downarrow O_2$$

$$C_6H_5-\overset{O}{\overset{\|}{C}}\cdot + C_6H_5-\overset{O}{\overset{\|}{C}}-O-O-H \xleftarrow{C_6H_5-\overset{O}{\overset{\|}{C}}-H} C_6H_5-\overset{O}{\overset{\|}{C}}-O-O\cdot$$

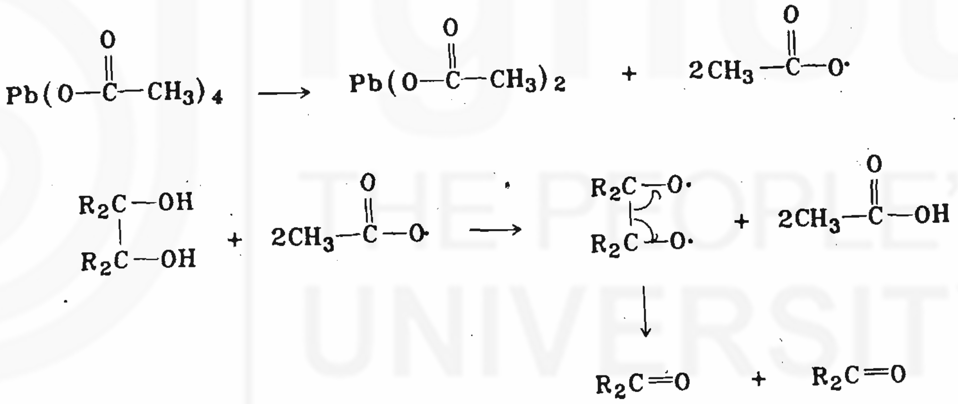
perbenzoic acid perbenzoate radical

$$C_6H_5-\overset{O}{\overset{\|}{C}}-O-O-H + C_6H_5-\overset{O}{\overset{\|}{C}}-H \longrightarrow 2C_6H_5-\overset{O}{\overset{\|}{C}}-OH$$

The perbenzoate radical, obtained by addition of O_2 to the first formed benzoyl radical removes hydrogen from a second benzaldehyde molecule to form perbenzoic acid and a benzoyl radical. While the latter continues the reaction chain, perbenzoic acid reacts with another molecule of the aldehyde yielding two molecules of benzoic acid. Presence of electron donating substituents in benzene nucleus facilitates the reaction. Autoxidation of aldehydes can be lessened by addition of anti-oxidants like phenols or aromatic amines.

Oxidation with Lead tetra-acetate

Lead tetra-acetate is a reagent of considerable preparative value. It is used for fission of 1 : 2-glycols in non-hydroxylic solvents. The reaction is supposed to proceed by radical mechanism.



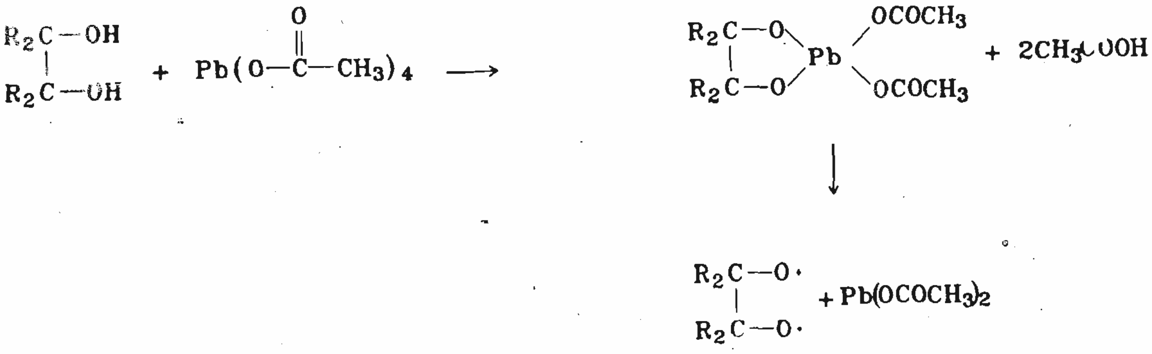
$$Pb(O-\overset{O}{\overset{\|}{C}}-CH_3)_4 \longrightarrow Pb(O-\overset{O}{\overset{\|}{C}}-CH_3)_2 + 2CH_3-\overset{O}{\overset{\|}{C}}-O\cdot$$

$$\begin{matrix}R_2C-OH\\ |\\ R_2C-OH\end{matrix} + 2CH_3-\overset{O}{\overset{\|}{C}}-O\cdot \longrightarrow \begin{matrix}R_2C-O\cdot\\ |\\ R_2C-O\cdot\end{matrix} + 2CH_3-\overset{O}{\overset{\|}{C}}-OH$$

$$\downarrow$$

$$R_2C{=}O + R_2C{=}O$$

The diradical, obtained by removal of hydrogen atoms from the glycol, breaks up into two molecules of ketone. It has alternately been suggested that the diradical is obtained by spontaneous fission of the first formed cyclic intermediate.



$$\begin{matrix}R_2C-OH\\ |\\ R_2C-OH\end{matrix} + Pb(O-\overset{O}{\overset{\|}{C}}-CH_3)_4 \longrightarrow \begin{matrix}R_2C-O\\ |\\ R_2C-O\end{matrix}\!\!>Pb\!\!<\!\begin{matrix}OCOCH_3\\ \\ OCOCH_3\end{matrix} + 2CH_3COOH$$

$$\downarrow$$

$$\begin{matrix}R_2C-O\cdot\\ |\\ R_2C-O\cdot\end{matrix} + Pb(OCOCH_3)_2$$

The fact that *cis*-diols are cleared considerably faster than the *trans* isomer, supports this view.

Arylation

As mentioned earlier, Sandmeyer reaction of a diazonium salt with cuprous chloride or bromide is also supposed to involve radical intermediates. Here the aryl radical is believed to be generated by an electron transfer, coupled with loss of nitrogen.

$$ArN_2^+ + CuCl + Cl^- \longrightarrow Ar\cdot + N_2 + CuCl_2$$

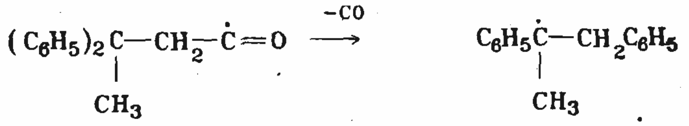
which reacts further with cupric chloride to give aryl halide.

$$Ar\cdot + CuCl_2 \longrightarrow ArCl + CuCl$$

10.7.4 Rearrangements

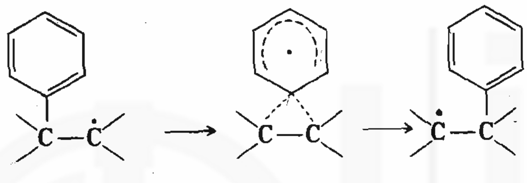
Though alkyl radicals show the same order of stability in terms of structure as carbocations, radical rearrangements are not very common.

The few known rearrangement reactions of radicals nearly always involve migration of the aryl group, e.g.,



$$(C_6H_5)_2\underset{\displaystyle CH_3}{\underset{|}{C}}-CH_2-\dot{C}=O \xrightarrow{-CO} C_6H_5\underset{\displaystyle CH_3}{\underset{|}{\dot{C}}}-CH_2C_6H_5$$

It has been suggested that migration of aryl rather than an alkyl group is encouraged by the possibility that the former can proceed via an intermediate stabilised by delocalisation

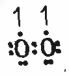


10.8 DIRADICALS AND RADICAL IONS

In this section we will briefly describe diradicals and radical ions.

10.8.1 Diradicals

Diradicals contain two unpaired electrons. Oxygen molecule is considered to be a diradical, though comparatively an unreactive one:



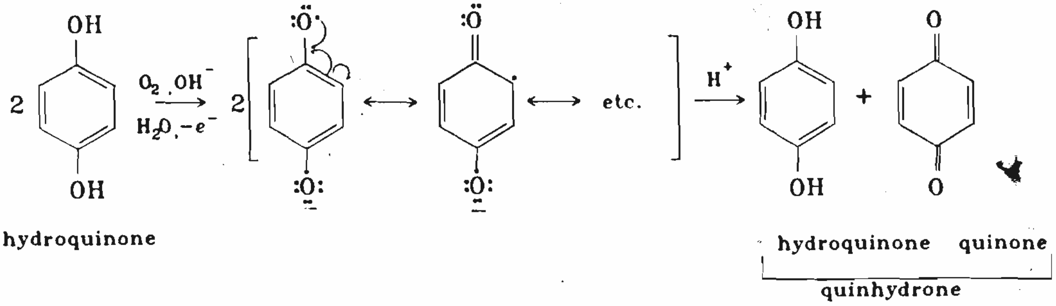
Methylene diradical or carbene formed by photochemical decomposition of ketene or diazo-methane is by contrast extremely reactive. You have read about carbenes in the previous unit.

Photochemical excitation of anthracene and other lin aromatic hydrocarbons referred to above is supposed to lead to the formation of diradicals.

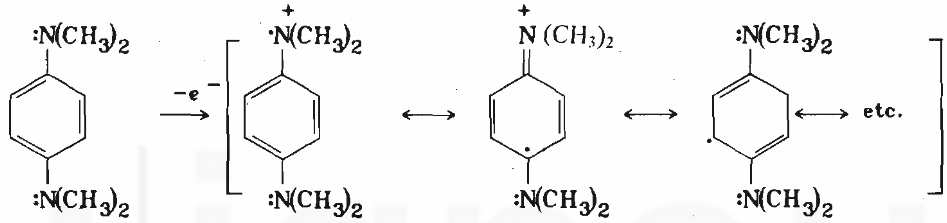
10.8.2 Radical Ions

Both radical anions and radical cations are known.

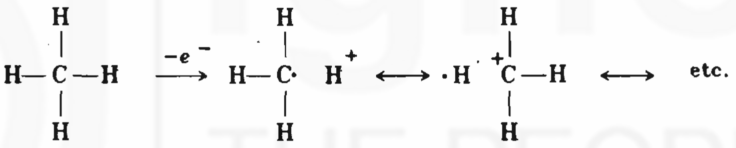
Radical Anions: Careful oxidation of hydroquinones or controlled reduction of quinones in basic solution produces semiquinones which are radical anions of moderate stability in basic media. When acidified semiquinones disproportionate to mixtures of quinones and hydroquinones which in many cases form π– molecular complexes, e.g., quinhydrone:



Radical Cations: A number of radical cations have also been detected. Their stabilities vary over a wide range. At the high end of the stability scale are the Wurster radical cations, in which the positive charge and the odd electron are highly delocalised. At the opposite end is $CH_4^{+}\cdot$, which is formed in a mass spectrograph by knocking an electron out of methane by bombardment with electrons accelerated under moderate potentials.



Würster radical cation



10.9 CHEMICAL ACTION OF X-RAYS

X-rays and other ionising radiations can cause degradative reactions in chemical compounds. For example the reaction with water in the living tissues as well as in *vitro* systems is as follows:

$$\begin{array}{ccccc} H_2O & \xrightarrow{h\nu} & [H_2O]^{+} & + & -e^{-} \\ & & \downarrow & & \downarrow H_2O \\ & & \overset{+}{H} + \cdot OH & & \overset{-}{HO} + H\cdot \end{array}$$

The primary process is abstraction of an electron. Two radicals are formed by the secondary processes, one of them involving a second molecule of water. Since the ejected electron may not react with the second molecule of water immediately, any reaction chains set in motion by the two radicals may occur with some time interval.

In living tissue, these reactions can cause considerable harm.

10.10 SUMMARY

- Free radicals are formed by homolytic cleavage of covalent bonds. They are characterised by one or more unpaired electrons as shown in their colour and esr spectrum. In this unit we have traced their historic background and discussed their nature, generation, stability and reactions.

- Free radicals can be generated by photolysis, thermolysis or by redox reactions. Free radicals can have both a planar as well as pyramidal shape. Epr as well as stereochemical studies have been conducted to throw light on the configuration of free radicals. Free radicals differ in their stability from the transient ones like $CH_3\cdot$, to the stable ones like 2,6-di-*tert*-butyl phenoxy radical. Both electronic and steric factors contribute to the stability of free radicals.
- Free radicals have been postulated as intermediates in substitution, addition and rearrangement reactions.
- Free radical reactions are chain reactions characterised by well defined initation, propagation and termination steps. They are catalysed by light and free radical generators and inhibited by free radical inhibitors.
- Halogenation is the most important of free radical substitution reactions. Bromination is more selective than chlorination due to lower reactivity of bromine. Bromination with NBS takes place exclusively at allylic or benzylic positions.
- Peroxide catalysed addition of HBr to alkenes is another important reaction. The product here has an orientation different from the Markowni koff's product.
- Other important free radical reactions are polymerisation and autoxidation.
- Free radical rearrangements are not very common.

10.11 TERMINAL QUESTIONS

1) Give the products formed and account for the fact that addition of $CBrCl_3$ in the presence of peroxide takes place faster to 2-ethyl-1-hexene than to 1-octene.

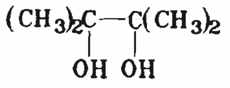
2) Write all the steps in free radical addition of (a) HBr (b) HCl to propene (c) using the data given in the text, suggest a possible reason why the peroxide effect is observed for HBr and not for HCl.

3) Outline the steps by which the following transformations can be affected.

a) $CH_3—CHBr—CH_3 \longrightarrow CH_3CH_2—CH_2Br$

b) $CH_3—CHOH—CH_3 \longrightarrow CH_3CH_2—CH_2OH$

c) $(CH_3)_2CO \longrightarrow$

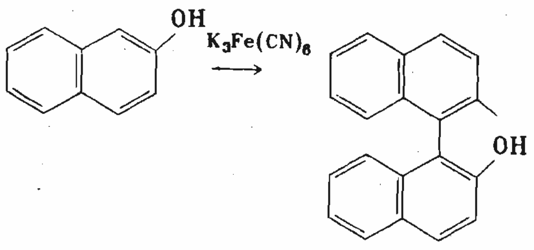


$$(CH_3)_2\underset{OH}{C}—\underset{OH}{C}(CH_3)_2$$

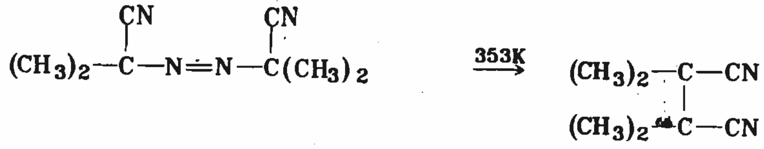
d) $CH_3—CH=CH_2 \longrightarrow CH_2=CH—CH_2-CH_2-CH=CH_2$

4) Formulate a reasonable mechanism for the following:

a)



b)

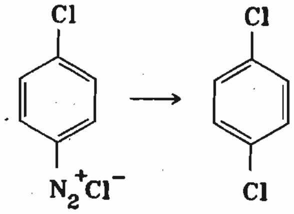


$$(CH_3)_2\overset{CN}{\overset{|}{C}}{-}N{=}N{-}\overset{CN}{\overset{|}{C}}(CH_3)_2 \xrightarrow{353K} \begin{array}{l}(CH_3)_2{-}C{-}CN\\ \qquad\quad |\\ (CH_3)_2{-}C{-}CN\end{array}$$

c)

$$CH_3CH{=}CHCH_3 + Cl_2 \xrightarrow{sunlight} CH_3\underset{Cl}{\underset{|}{C}}HCH{=}CH_2 + \text{other products}$$

d)

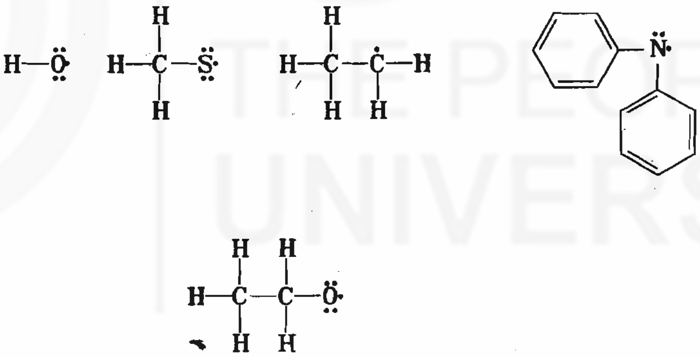


5) A hydrocarbon C_6H_{14} gives a mixture containing only two monochlorides in photochemical chlorination. One of these compounds solvolyses very rapidly in ethanol, whereas the other is very slow. What is the hydrocarbon? Identify the monochlorides and explain the difference in the rate of their solvolysis.

10.12 ANSWERS

Self-assessment Questions

1) a) Lewis formulas show a pair of shared electrons by a bond and unshared electrons as dots.



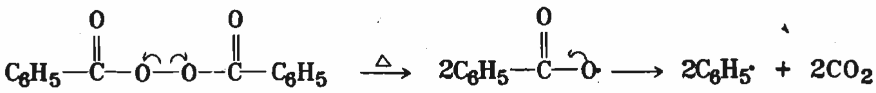
b) *p, tert, tert, tert, allylic, benzylic*

2)

i)

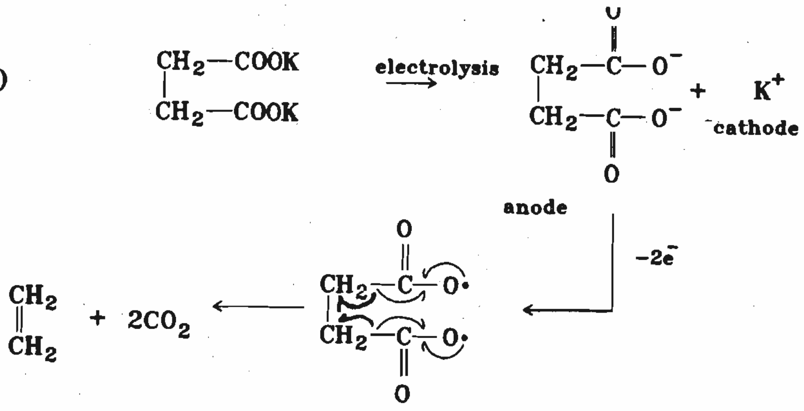
$$(CH_3)_2\overset{CN}{\overset{|}{C}}{-}N{=}N{-}\overset{CN}{\overset{|}{C}}(CH_3)_2 \xrightarrow{\Delta} 2(CH_3)_2{-}\dot{C}{-}CN + N_2$$

ii)

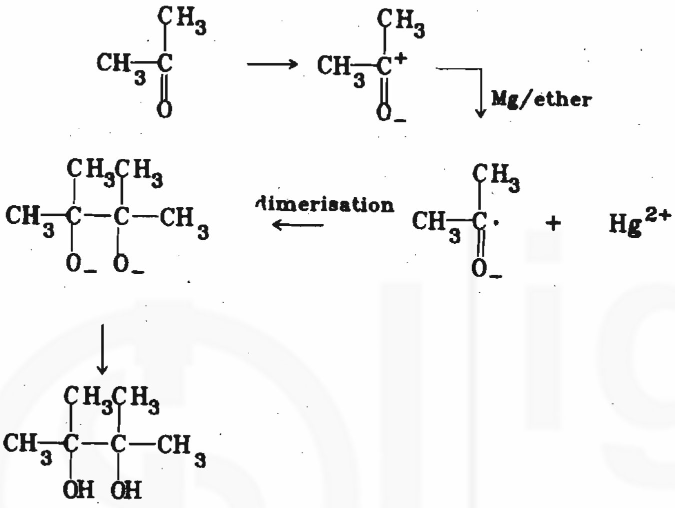


$$C_6H_5{-}\overset{O}{\overset{\|}{C}}{-}O{-}O{-}\overset{O}{\overset{\|}{C}}{-}C_6H_5 \xrightarrow{\Delta} 2C_6H_5{-}\overset{O}{\overset{\|}{C}}{-}O\cdot \longrightarrow 2C_6H_5\cdot + 2CO_2$$

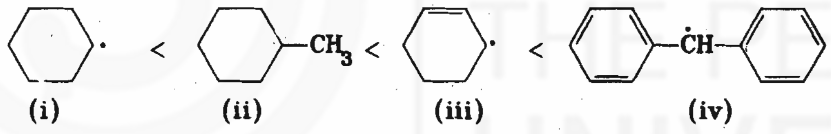
iii)



iv)

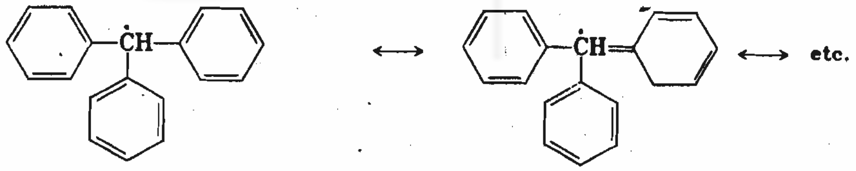


3) a)


(i) (ii) (iii) (iv)

i) is a secondary, ii) a tertiary, iii) an allylic and iv) a benzyl radical stabilised by two benzene rings.

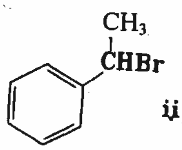
b)



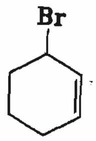
4) a) 9 :1

b)

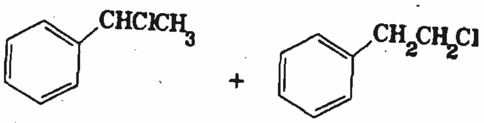
i)



ii)



iii)



, also polychlorination products.

Chlorine being more reactive, substitution is less specific.

5) a) i) $CH_3CHBr-CH_2Br$

ii) $CH_2BrCH_2CH_2Br$

b) i) alc KOH, HBr/peroxide

ii) aq KOH

Terminal Questions

1)

$$CBrCl_3 \xrightarrow{\text{peroxide}} \cdot CCl_3$$

2 Ethyl-1-hexene would give a tertiary radical on addition of CCl_3 radical which is more stable than the secondary radical given by 1-octene, therefore, the former forms faster.

$$\begin{tikzcd} CH_3-CH=CH_2 + Br\cdot \arrow[r, "(iii)"] & CH_3-\dot{C}H-CH_2Br \arrow[d, "HBr", "(iv)"'] \\ & CH_3-CH_2-CH_2Br + Br\cdot \end{tikzcd}$$

2) a) i) Peroxide $\longrightarrow$ Ra·

ii) $Ra\cdot + HBr \longrightarrow RaH + Br$

b) i) Peroxide $\longrightarrow$ Ra·

ii) $Ra\cdot + HCl \longrightarrow RaH + Cl$

$$\begin{tikzcd} CH_3-CH=CH_2 + Cl\cdot \arrow[r, "(iii)"] & CH_3-\dot{C}H-CH_2Cl \arrow[d, "HCl", "(iv)"'] \\ & CH_3-CH_2-CH_2Cl + Cl\cdot \end{tikzcd}$$

c) Steps (ii) + (iv) are too dificult in the case of HCl. Because of the high bond energy of HCl, the free radicals find it difficult to break H—Cl bond.

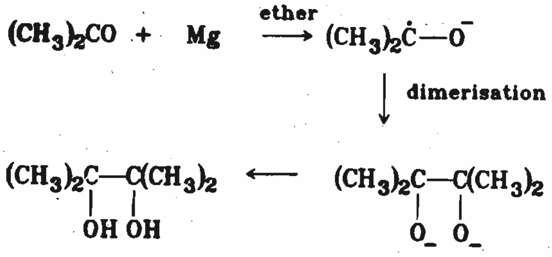
3) a)

$$\begin{tikzcd} CH_3-CHBr-CH_3 \arrow[r, "alc\ KOH"] & CH_3-CH=CH_2 \arrow[d, "HBr/peroxide"] \\ & CH_3CH_2CH_2Br \end{tikzcd}$$

b)

$$\begin{tikzcd} CH_3CHOH\,CH_3 \arrow[r, "H^+", "heat"'] & CH_3-CH=CH_2 \arrow[d, "HBr/peroxide"] \\ CH_3CH_2CH_2OH & CH_3CH_2CH_2Br \arrow[l, "aq.\ KOH"'] \end{tikzcd}$$

c)



$$(CH_3)_2CO + Mg \xrightarrow{ether} (CH_3)_2\dot{C}-O^-$$

$$\downarrow \text{dimerisation}$$

$$(CH_3)_2\underset{OH}{C}-\underset{OH}{C}(CH_3)_2 \longleftarrow (CH_3)_2\underset{O^-}{C}-\underset{O^-}{C}(CH_3)_2$$

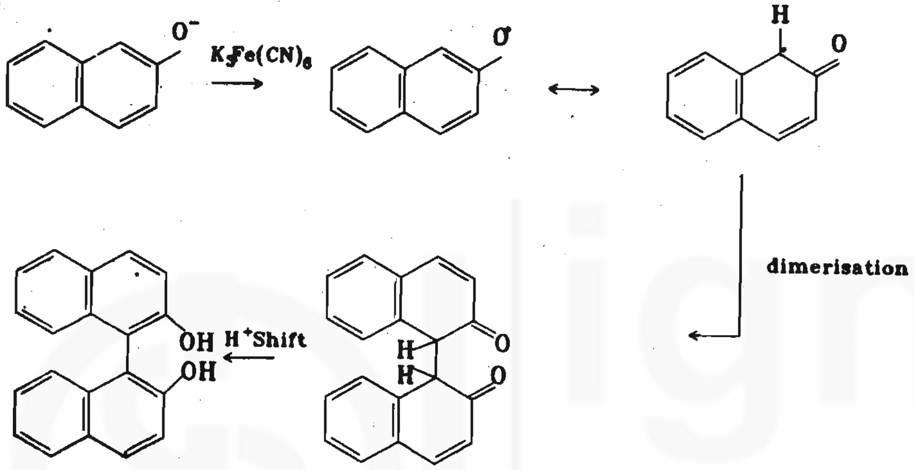
d)

$$CH_3CH{=}CH_2 \xrightarrow[CCl]{NBS} BrCH_2CH{=}CH_2$$

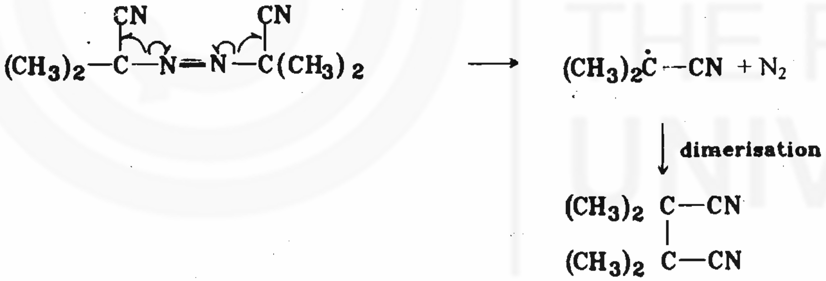
$$\downarrow Na/ether$$

$$CH_2{=}CH-CH_2-CH_2-CH{=}CH_2$$

4) **a)**



b)



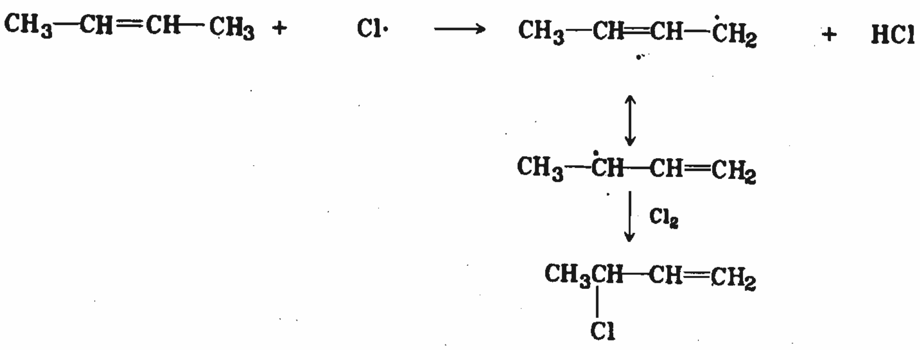
$$(CH_3)_2-\overset{CN}{C}-N{=}N-\overset{CN}{C}(CH_3)_2 \longrightarrow (CH_3)_2\dot{C}-CN + N_2$$

$$\downarrow \text{dimerisation}$$

$$\begin{array}{l}(CH_3)_2\ C-CN\\ \qquad\quad\ |\\ (CH_3)_2\ C-CN\end{array}$$

c)

$$Cl_2 \xrightarrow{h\nu} 2Cl\cdot$$



$$CH_3-CH{=}CH-CH_3 + Cl\cdot \longrightarrow CH_3-CH{=}CH-\dot{C}H_2 + HCl$$

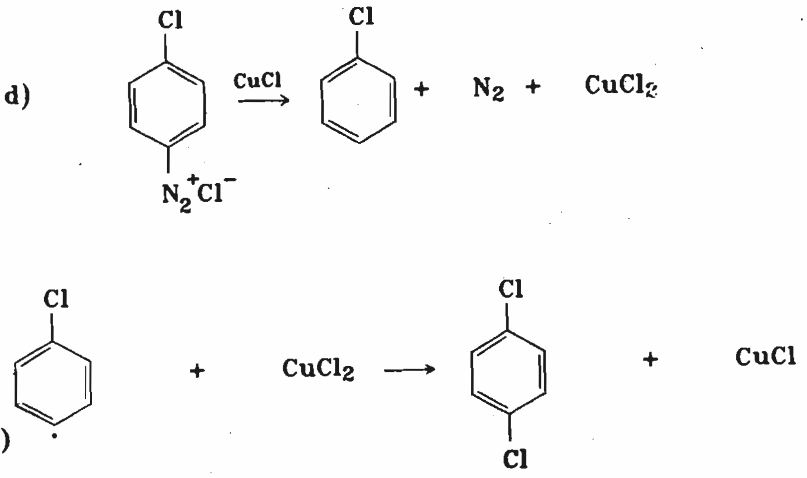
$$\updownarrow$$

$$CH_3-\dot{C}H-CH{=}CH_2$$

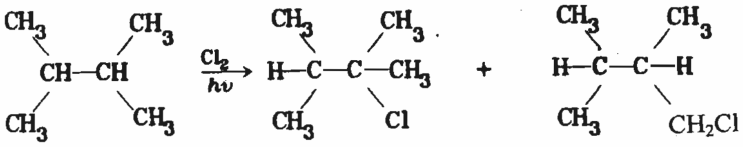
$$\downarrow Cl_2$$

$$CH_3\underset{Cl}{CH}-CH{=}CH_2$$

d)



5)



Since it gives only two monochlorides, it must have only two types of hydrogens, tertiary and primary and, therefore, the structure shown. Replacement of the former gives a tertiary chloride which reacts faster with the solvent than the primary chloride formed by the replacement of the latter.

UNIT 11 MOLECULAR REARRANGEMENT

Structure

11.1 INTRODUCTION

You know that organic reactions inspite of their complexity and diversity, can basically be placed in four well defined categories. Reactions in which substituents enter or leave a molecule are subdivided into substitution, addition or elimination reactions. Those in which the oxidation level of a molecule changes are put under the heading of redox reactions. Reactions in which a group shifts from one position in the reactant to a different one in the product are called rearrangement reactions. Rearrangements frequently result in the formation of an isomer but generally migration of the group produces a reactive site in the molecule which stabilises itself by an addition or elimination reaction. In this unit, we will discuss such rearrangement reactions.

Objectives

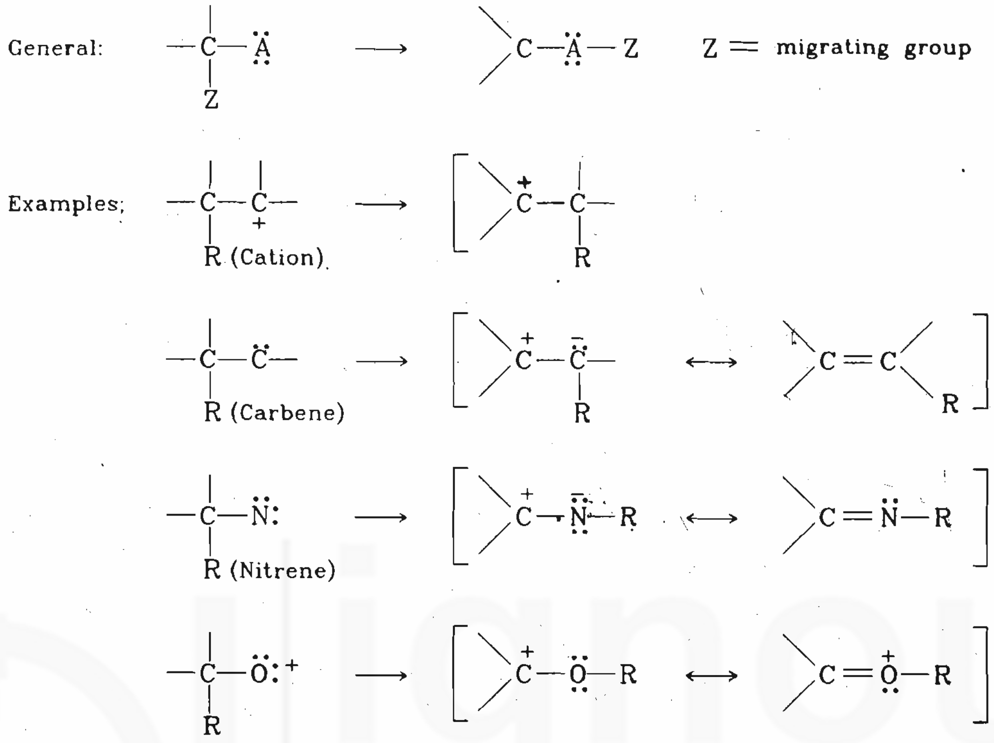
After studying this unit you should be able to:

- classify rearrangement reactions,
- identify the reactive intermediate involved,
- relate a particular rearrangement to the appropriate energy diagram,
- identify the electron deficient site formation in a rearrangement,
- identify the group that is most likely to migrate, and
- explain the detailed course of the reaction.

11.2 REARRANGEMENTS OF ELECTRON DEFICIENT SYSTEMS

A very important group of rearrangements involves migration of a group from one position to an adjacent one in the molecule. Such rearrangements are known as 1,2 shifts and they form by far the largest group of rearrangement reactions.

The starting point of 1,2 shifts is the creation of an electron deficient centre in the molecule which may be a carbon, nitrogen or oxygen atom. The electron deficient atom may carry a positive charge or it may have only an electron sextet as in carbenes and nitrenes. These rearrangements are shown diagrammatically in scheme-1. The position from which the group migrates is called the **migration origin** and the one to which it migrates is called the **migration terminus**. The migrating group never leaves the molecule. The migrating group may be halogen, oxygen, sulphur, carbon or hydrogen. By far the most common and important are the carbon migrations.

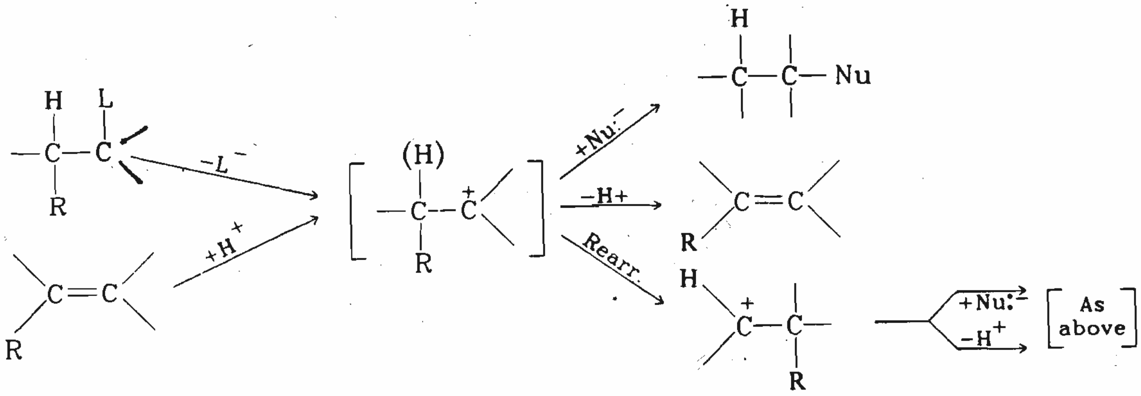


Scheme–1

We will first discuss rearrangements involving carbocations. Then we will take up rearrangements involving migrations to electron deficient nitrogen and oxygen.

11.3 CARBOCATION REARRANGEMENTS

Carbocations are formed either through heterolytic cleavage of a C—L bond, L being a halogen atom, an OH or OR group, or through protonation of a double bond. The positive charge on carbon is neutralised through solvolysis, combination with a nucleophile or loss of proton from an adjacent position. You have studied these reactions in earlier units. A third possibility in the case of appropriate substrates is migration of a group, as shown in scheme-2 from a neighbouring carbon. More stable the new carbocation is compared to the one initially formed, more readily is this likely to happen.



Scheme–2

This is also clear from the energy diagram (Fig. 11.1), which shows three transition states between the starting material A and the product E. The minima in between represent the initially formed carbocation B and that after rearrangement, D. Notice that in the curve, D occupies a lower position than B on the energy coordinate, indicating that it is more stable than B. Such open \or discrete carbocations, like B and D, are known as classical carbocations. The transition from B to D may involve a geometrically symmetrical bridged or nonclassical ion C, in which three atoms are bonded with only two electrons. C could simply be a transition state as the migrating group slips across from one bonding orbital to another.

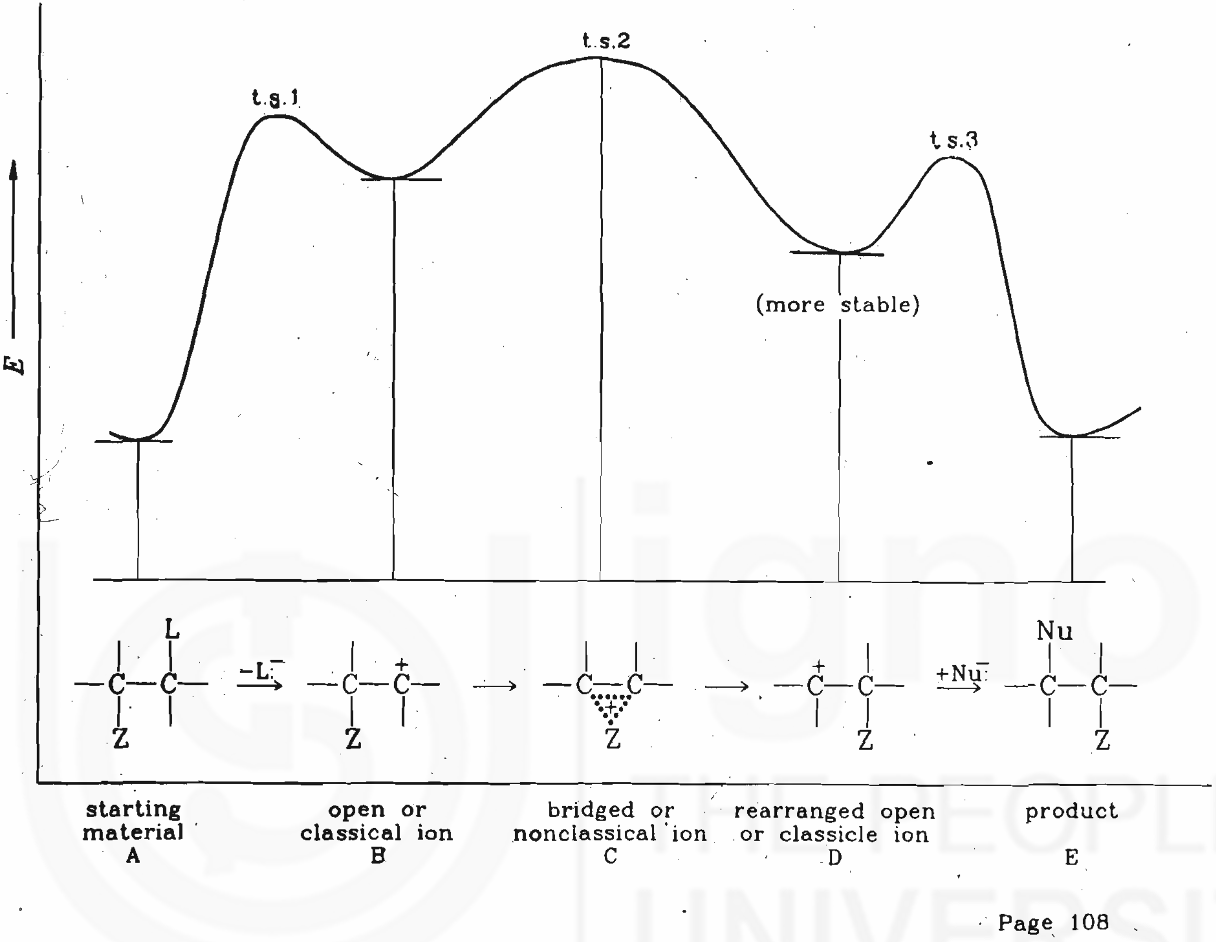


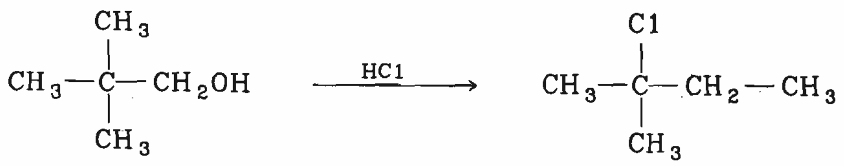
Fig. 11.1 : Mechanism and potential energy diagram for 1,2-shifts

In some cases, kinetic and stereochemical evidence suggests the involvement of the migrating group, Z in the process of cleavage of the C—L bond. The migrating group does this by accommodating or delocalising the positive charge on the carbocation being formed. This effect, known as neighbouring group participation, or anchimeric assistance acts as a driving force for the reaction and also determines the stereochemical course of the reaction. These points will be illustrates by the examples discussed here.

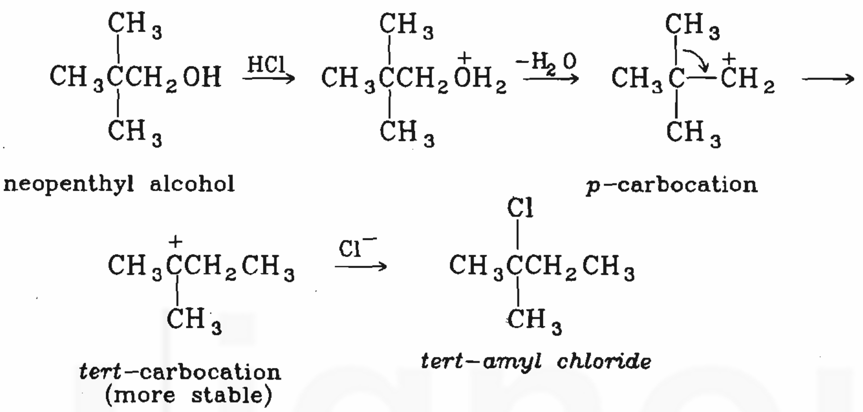
We will now take some well known carbocation rearrangements.

11.3.1 Wagner-Meerwein Rearrangements

Originally rearrangements of alcohols under acidic conditions were known as the Wagner-Meerwein rearrangements. The term has since been broadened to include various other rearrangements involving carbocation. A typical example is the rearrangement of neopentyl compounds. For example 2,2-dimethyl propanol-1, or neopentyl alcohol when treated with hydrochloric acid gives 2-chloro-2-methyl-butane



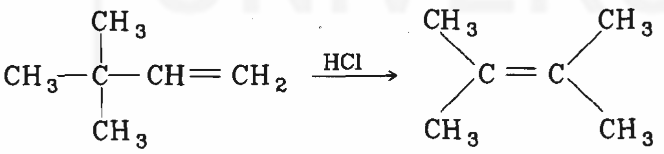
Obviously a rearrangement has taken place here. Let us work out the course of this reaction. As you can see the primary carbocation formed first rearranges to the tertiary carbocation which adds chloride ion to give the product.



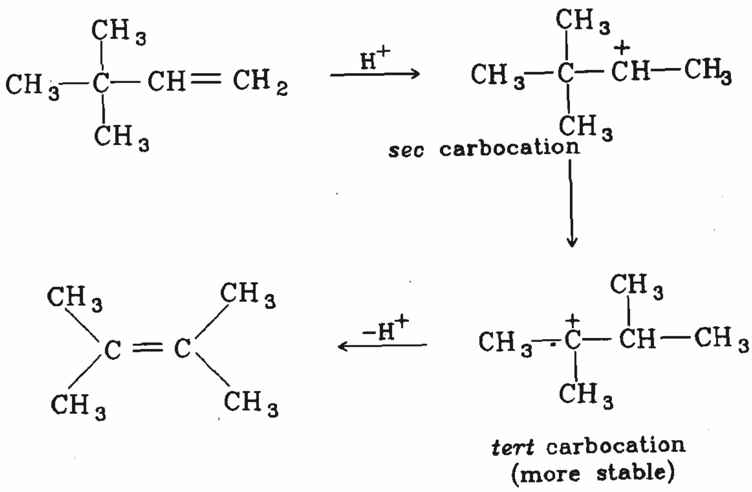
The motivating factors for the rearrangement, as you can see are:

- the greater stability of the tertiary carbocation as compared to the primary carbocation
- relief in steric overcrowding

Wagner-Meerwein rearrangements also occur in unsaturated compounds. Rearrangement of 3,3-dimethyl butene-1 to 2,3-dimethylbutene-2 under acidic conditions is one such example.



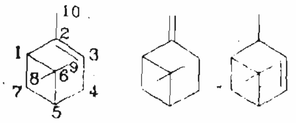
Here the carbocation formed by initial protonation of the alkene undergoes rearrangement.



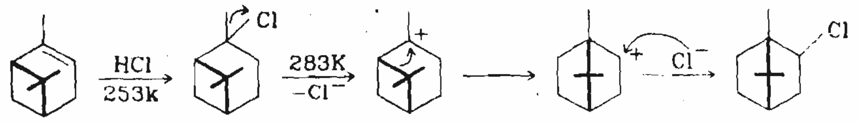
Branched chain alkenes obtained by acid catalysed isomerisation are better fuels. Advantage of such reactions is taken in reforming of petroleum.

Another good example of such a rearrangement is from terpene chemistry where such rearrangements are most common. α-Pinene is a bicyclic monoterpene. It has a six membered ring in which a gem-dimethyl group bridges carbon atoms 1 and 5. The bridge is above the plane of the paper as shown with thick lines. When treated with HCl at low temperatures, α-pinene gives pinene hydrochloride. This is unstable and decomposes with the elimination of Cl⁻ and migration of the gemdimethyl group from 1, 5 position to 5, 2 position. As this bond migration occurs, Cl⁻ approaches from the other side of the molecule to give bornyl chloride. As you can see, Cl⁻ is α in bornyl chloride. No isobornyl chloride, in which Cl is β , is formed in the reaction which establishes that this reaction is fully concerted and therefore stereospecific.

On the basis of the position of 1the double bond. pinenes have named as α,β, or γ as shown:

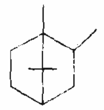


α-pinene β-pinene γ-pinen



α-pinene α-pinene hydrochloride bronyl chloride

In ring systems like cyclohexane, Substituents below the plane of the ring are called α and those above the plane of the ring are called β



isobornyl chloride

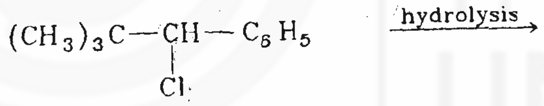
The open or classical carbocation ion, therefore, has no actual existence and has been shown only to help your understanding. In the concerted reaction, Cl⁻ leaves from the underside as the gem-dimethyl group approaches from the topside of the molecule preserving stereospecificity of the reaction.

Before we proceed furrther you may try the following SAQ.

SAQ 1

Give the mechanism and expected products in the following reactions:

(i) $(CH_3)_3C-CH=CH_2 \xrightarrow{AlCl_3}$

(ii) 

$$(CH_3)_3C-\underset{\displaystyle Cl}{\underset{|}{CH}}-C_6H_5 \xrightarrow{\text{hydrolysis}}$$

....

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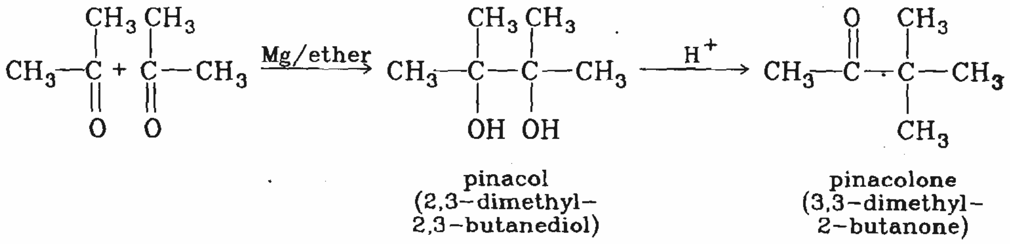
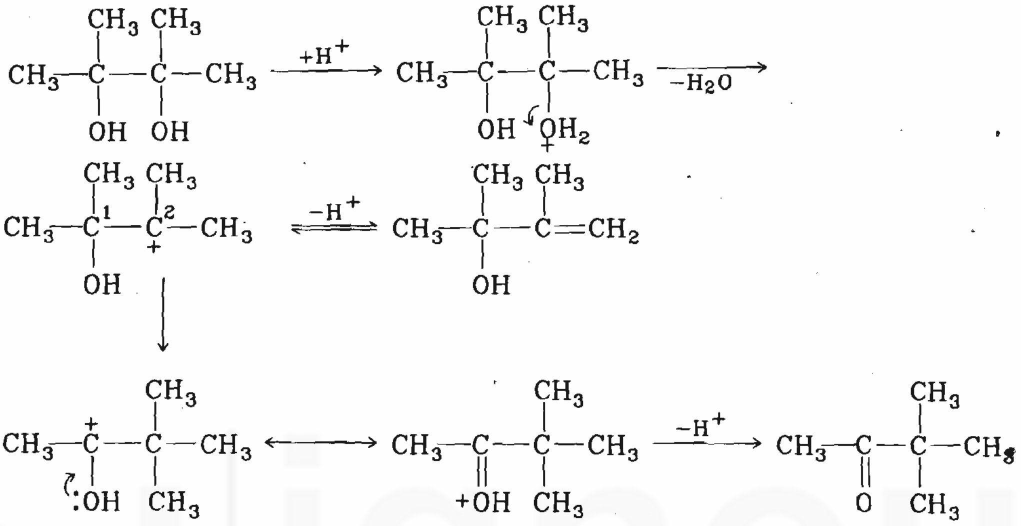
11.3.2 Pinacol-Pinacolone Rearrangement

This rearrangement occurs in vic diols under acidic conditions and derives its name from the transformation of pinacol, a glycol formed on reduction of propanone (acetone) with Mg, to the ketone, pinacolone.



The rearrangement involves the formation of an intermediate carbocation. The sequence of reactions is postulated as shown:

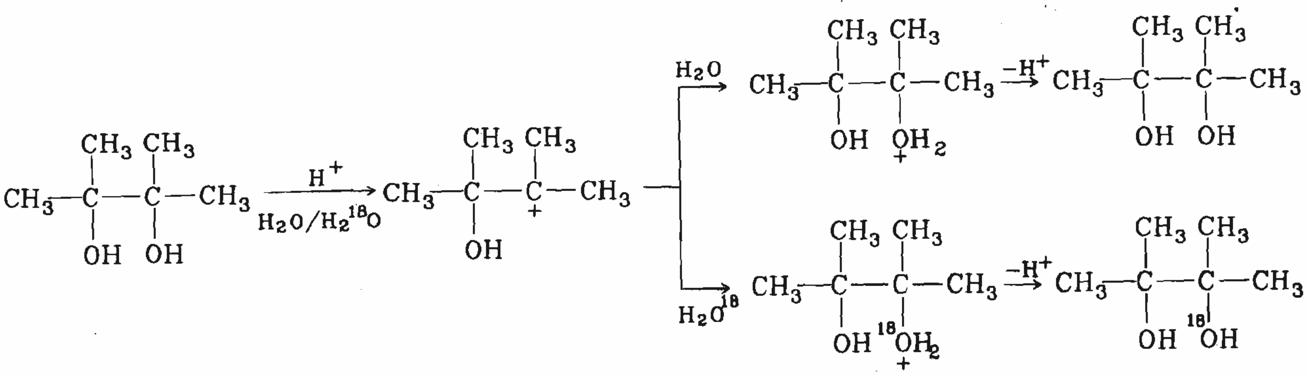


The first step in this sequence of reactions is protonation of a hydroxyl group. We have put the proton on the hydroxyl group attached to C-2, but the result, in this case, would be the same if the C-1 hydroxyl group were protonated instead. As a result of positive charge on oxygen, the bond linking — OH group to the carbon atom is weakened and cleaves with creation of a carbocation intermediate.

Now let us consider the ways in which this unstable carbocation intermediate can give rise to a stable product. One possibility, we have seen, is the loss of a proton from the methyl group. This would, however, only postpone the issue of stabilisation of the carbocation because under the acidic reaction conditions the double bond would get protonated again as shown. So as you will see, the best solution to the stabilisation problem is migration of a methyl group, along with its bonding electron pair, from C-1 to C-2.

C-1 can easily neutralise its positive charge by drawing the non-bonding electrons on oxygen towards it; and all that need happen now to give the rearranged product is release of the proton on oxygen to the solution, thereby maintaining the initial acidity of the reaction medium.

To obtain conclusive evidence for the formation of the carbocation, the reaction was carried out in water containing some amount of $H_2{}^{18}O$. Such water molecules are said to be labelled as they contain the heavier isotope of oxygen. What will now happen is depicted in the sequence shown below:

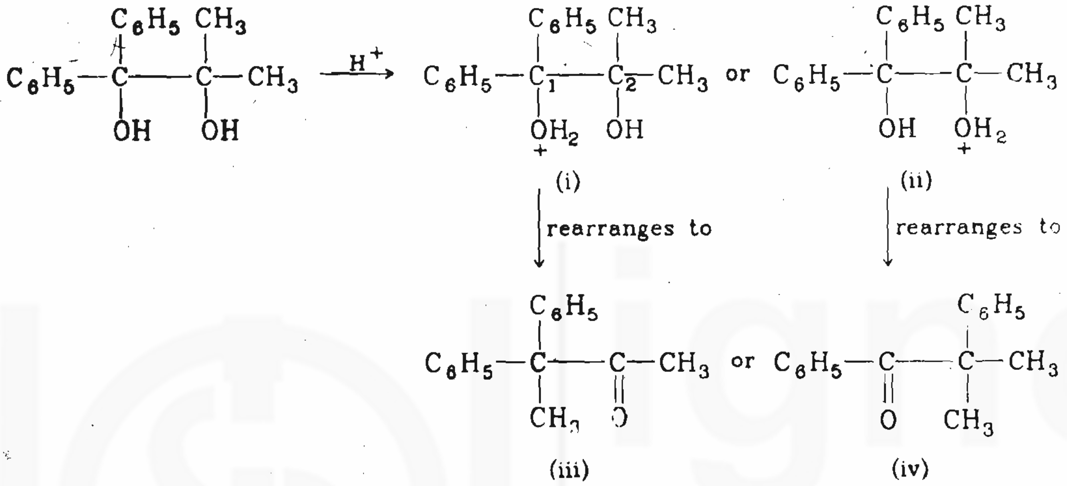


The cationic intermediates are never entirely free. They are solvated, i.e. surrounded by solvent molecules. The solvent in this case is water. It can not only solvate but also, in the reverse reaction, possible under the equilibrium conditions that obtain in solution, regenerate the original diol. Now if in the vicinity of the reaction site, labelled, i. e. $H_2{}^{18}O$ molecules are present, there will be some exchange between labelled and unlabelled molecules and when a labelled molecule gets close enough to the carbocation, a bond will be formed with elimination of a proton. Thus gradually the solution will contain significant amounts of the labelled diol which can be identified in a mass spectrometer because of its higher molecular weight.

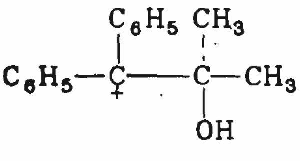
^{18}O can be detected in a mass spectrometer and this helps to trace the course of a reaction.

Relative Stability of Carbocation

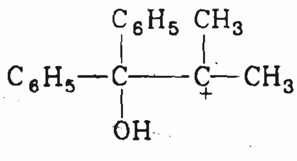
At the start of our discussion on the mechanism of pinacol-pinacolone rearrangement, we said that in this particular case it does not matter which of the two —OH groups of the diol is protonated. This implies that there are cases where it does matter. Let us take up another example in which the two carbon atoms are substituted differently to make this point clear.



Acid catalysed rearrangement of 2-methyl 3,3,-diphenyl 2,3 dihydroxy-propane is one such example. In the case of this diol, C-1 is not identical with C-2, because, as you can see, the substituents on C-1 are C_6H_5—,C_6H_5 — and —OH, while on C-2, the substituents are — CH_3, — CH_3 and —OH. In other words, unlike pinacol this diol is not symmetrically substituted. Under acidic conditions, protonation can give either (i) or (ii). If the reaction were to proceed as before, (i) will give the ketone (iii) while (ii) will give the ketone (iv). In actual fact only (iii) is formed. Why is this so? Since this may have to do with relative stabilities of carbocation intermediates formed, let us examine both the possible carbocation intermediates, a and b

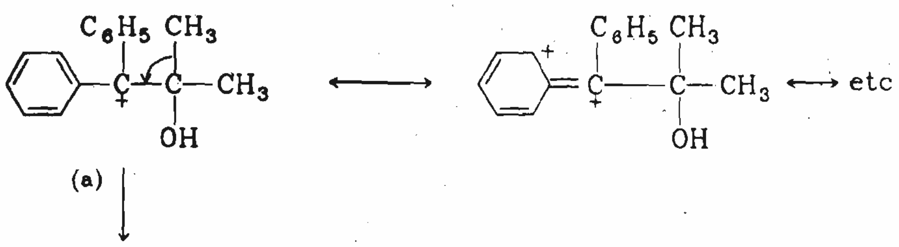


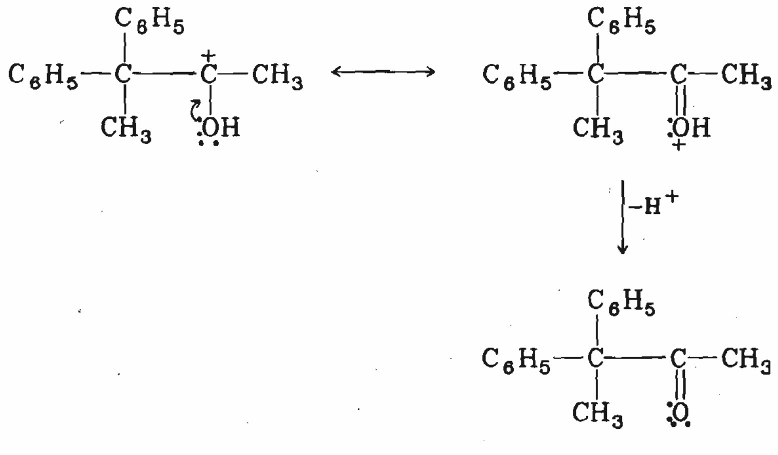
(a)



(b)

It is obvious that (a) is more stable than (b) because positive charge on the benzylic carbon is delocalised in two benzene ring. So we should get ketone (iii) through methyl migration from C-2 and this indeed is the case.

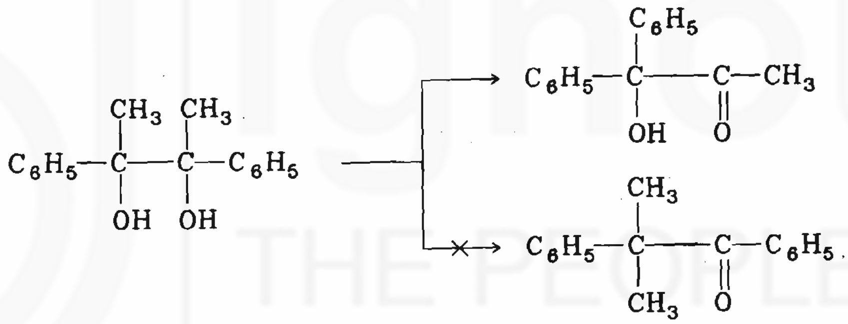




(iii)

Migratory Aptitude

A different kind of problem arises with symmetrical diols of the type, 2,3-diphenyl-2,3-butanediol where carbocation stability is no longer a deciding factor but two different ketones can result depending on whether the methyl or the phenyl group migrates. It has been observed that where the choice is between migration of an alkyl or a phenyl group, the latter migrates preferentially and very little, if any, product of methyl migration results. In the case at hand, the rearrangement goes exclusively as shown.



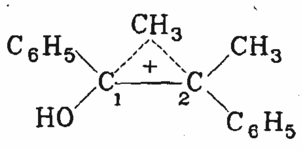
Rearrangements were also tried on diols having aromatic groups with different substituents.

From a study of a large number of such reactions, the following migratory aptitudes have been established.

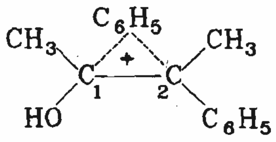
$$p\ CH_3OC_6H_4 \longrightarrow p\ CH_3C_6H_4 \longrightarrow C_6H_5 \longrightarrow CH_3 \longrightarrow H-$$

You may well ask what is the mechanistic justification for the existence of these migratory aptitudes.

To understand this, let us take a closer look at the process of migration. Obviously it must involve an intermediate stage at which the migrating group is not completely detached from the migration origin and has not become finally attached to the migration terminus. At this stage, the migrating group is partially attached to both C-1 and C-2, so that a cyclic carbocation is formed with the resultant delocalisation of the positive charge. In the case of methyl migration this ion would have structure (a) and in the case of phenyl migration, structure (b). As you know, cyclic ions of this type are known as nonclassical or bridged carbocations.

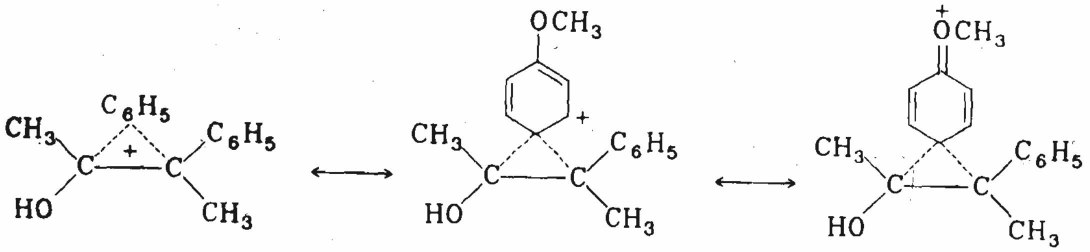


(a)

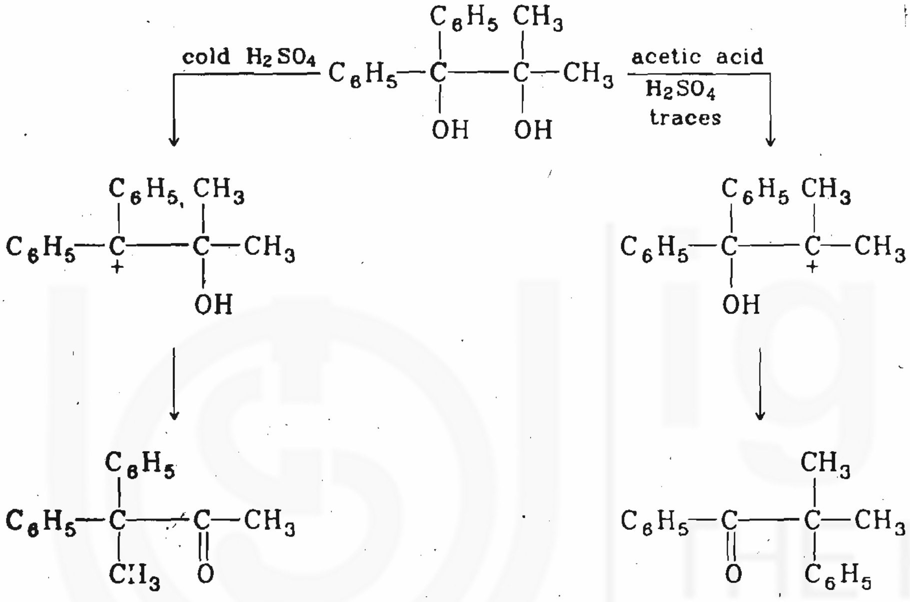


(b)

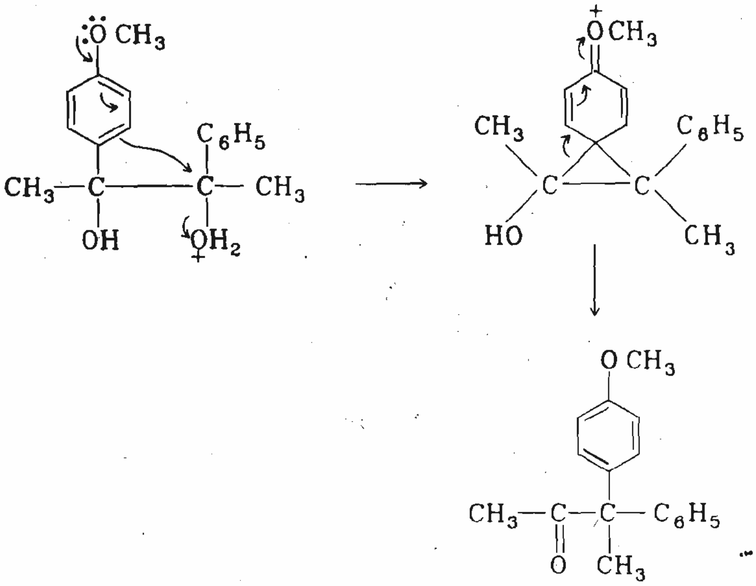
Now which of these ions would you consider as more stable? Obviously (b), because donation of π electrons from the benzene ring is easier than that of σ electrons from the methyl group. Thus, (b) can be stabilised by resonance. This resonance stabilisation is even greater with a *p*-methyl or a *p*-methoxy group in the aromatic ring for the charge can now be shared by the electron releasing *p*-methyl or *p*-methoxy group.



The above migratory aptitudes are, however, not absolute and structural effects or reaction conditions may alter the situation. This is illustrated by the rearrangement of 2-methyl-3,3-diphenyl-2,3-propanediol under different conditions. The reaction in the presence of cold H_2SO_4 proceeds as expected. But that in acetic acid with only traces of sulphuric acid must involve the formation of the less stable carbocation and consequent phenyl migration.



Donation of π electrons may also assist in formation of the carbocation and thereby enhance the rate of the reaction. This is a common feature in reactions involving carbocation formation and is known as **neighbouring group participation.** Migrations involving a cyclic carbocation may be fully concerted, i.e. departure of the OH group is synchronised with formation of the cyclic or bridged ion. The energy diagram in that case would have only two transition states between the starting material A and the product E. (Compare with Fig. 11.1).



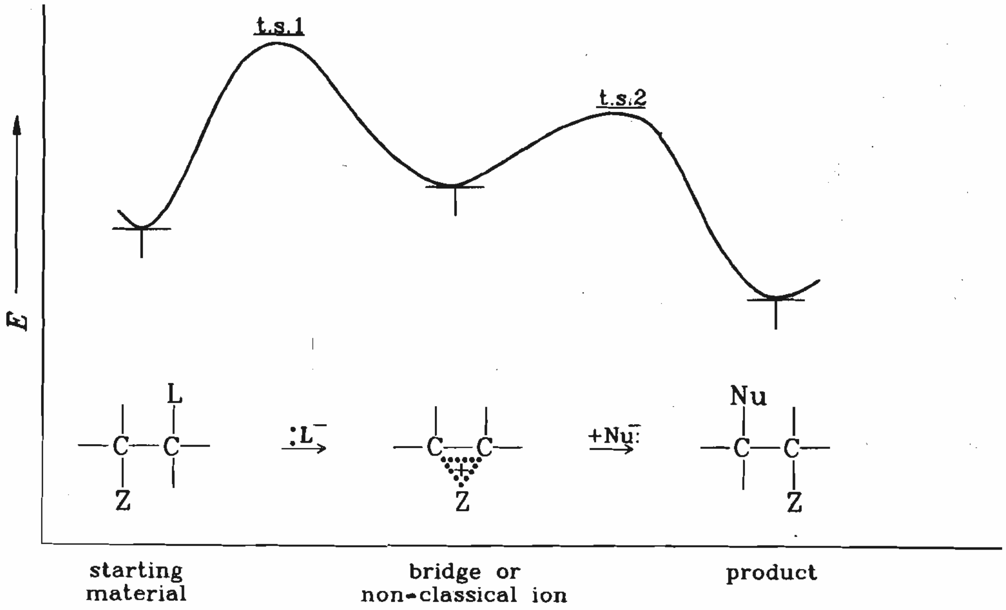
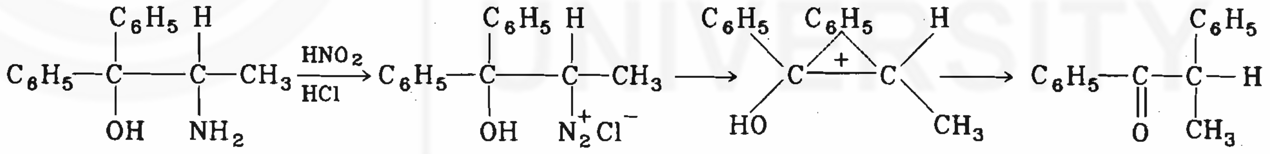


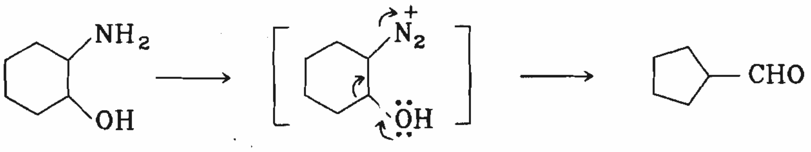
Fig. 11.2 : Mechanism and energy diagram of a 1, 2 shift involving a bridged or nonclassical ion

It is obvious that in such concerted reactions, the configuration at the migration terminus would be inverted since the migrating group approaches from the side opposite to that of the leaving OH group.

Such rearrangements are not restricted only to 1,2 diols. An interesting example is deamination of 1,1-diphenyl-2-amino-propanol-1 with nitrous acid. Nitrous acid reacts with the amino function to give the unstable diazonium salt, spontaneous decomposition of which produces the nonclassical carbocation as shown. Migration of the phenyl group with loss of a proton from oxygen gives a product similar to pinacolone. Note that the starting material and the product both are optically active. This means that the reaction is fully concerted, i.e. formation of the carbocation occurs with involvement of the phenyl group from the opposite side to give the nonclassical carbocation.



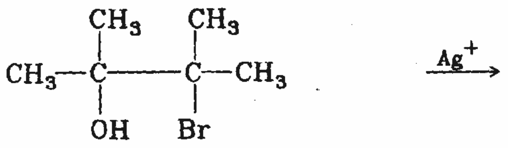
In the case of 2-aminocyclohexanol deamination is accompanied by ring contraction:



SAQ 2

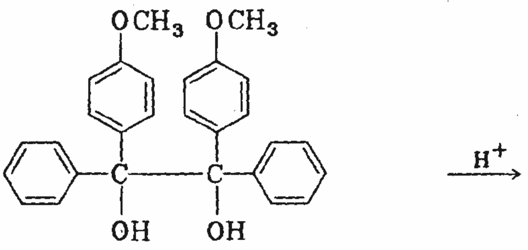
Give the expected products in the following arrangement reactions.

i)

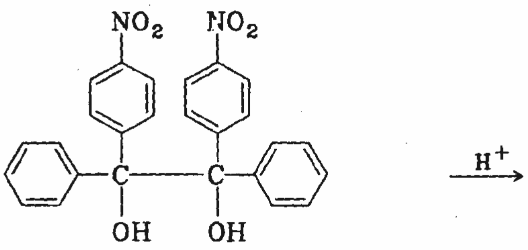


$$CH_3-\overset{CH_3}{\underset{OH}{C}}-\overset{CH_3}{\underset{Br}{C}}-CH_3 \xrightarrow{Ag^+}$$

ii)



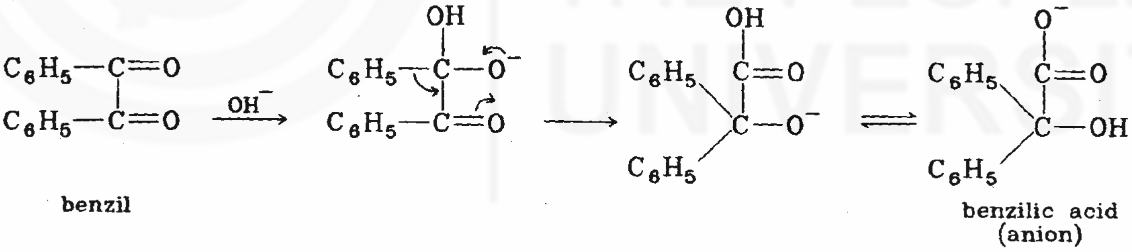
iii)



iv)

11.3.3 Benzil-Benzilic Acid Rearrangement

This rearrangement takes place on treatment of the diketone benzil with concentrated alkali. The product is benzilic acid. The mechanism of the rearrangement has been postulated as shown. In the first step, OH$^-$ adds to one of the carbonyl groups generating the anion. The negative charge on oxygen induces migration of the phenyl group to the adjoining carbonyl which is followed by shift of the acidic proton to oxygen.



The rearrangement is similar to the pinacol rearrangement, but whereas the migration terminus in the pinacol rearrangement has a full positive charge, the carbonyl carbon in the benzilic acid rearrangement has only a partial positive charge. The rearrangement is applicable only to aromatic diketones. Aliphatic diketones react but yields are too low for this reaction to be useful in synthesis. This is due to the formation of side products through aldol type of condensations.

11.4 MIGRATION TO ELECTRON DEFICIENT NITROGEN

A number of rearrangements of great preparative value involve migration to nitrogen. Hofmann and Curtius rearrangements belong to this category. The driving force for these rearrangements is also an electron deficient atom but because of the trivalency of nitrogen, the course of the reaction is somewhat different from the rearrangements you have studied so far.

11.4.1 Hofmann Rearrangement

In this rearrangement an acid amide is treated with sodium hypobromite or, sodium hydroxide and bromine. The product is an amine.

$$RCONH_2 \xrightarrow{NaOH/Br_2} RNH_2$$

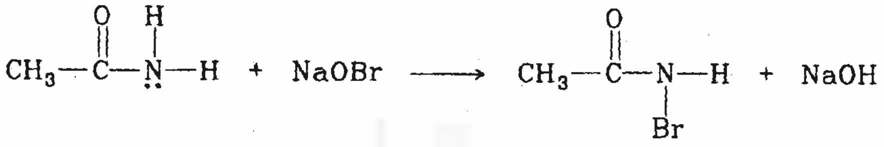
Sodium hydroxide reacts with bromine to give NaOBr and HBr. HBr is neutralised by excess NaOH.

$$NaOH + Br_2 \longrightarrow NaOBr + HBr$$

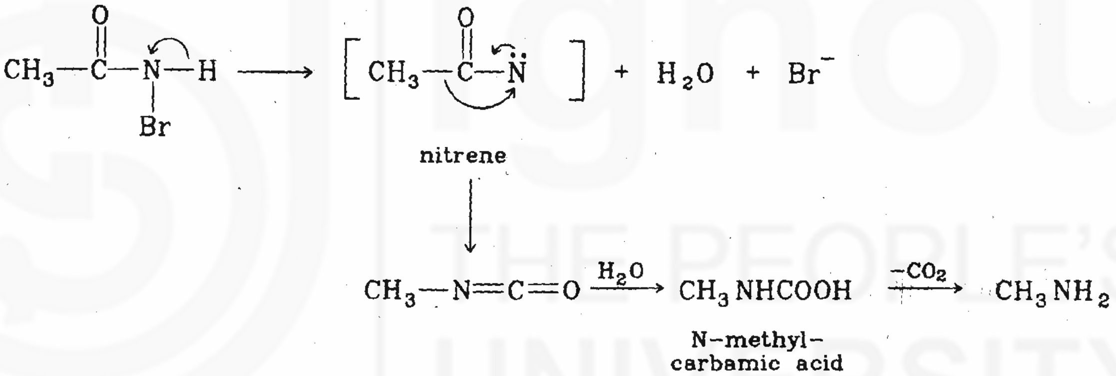
$$NaOH + HBr \longrightarrow NaBr + H_2O$$

$$2NaOH + Br_2 \longrightarrow NaOBr + NaBr + H_2O$$

Sodium hypobromite is a source of positively charged bromonium ion, Br^+, as on heterolysis of the O—Br bond, oxygen retains the bonding electron pair Br^+ adds to the lone pair on nitrogen and the —NH_2 proton is released to NaO^-. Let us take the reaction of ethanamide with Br_2 and NaOH as an example.



$$CH_3-\overset{\overset{O}{\|}}{C}-\overset{\overset{H}{|}}{\ddot{N}}-H + NaOBr \longrightarrow CH_3-\overset{\overset{O}{\|}}{C}-\underset{\underset{Br}{|}}{N}-H + NaOH$$

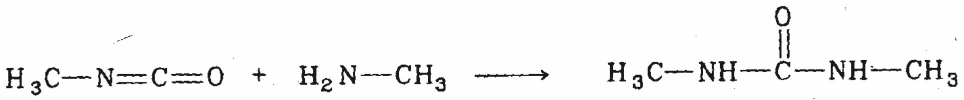


The proton on the nitrogen atom of bromoethanamide becomes acidic, in other words, labile due to the presence two electron withdrawing groups, CH_3—C = O and Br, on nitrogen and hence it is taken up by OH^-. The departure of bromine is now spontaneous giving an electron deficient species in which the nitrogen atom has only a sextet of electrons and no net charge. As you know such nitrogen intermediates known as nitrenes are not a stable species. Formation of nitrenes intermediate provides the driving force for both Hofmann and Curtius rearrangements.

The migration of CH_3 (generally any R group), with its bonding electron pair, to nitrogen gives methyl isocyanate. This is a very reactive compound, which can be isolated under appropriate conditions. However, under the aqueous alkaline reaction conditions,methyl isocyanate adds a molecule of water of give a carbamic acid. This carbamic acid suffers loss of CO_2 to give the final product, an amine, CH_3NH_2. Thus the reaction converts an amide into an amine with loss of a carbon atom.

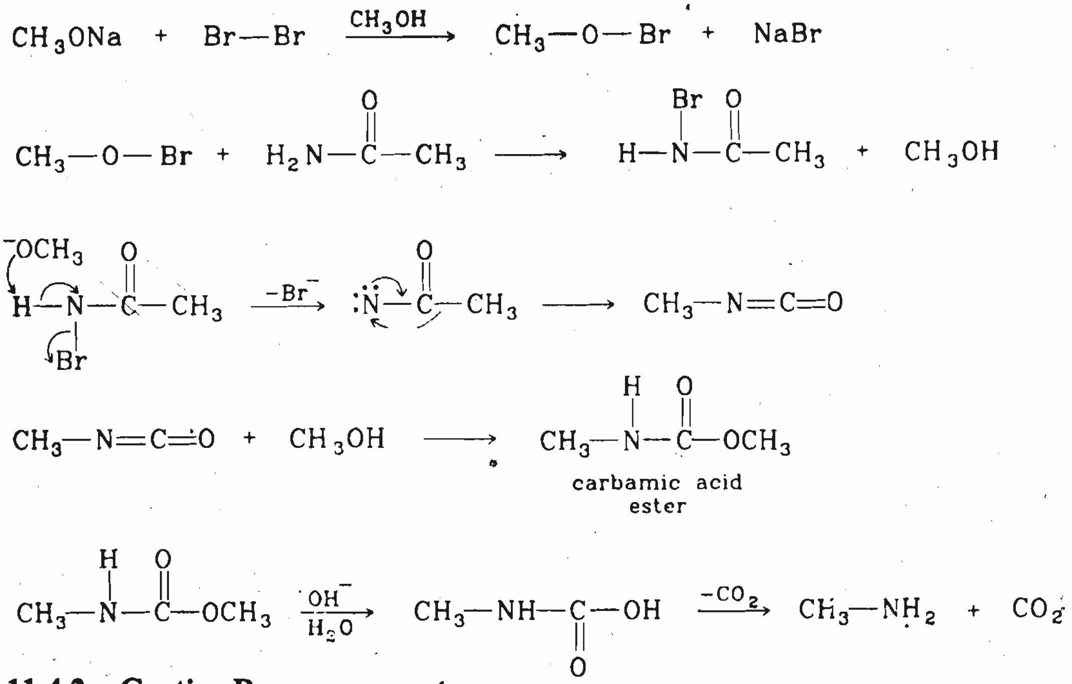
Methyl isocyanate is an intermediate in the manufacture of carbamoyl pesticides. The Bhopal gas tragedy was the result of leakage of methyl isocyanate gas from storage tanks.

A complication in the rearrangement reaction is that the amine, as it is formed, can also combine with the unreacted isocyanate to give a derivative of urea.



$$H_3C-N=C=O + H_2N-CH_3 \longrightarrow H_3C-NH-\overset{\overset{O}{\|}}{C}-NH-CH_3$$

Formation of urea in the above reaction sequence is avoided if sodium methoxide/ methanol are used instead of $NaOH/H_2O$. Methanol adds to the isocyanate to give a carbamic acid ester which can be isolated and hydrolysed subsequently.



$$CH_3ONa + Br{-}Br \xrightarrow{CH_3OH} CH_3{-}O{-}Br + NaBr$$

$$CH_3{-}O{-}Br + H_2N{-}\overset{O}{\overset{\|}{C}}{-}CH_3 \longrightarrow H{-}\overset{Br}{\overset{|}{N}}{-}\overset{O}{\overset{\|}{C}}{-}CH_3 + CH_3OH$$

$$H{-}\underset{Br}{\underset{|}{N}}{-}\overset{O}{\overset{\|}{C}}{-}CH_3 \xrightarrow{-Br^-} :\ddot{N}{-}\overset{O}{\overset{\|}{C}}{-}CH_3 \longrightarrow CH_3{-}N{=}C{=}O$$

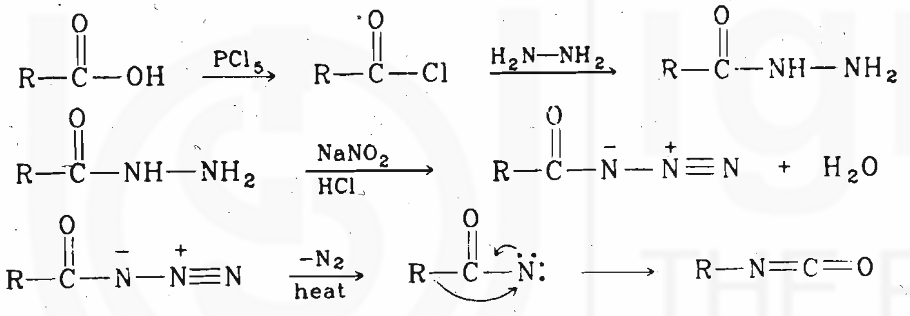
$$CH_3{-}N{=}C{=}O + CH_3OH \longrightarrow CH_3{-}\overset{H}{\overset{|}{N}}{-}\overset{O}{\overset{\|}{C}}{-}OCH_3$$

carbamic acid
ester

$$CH_3{-}\overset{H}{\overset{|}{N}}{-}\overset{O}{\overset{\|}{C}}{-}OCH_3 \xrightarrow[H_2O]{OH^-} CH_3{-}NH{-}\underset{O}{\underset{\|}{C}}{-}OH \xrightarrow{-CO_2} CH_3{-}NH_2 + CO_2$$

11.4.2 Curtius Rearrangement

This rearrangement takes place on thermal degradation of acid azides. It also involves the intermediacy of a nitrene and the immediate product of the reaction is again an isocyanate. The leaving group in this rearrangement is molecular nitrogen and the starting material is an acyl azide. Acyl azides are readily available from acids by the sequence outlined below.

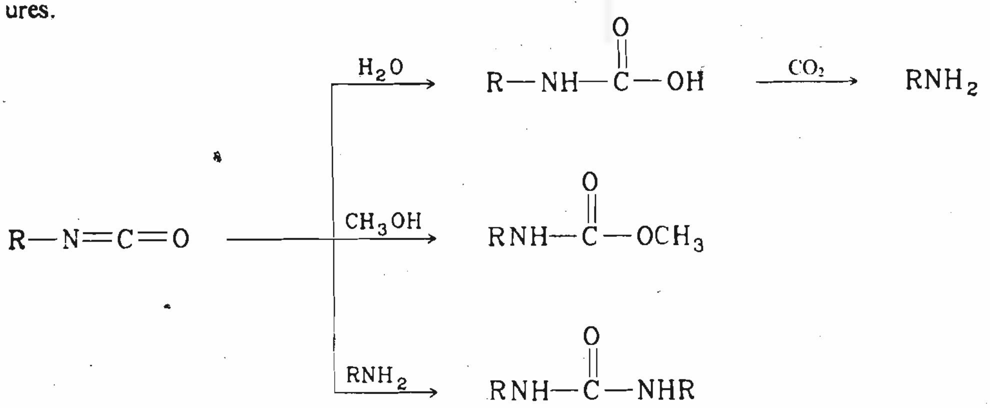


$$R{-}\overset{O}{\overset{\|}{C}}{-}OH \xrightarrow{PCl_5} R{-}\overset{O}{\overset{\|}{C}}{-}Cl \xrightarrow{H_2N{-}NH_2} R{-}\overset{O}{\overset{\|}{C}}{-}NH{-}NH_2$$

$$R{-}\overset{O}{\overset{\|}{C}}{-}NH{-}NH_2 \xrightarrow[HCl]{NaNO_2} R{-}\overset{O}{\overset{\|}{C}}{-}\overset{-}{N}{-}\overset{+}{N}{\equiv}N + H_2O$$

$$R{-}\overset{O}{\overset{\|}{C}}{-}\overset{-}{N}{-}\overset{+}{N}{\equiv}N \xrightarrow[heat]{-N_2} R{-}\overset{O}{\overset{\|}{C}}{-}\ddot{N}: \longrightarrow R{-}N{=}C{=}O$$

It is apparent that the remote precursor of both Hofmann and Curtius rearrangements is a carboxylic acid. Acyl azides are, however, reactive compounds and decompose, simply on heating, to isocyanates. The intermediacy of nitrene is apparent in both the cases but as discussed earlier in Unit 9 intrenes have never been isolated. An isocyanate can be converted at will to the desired product, a carbamic acid or its ester, amine or substituted ures.

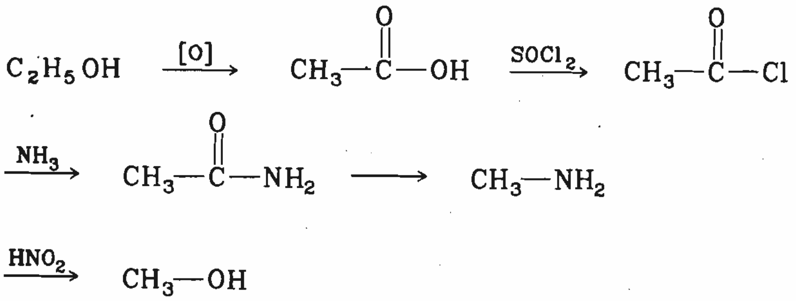


$$R{-}N{=}C{=}O \xrightarrow{H_2O} R{-}NH{-}\overset{O}{\overset{\|}{C}}{-}OH \xrightarrow{CO_2} RNH_2$$

$$R{-}N{=}C{=}O \xrightarrow{CH_3OH} RNH{-}\overset{O}{\overset{\|}{C}}{-}OCH_3$$

$$R{-}N{=}C{=}O \xrightarrow{RNH_2} RNH{-}\overset{O}{\overset{\|}{C}}{-}NHR$$

An interesting application of Hofmann and Curtius rearrangement is in descent of the series, i.e. preparation of a homologue with one carbon atom less. Thus, for example, ethanol can be converted to methanol through the sequence of reactions given below.

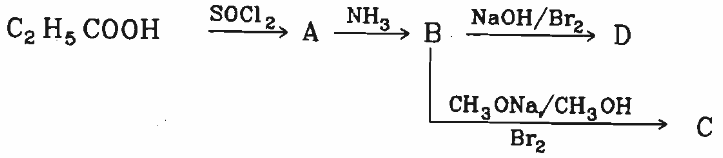


$$C_2H_5OH \xrightarrow{[O]} CH_3-\overset{O}{\overset{\|}{C}}-OH \xrightarrow{SOCl_2} CH_3-\overset{O}{\overset{\|}{C}}-Cl \xrightarrow{NH_3} CH_3-\overset{O}{\overset{\|}{C}}-NH_2 \longrightarrow CH_3-NH_2 \xrightarrow{HNO_2} CH_3-OH$$

SAQ 3

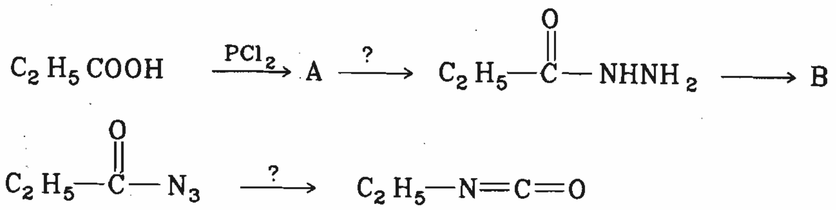
Complete the following :

(i)



$$\begin{tikzcd} C_2H_5COOH \arrow[r, "SOCl_2"] & A \arrow[r, "NH_3"] & B \arrow[r, "NaOH/Br_2"] \arrow[dr, "CH_3ONa/CH_3OH", "Br_2"'] & D \\ & & & C \end{tikzcd}$$

(ii)

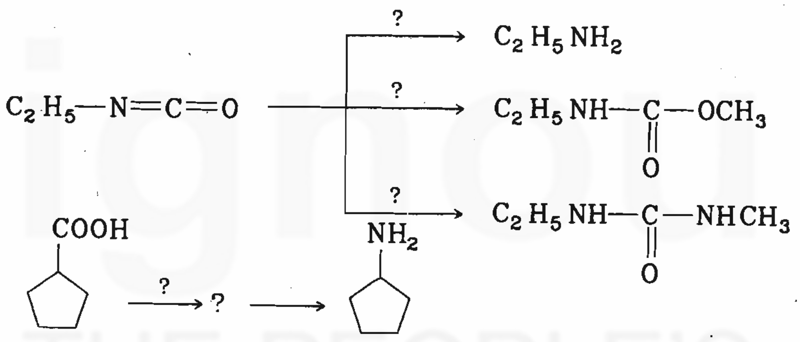


$$C_2H_5COOH \xrightarrow{PCl_2} A \xrightarrow{?} C_2H_5-\overset{O}{\overset{\|}{C}}-NHNH_2 \longrightarrow B$$

$$C_2H_5-\overset{O}{\overset{\|}{C}}-N_3 \xrightarrow{?} C_2H_5-N{=}C{=}O$$

(iii)

(iv)

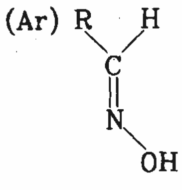


$$\begin{tikzcd} & C_2H_5NH_2 \\ C_2H_5-N{=}C{=}O \arrow[ur, "?"] \arrow[r, "?"] \arrow[dr, "?"] & C_2H_5NH-\underset{\underset{O}{\|}}{C}-OCH_3 \\ & C_2H_5NH-\underset{\underset{O}{\|}}{C}-NHCH_3 \end{tikzcd}$$

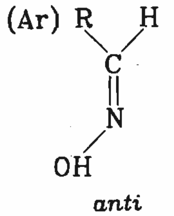
11.4.3 Beckmann Rearrangement

This rearrangement offers a very convenient route for the conversion of ketones, *via* their oximes to N-substituted amides. The reaction involves migration to an electron deficient nitrogen atom, generated by the departure of the —OH group of the oxime. The reaction is catalysed by strong acids, e.g., H_2SO_4, PPA, or by PCl_5, $SOCl_2$, etc. Before we take up the mechanism of this rearrangement, it would be useful to recapitulate the isomerism exhibited by oximes. Oximes exhibit geometric isomerism as rotation about the >C = N—bond is restricted. The terms *syn* and *anti* are often used in place of *cis* and *trans* to denote the isomers. Thus the two geometric isomers of aldoximes are known as *syn* and *anti* depending on whether the oxime OH is on the same side or opposite to aldehyde H.

PPA is polyphosphosic acid

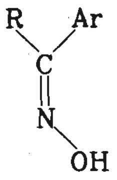


syn

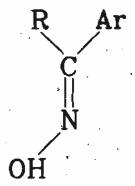


anti

For ketoxime, however, it has to be further specified whether a particular group is *syn/cis* or *anti/trans* to oxime -OH.

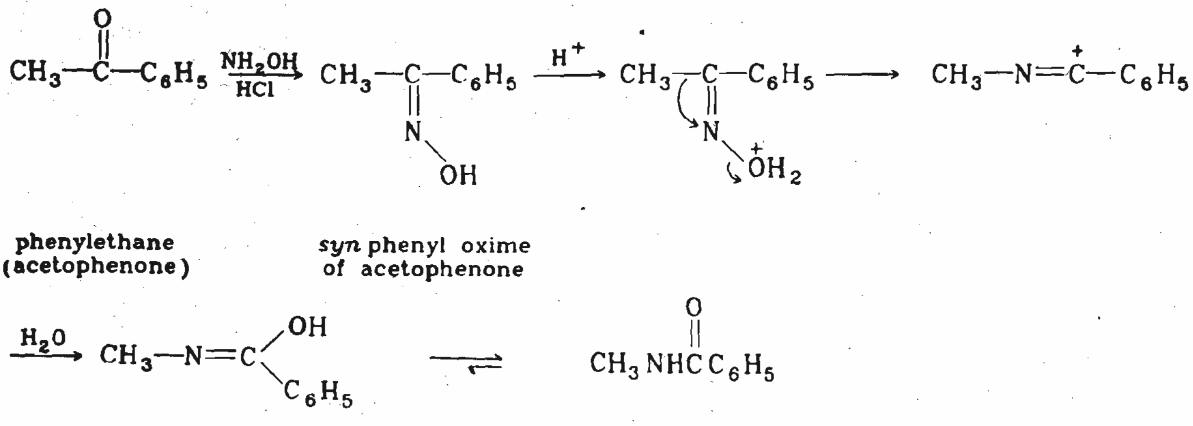


syn aryl
or
anti alkyl



syn alkyl
or
anti aryl

Beckmann transformation is highly stereospecific in that only the group *trans* to the oxime hydroxyl migrates. *Cis* migration, if it occurs at all, is attributed to prior isomerisation of the *cis* group to the *trans* position. The reaction postulates a carbonium ion as an intermediate. Rearrangement of acetophenone oxime in the presence of conc. H_2SO_4 is believed to proceed as shown below:

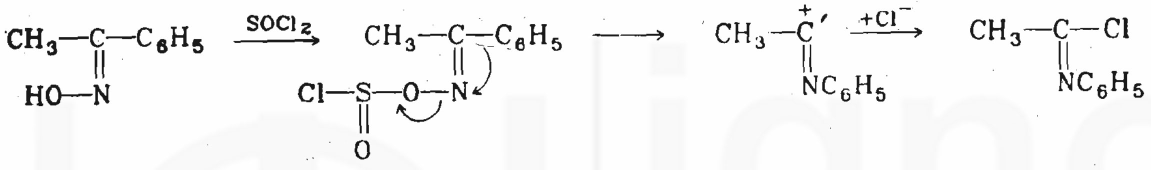


phenylethane (acetophenone)

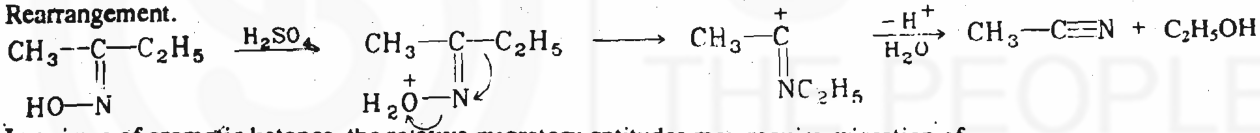
syn phenyl oxime of acetophenone

N-methylbenzamide

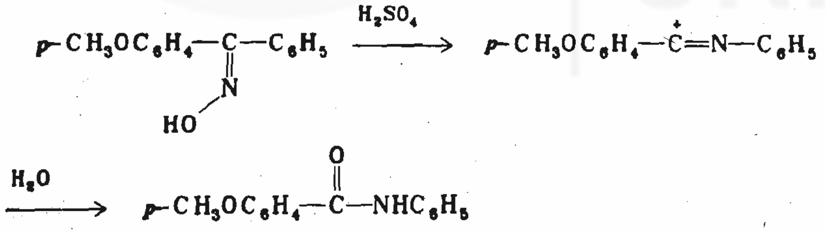
If phosphorus or sulphur halides are employed, the oxime ester functions as the intermediate, for example with thionyl chloride:



A side reaction in Beckmann rearrangement, specially when oximes of dialkyl ketones are the substrate is the formation of nitriles. This is known as the abnormal Beckmann Rearrangement.

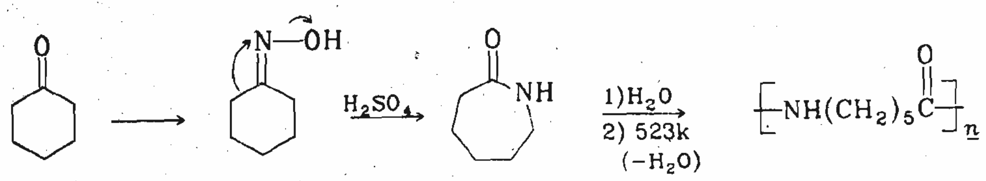


In oximes of aromatic ketones, the relative migratory aptitudes may require migration of the *cis* group but the *trans* group will migrate as the stereoelectronic factor overweighs the migratory aptitude requirement. In the case of *anti*-phenyl oxime of *p*-methoxy benzophenone, it is phenyl group which migrates.



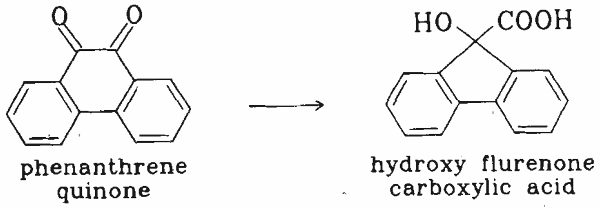
However, as noted already, this method is not reliable for defining the configuration of the oxime as isomerisation prior to migration may confuse the result. Formation of a mixture of two products is not uncommon in these rearrangements.

Applied to the oximes of cyclic ketones, the rearrangement offers a means of enlarging the ring size. The reaction applied to cyclohexanone oxime yields the commercially important caprolactam which is used for making Nylon-6.



caprolactam

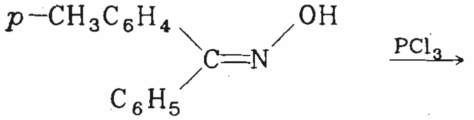
An interesting application of the reaction is degradation of phenanthrene quinone to hydroxy fluorenone carboxylic acid.



Before we take up migration to electron deficient oxygen, you may try the following SAQ.

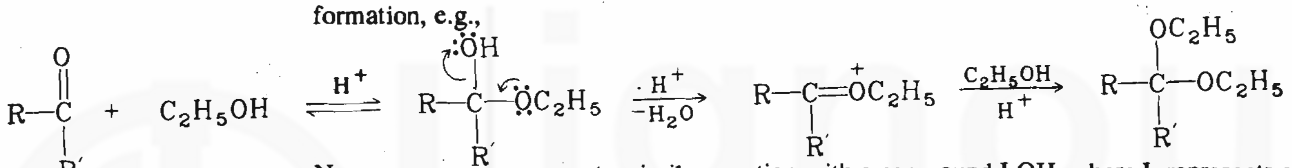
SAQ 4

Complete the following reaction:

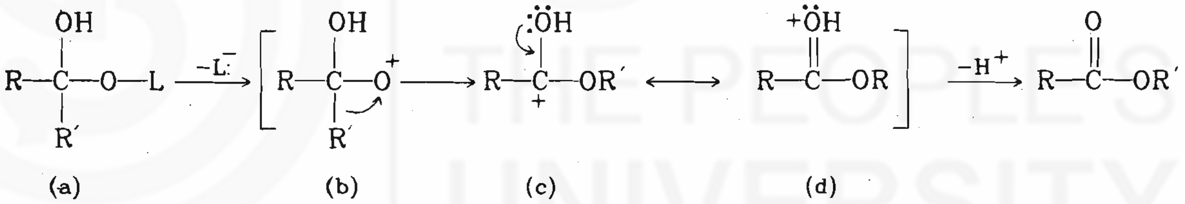


11.5 MIGRATION TO ELECTRON DEFICIENT OXYGEN

The substrate in such rearrangement is an alkyl aryl ketone. You are familiar with the nucleophilic addition reactions of carbonyl compounds such as hydration and acetal formation, e.g.,

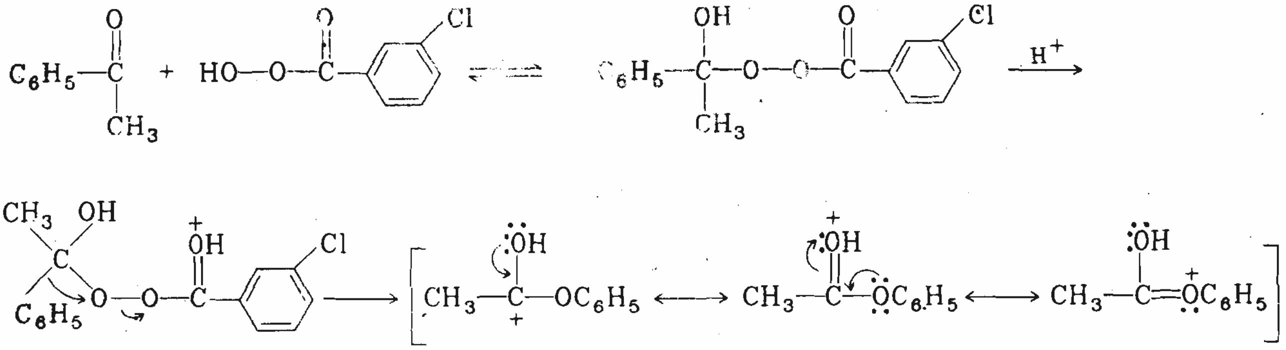


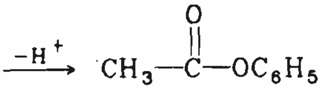
Now suppose we carry out a similar reaction with a compound LOH, where L represents a good leaving group, to give the adduct a.



If the O — L bond is now cleaved by departure of L$^-$, we will end up with a positively charged oxygen atom. The situation is similar to carbocation rearrangements. However, the intermediate b with a positively charged oxygen is more unstable than any carbocation intermediate, hence R$'$ will migrate to give c. This carbocation intermediate, besides being much more stable than the O$^+$ intermediate, can draw the non-bonded electrons from oxygen to give d. Departure of a proton from the OH group now yields the final product of the rearrangement, an ester. This type of rearrangement was first observed by Baeyer and is known after him and another worker in the field, as Baeyer-Villiger rearrangement. It is brought about when ketones are exposed to peracids, such as *m*-chloroperbenzoic acid or peroxytrifluoroacetic acid.

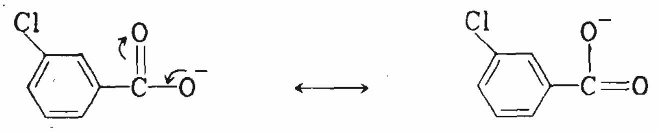
The rearrangement of acetophenone in the presence of m-chloroperbenzoic acid is given below.





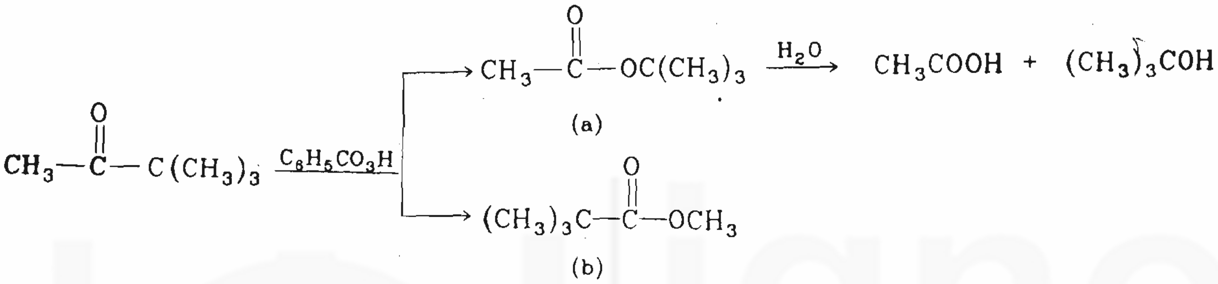
$$\xrightarrow{-H^+} CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-OC_6H_5$$

You will note that $m-Cl\,C_6H_5CO_2^-$ in the above reaction corresponds to L^-. It is a good leaving group because the negative charge on oxygen is delocalised by the adjacent carbonyl group.



$CF_3CO_2^-$ is a good leaving group because of the three fluorine atoms which draw electrons away from the carbonyl group by inductive effect, thereby further facilitating cleavage of the peroxide bond.

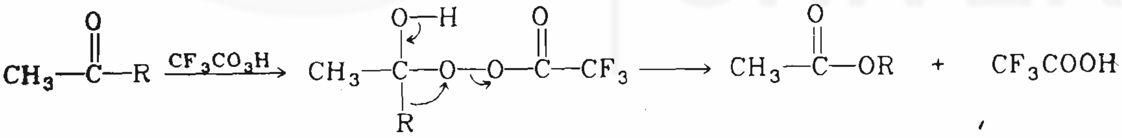
The problem of migratory aptitudes arises here also. Thus in the reaction of *tert*-butyl methyl ketone, pinacolone, migration of the *tert*-butyl group would give *a* and that of the methyl group *b*. The exclusive formation of *a*. as confirmed from its hydrolysis products, shows that *tert*-butyl group migration is preferred to methyl migration.



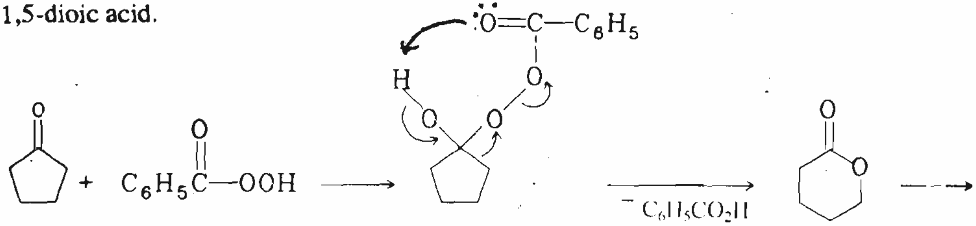
In this way the following migratory aptitudes have been established.

tert alkyl > *sec* alkyl > aryl >*p* alkyl > methyl

As expected, migrating ability of an aryl group is enhanced by electron donating groups and is reduced by electron withdrawing groups. We have illustrated the Baeyer-Villiger rearrangement as involving the formation of an O^+ ion, i.e. an oxygen atom with a full positive charge. This is, however, not exactly the case. It was done only to help your understanding and to stress the closeness of this rearrangement to the carbocation rearrangements. Actually the reaction is concerted, that is, migration of alkyl group is synchronised with cleavage of the peroxide bond. In view of this, the following may be a better representation of the way the reaction proceeds.



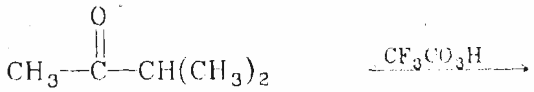
A useful application of the reaction is preparation of highly substituted alcohols. Thus *tert* butyl alcohol which is not easily available through nucleophilic substitution reaction of *tert*-butyl chloride can be obtained by this method as shown above. This rearrangement is also frequently employed in synthetic work for cleavage of cyclic ketones. Thus cyclopentanone reacts with perbenzoic acid to give a lactone which, if desired, can be hydrolysed to a hydroxy acid, which can in turn, be oxidised to a dicaroxylic acid, pentan-1,5-dioic acid.



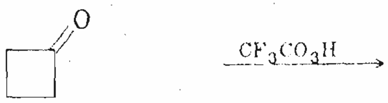
$$HOOC(CH_2)_3CH_2OH \xrightarrow{[O]} HOOC(CH_2)_3COOH$$

SAQ 5

(a) Give the probable products in the following reactions

i) 

$CH_3-\overset{\overset{O}{\|}}{C}-CH(CH_3)_2 \xrightarrow{CF_3CO_3H}$

ii) 

(b) Explain why an intermediate with positively charged oxygen is less stable than a carbocation?

....

....

....

11.6 SUMMARY

Molecular rearrangements in which a group shifts from one position in the molecule to a different on in the product, is an important class of reactions, 1,2-shifts are the most common.

In this unit we have discussed rearrangements of electron deficient systems. We have first discussed rearrangements involving carbocations, like WagnerMeerwein, pinacol-pinacolone and benzilic acid rearrangements. Factors deciding the course of rearrangement reactions like the stability of the carbocations and the migratory aptitudes of the migrating groups have been taken up in detail.

In rearrangements involving electron deficient nitrogen, Hofmann, Curtius and Beckmann have been discussed along with their synthetic utility. Baeyer-Villiger rearrangement has been taken as an example of a rearrangement involving electron deficient oxygen.

11.7 TERMINAL QUESTIONS

1) Suggest a scheme for synthesising the following compounds utilising a rearrangement reaction. Give the mechanism in each case.

   i) N-phenylbenzamide

   ii) Aniline

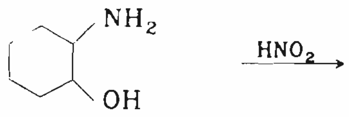
   iii) Phenyl propinonate

   iv) 6-Hydroxyhexanoic acid lactone

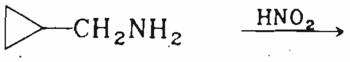
   v) 2-3, dimethyl-2-butene

2) Predict the product(s) from each of the following reactions:

i)



ii)

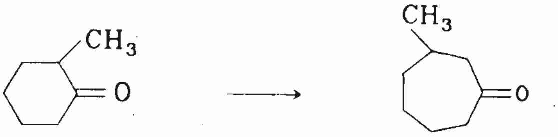


iii)

3) Show how each of the following conversion could be accomplished.

i) $(C_6H_5)_2CO \longrightarrow C_6H_5CONHC_6H_5$

ii)



iii)

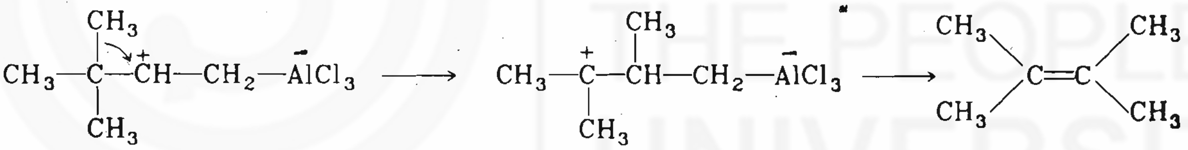
iv)

$$(C_6H_5)_2\underset{OH}{\underset{|}{C}}-\underset{OH}{\underset{|}{C}}(C_6H_5)_2 \longrightarrow C_6H_5-\underset{O}{\underset{\|}{C}}-C(C_6H_5)_3$$

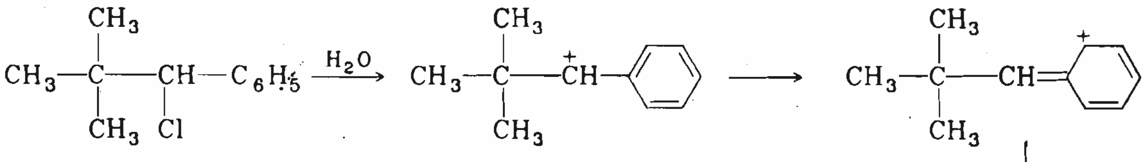
11.8 ANSWERS

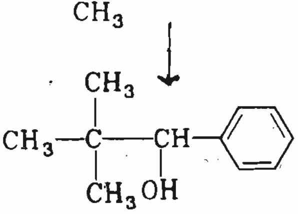
Seft-assessment Questions

i)



ii)

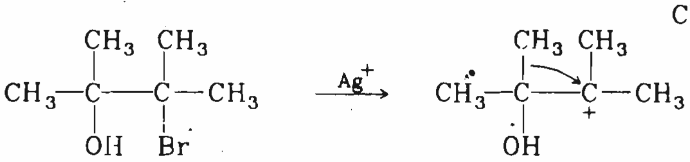


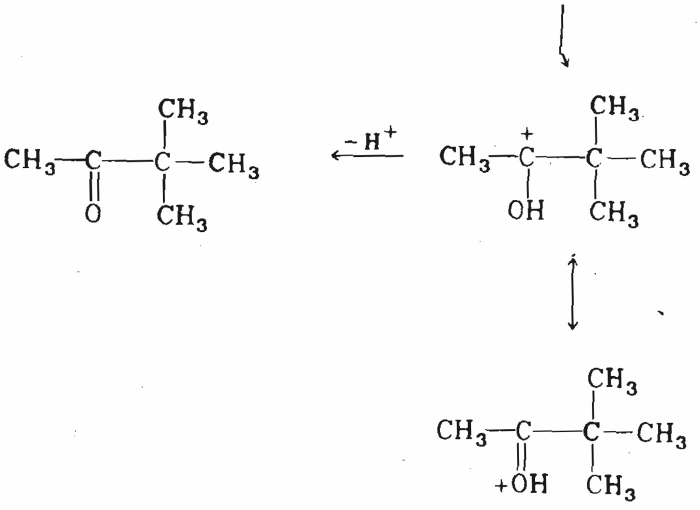


Benzylic carbonium ion is stabilised by resonance so no rearrangement takes palce.

2) i)

i)

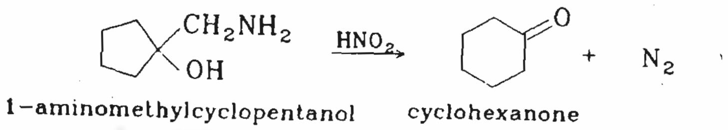




ii) *p*-Methoxy phenyl will migrate in preference to phenyl.

iii) Phenyl will migrate in preference to *p*-nitrophenyl.

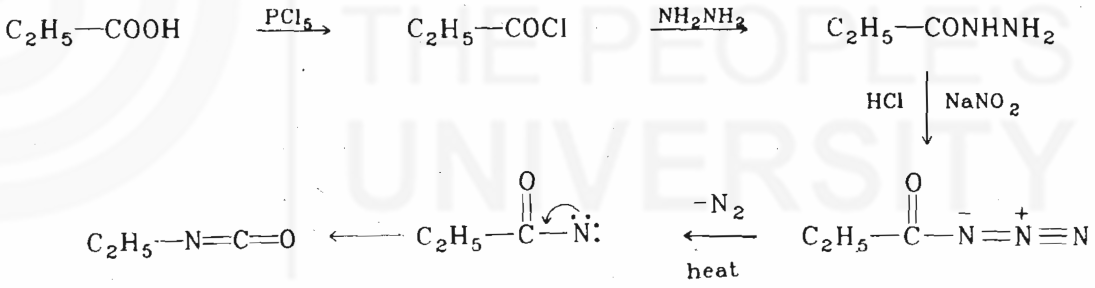
iv)



3) i)

$$\begin{tikzcd} C_2H_5COOH \arrow[r, "SOCl_2"] & C_2H_5COCl \arrow[r, "NH_3"] & C_2H_5CONH_2 \arrow[d, "NaOH/Br_2"] \arrow[dll, "\begin{matrix}CH_3ONa\\CH_3OH\end{matrix}"'] \\ C_2H_5\!-\!NHCOOCH_3 & & C_2H_5NH_2 + CO_2 \end{tikzcd}$$

ii)

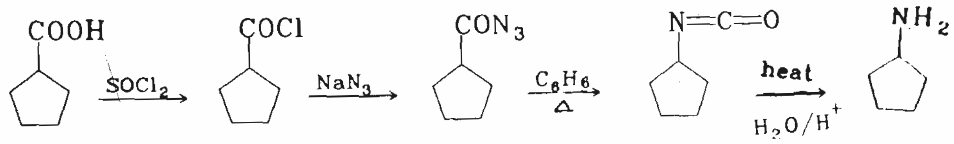


$$\begin{tikzcd} C_2H_5\!-\!COOH \arrow[r, "PCl_5"] & C_2H_5\!-\!COCl \arrow[r, "NH_2NH_2"] & C_2H_5\!-\!CONHNH_2 \arrow[d, "HCl\ \ NaNO_2"] \\ C_2H_5\!-\!N\!=\!C\!=\!O & C_2H_5\!-\!\overset{O}{\overset{\|}{C}}\!-\!\ddot{N}: \arrow[l] & C_2H_5\!-\!\overset{O}{\overset{\|}{C}}\!-\!\overset{-}{N}\!=\!\overset{+}{N}\!\equiv\!N \arrow[l, "-N_2"', "heat"] \end{tikzcd}$$

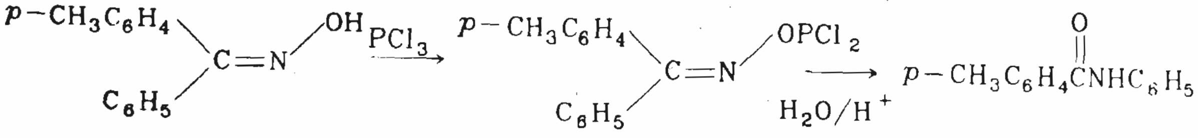
iii)

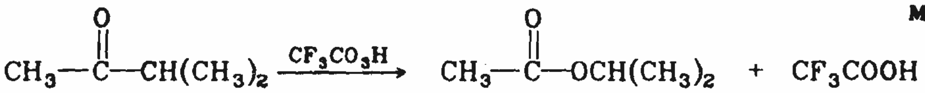
$$\begin{tikzcd} & C_2H_5\!-\!NH_2 \\ C_2H_5\!-\!N\!=\!C\!=\!O \arrow[ur] \arrow[r] \arrow[dr] & C_2H_5\!-\!NHCOOCH_3 \\ & C_2H_5\!-\!NHCONHCH_3 \end{tikzcd}$$

iv)



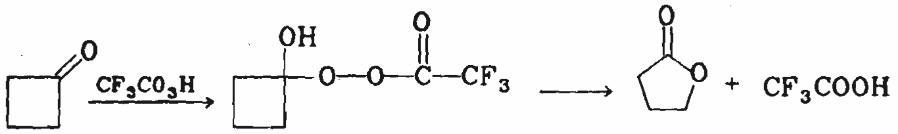
4)



5) a) i) 

$CH_3-\overset{O}{\overset{\|}{C}}-CH(CH_3)_2 \xrightarrow{CF_3CO_3H} CH_3-\overset{O}{\overset{\|}{C}}-OCH(CH_3)_2 + CF_3COOH$

Isopropyl group migrates in preference to methyl.

ii) 

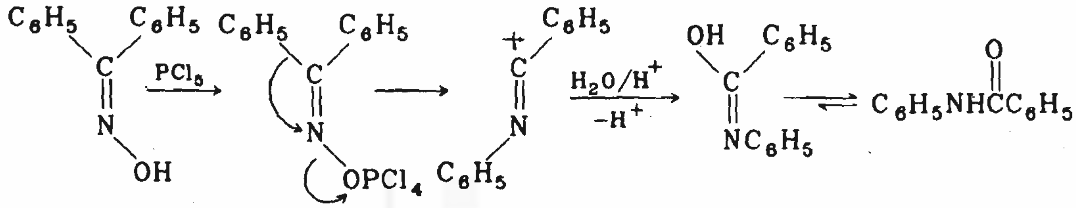
$\longrightarrow HO_2C-CH_2-CH_2-CH_2OH$

(b) Because of higher electronegativity of oxygen.

Terminal Questions

1) i) $(C_6H_5)_2C{=}NOH \xrightarrow[\text{Beckmann}]{PCl_5} C_6H_5CONHC_6H_5$

Mechanism

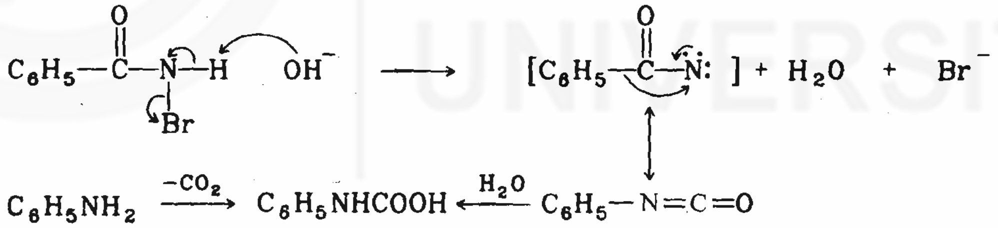


ii) $C_6H_5CONH_2 \xrightarrow[\text{Hofmann}]{NaOH/Br_2} C_6H_5NH_2$

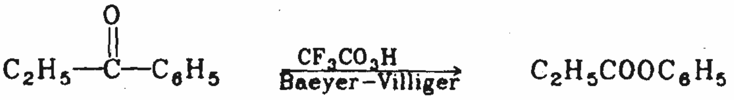
Mechanism

$2NaOH + Br_2 \longrightarrow NaOBr + NaBr + H_2O$

$C_6H_5\overset{O}{\overset{\|}{C}}-\overset{H}{\overset{|}{N}}-H + NaOBr \longrightarrow C_6H_5\overset{O}{\overset{\|}{C}}-\underset{Br}{\underset{|}{N}}-H + NaOH$

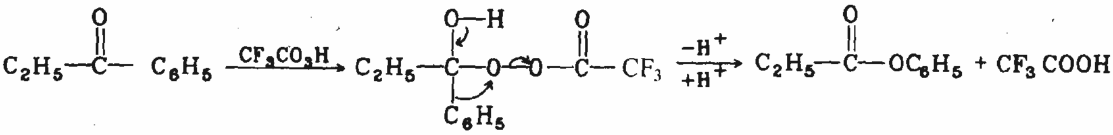


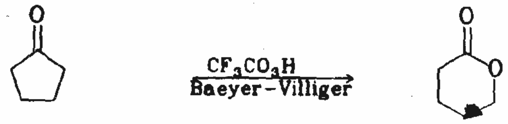
$C_6H_5NH_2 \xleftarrow{-CO_2} C_6H_5NHCOOH \xleftarrow{H_2O} C_6H_5-N{=}C{=}O$

iii) 

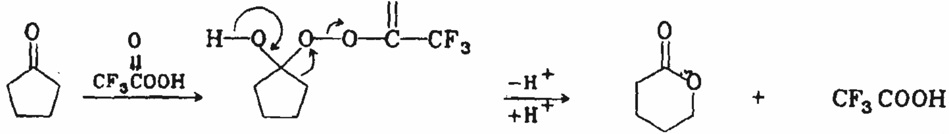
$C_2H_5-\overset{O}{\overset{\|}{C}}-C_6H_5 \xrightarrow[\text{Baeyer-Villiger}]{CF_3CO_3H} C_2H_5COOC_6H_5$

Mechanism

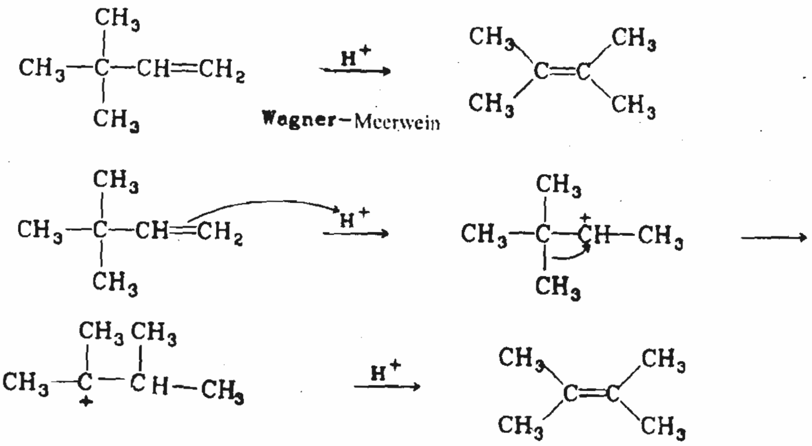


iv) 

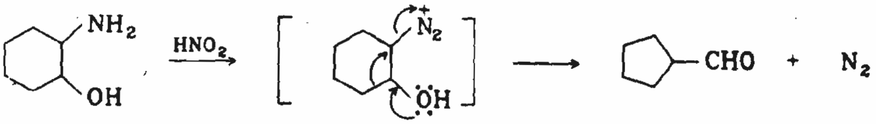
Mechanism



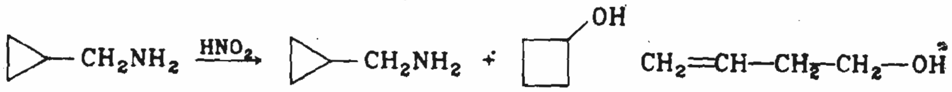
v)



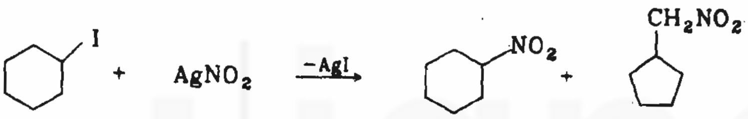
2) i)



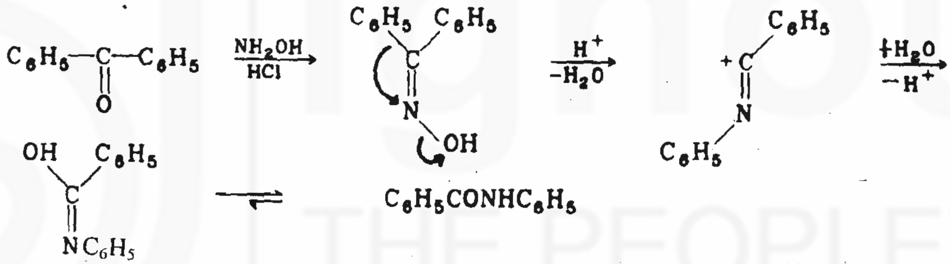
ii)



iii)



3) i)



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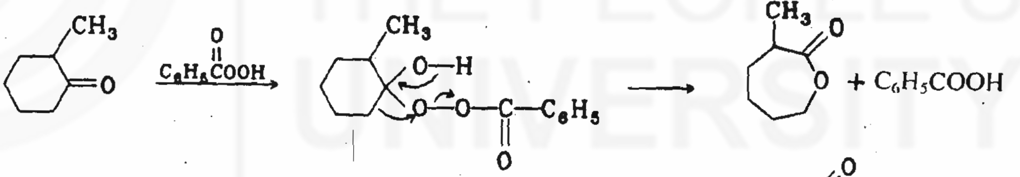

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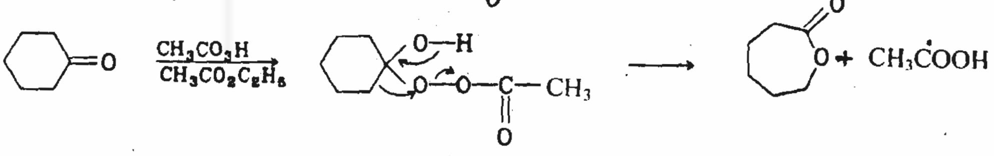

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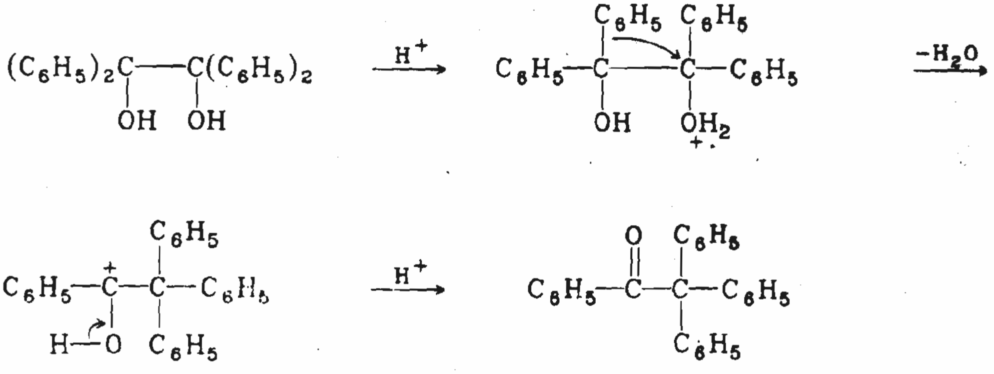


UNIT 12 PERICYCLIC REACTIONS

Structure

12.1 INTRODUCTION

Most of the organic reactions you have studied so far proceed stepwise, exceptions being the S_N2 and E2 type of reactions. A large number of reactions of conjugated polyenes, however, proceed by concerted mechanisms, i.e., the old bonds are broken and the new ones formed in a single concerted step. These reactions are called pericyclic reactions, they are characterised by a cyclic transition state involving sigma or pi-bonds. Pericyclic reactions are initiated by heat or light and are highly stereospecific. In this unit we will discuss these reactions.

Objectives

After studying this unit you should be able to:

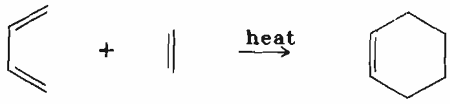
- define pericyclic reactions and describe their broad characteristics,
- classify pericyclic reactions into cyclo-addition reactions, electrocyclic reactions and sigmatropic rearrangements,and
- explain the mechanism of these reactions using the frontier orbital method.

12.2 PERICYCLIC REACTIONS

Pericyclic reactions are concerted reactions. They are characterised by the making or breaking of bonds in a single concerted step through a cyclic transition state involving π or σ electrons. Energy of activation for pericyclic reactions is supplied by heat in a thermally induced reaction and by ultraviolet light in a photo-induced reaction. Pericyclic reactions are highly stereospecific, often the thermal and photochemical processes yield products with different but specific stereochemistry. Since pericyclic peactions do not involve ionic or free radical intermediates, solvents, and nucleophilic or electrophilic reagents have no effect on the course of these reactions.

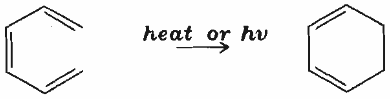
There are three principal types of pericyclic reactions.

1) **Cycloaddition reactions:** in which two molecules combine to form a ring; two π bonds being converted to two sigma bonds in the process. The best known example of a cycloaddition reactions is the **Diels-Alder reaction** shown below.



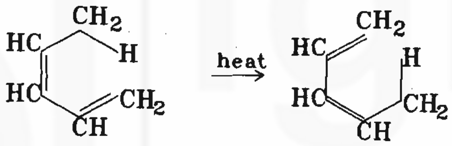
1,3–butadiene ethene cyclohexene

2) **Electrocyclic reactions** are reversible reactions in which a compound with conjugated double bonds undergoes cyclisation. In this process two pi electrons are used to form a sigma bond.



1,3,5–hexatriene 1,3–cyclohexadiene

3) **Sigmatropic rearrangements** are concerted intramolecular rearrangements in which an atom or a group of atoms shifts from one position to another.



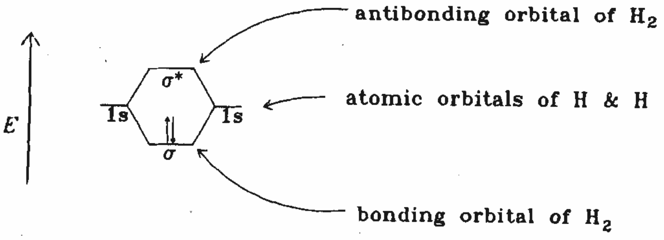
1,3–pentadiene

12.3 THEORETICAL BASIS OF PERICYCLIC REACTIONS

A theoretical understanding of pericyclic reactions had eluded chemists for many years. However, since 1960 several theories have been proposed to give a rational explanation of these reactions. Woodward and Hoffmann have proposed the principle of **conservation of orbital symmetry** as the theoretical basis for explaining these reactions. Fukui has used the **frontier orbital method.** We will use the latter here for studying pericyclic reactions. Before we discuss the mechanism of these reactions, it would be better to recapitulate salient features of the molecular orbital theory.

12.3.1 Molecular Orbital Theory

According to the molecular orbital theory, molecular orbitals are formed by linear combination of atomic orbitals (LCAO). For example when a molecule of hydrogen is formed from two atoms of hydrogen, the atomic orbitals are supposed to combine to give a bonding orbital which is lower in energy than the separate atomic orbitals. In addition, an antibonding orbital is also supposed to exist, which as its name implies does not contribute to the bond formation between the atoms. σ^* is higher in energy than σ orbital or the individual atomic orbitals.



The bonding molecular orbital is supposed to arise from reinforcement of in-phase *s*-atomic orbitals, whereas the antibonding molecular orbital arises from interference between the out-of-phase *s*-atomic orbitals. This is shown diagramatically in Fig. 12.1.

R.B. Woodward of Harvard University got Nobel prize in 1965 for his work on the synthesis of complex organic compounds including chlorophyll.

R. Hoffman of Cornell University **and K Fukui of Kyoto University shared the 1981 Nobel prize for their under standing of pericylic reactions**

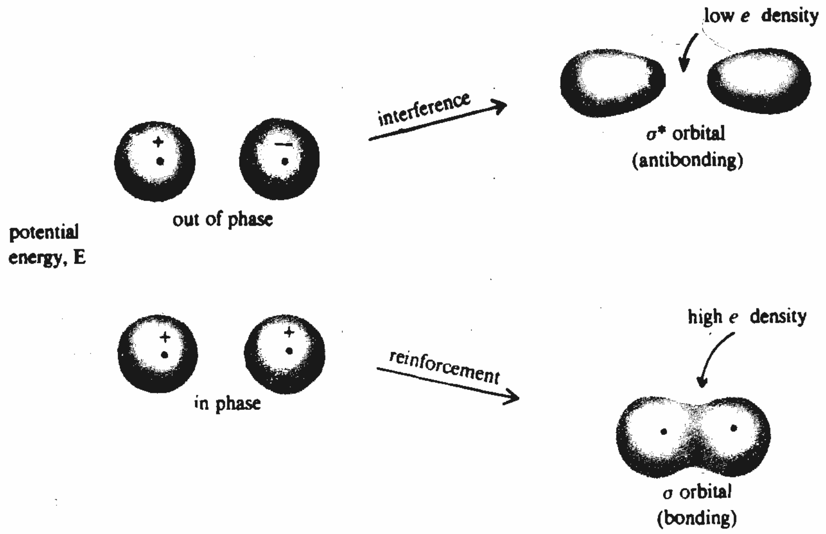


Fig. 12.1 : Bonding and antibonding orbitals of hydrogen molecular

As you know, in saturated hydrocarbons like methane or ethane carbon atoms are sp^3 hybridised and there are sigma bonds between carbon atoms as well as between carbon and hydrogen atoms formed by the overlap of sp^3-sp^3 or sp^3-s atomic orbitals. Each of these sigma bonds will have a bonding orbital and the corresponding antibonding orbital.

However, hybridisation of carbon atoms becomes different in an alkene like ethene. Here the carbon atoms are supposed to be sp^2 hybridised. The double bond between the two carbon atoms is supposed to comprise of a σ and a π bond. The carbon-carbon σ bond is formed by the overlap of two sp^2 orbitals, resulting in a bonding orbital and an antibonding orbital. The π bond is formed by the sideways overlap of *p*-orbitals resulting in two π - molecular orbitals. One of these is the bonding π orbital formed by the overlap of in-phase *p*-orbitals, the other, antibonding π * orbital, arises from the interference between two *p*-orbitals of opposite phases. These orbitals are also designated as π_1 and π_2^* respectively.

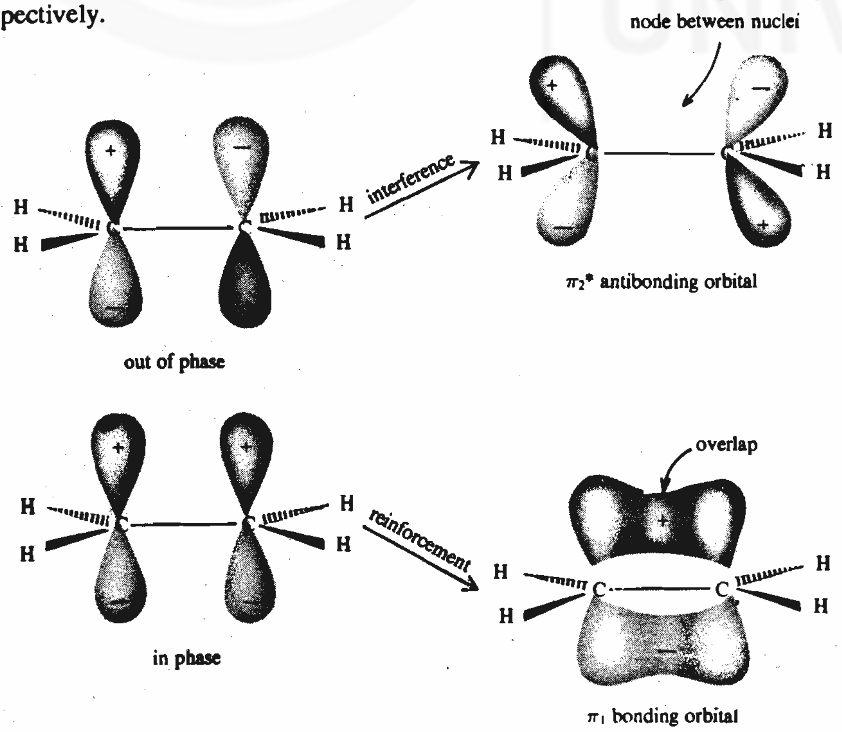
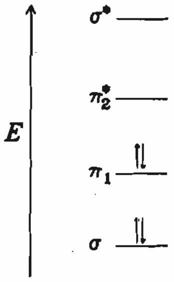


Fig. 12.2 : π_1 and π_2* orbitals of ethene

Fig. 12.2 shows the representation of π_1 and π_2^* orbitals of ethene. Note that π_2^*, which is formed by interference between the out-of-phase *p*-orbitals has a node or a region of minimum electron density between the nuclei. π_2^* Orbital is of higher energy than π_1.The following diagram compares the energies of σ, σ^*, π_1 and π_2^* orbitals. As expected the bonding electrons are in the two orbitals with lowest energies, σ and π_1 in the ground state of ethene.



Ground state of C=C in ethene

As you can see σ^* orbital is of higher energy than π_2^*.The amount of energy required to promote an electron from σ to σ^* orbital is greater than that required to promote a π electron to π^* orbital. Because of the large amount of energy required to promote a sigma electron, electron transitions of this types are rare and therefore unimportant to the organic chemist. However, $\pi \rightarrow \pi^*$ transitions, which require less energy, are important. In the reactions discussed in this unit, you will come across examples of such transitions.

12.3.2 Molecular Orbitals of Conjugated Polyenes

After this brief description of bonding and antibonding molecular orbitals, let us study some features of the molecular orbitals of conjugated polyenes. A conjugated polyene contains either $4n$ or $(4n+2)$ pi electrons in its conjugated system. n is an integer and the simplest $4n$ system is represented by 1,3-butadiene where $n=1$. Any conjugated diene contains n molecular orbitals similar to those of 1,3-butadiene. We can, therefore, use 1,3-butadiene as a model for all conjugated dienes.

In 1,3 -butadiene, four *p*-orbitals are used in the formation of the π molecular orbitals, thus four π molecular orbitals result. Of these π_1 and π_2 are bonding orbitals and π_3^* and π_4^* are antibonding orbitals. Fig. 12.3 depicts these orbitals in terms of increasing energy. As you can see higher energy orbitals are associated with greater number of nodes.

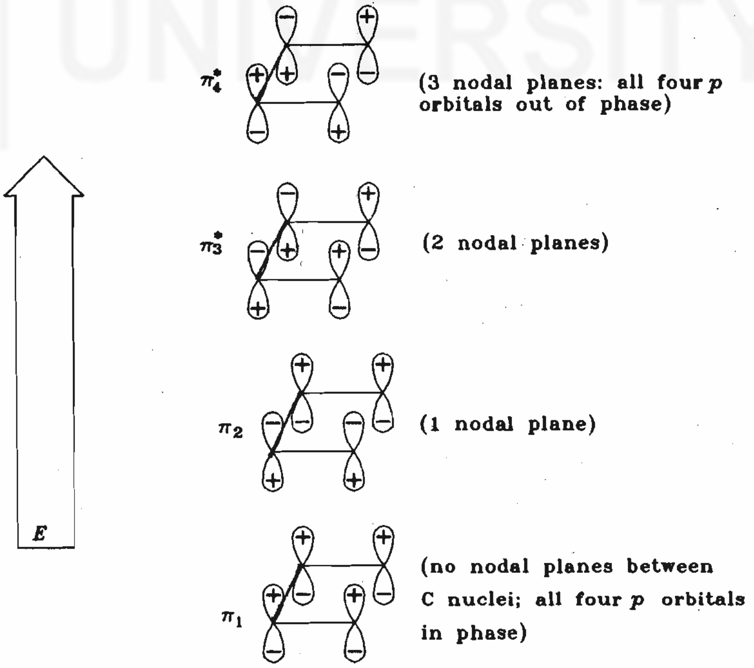
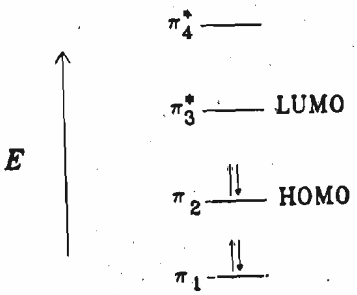
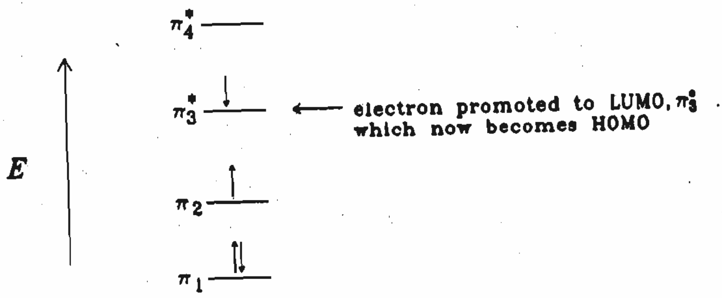


Figure 12.3 : The bonding and antibonding π molecular orbitals of 1,3-butadiene.

In the ground state of butadiene, the four π electrons are in the two orbitals of lowest energy π_1 and π_2 In this case

π_2 is the **Highest Occupied Molecular Orbital, HOMO** and π_3* is the **Lowest Unoccupied Molecular Orbital, LUMO.** HOMO and LUMO are referred to as **frontier orbitals.** These orbitals are used in the frontier orbital method of analysing pericyclic reactions.





When 1,3-butadiene absorbs a photon of the proper wavelength (in the uv range), an electron is promoted from π_2 to π_3* which then becomes the new HOMO.

Aside from ethene (n=0), the simplest ($4n$+2) system is represented by a conjugated triene (n=1), such as 1,3,5-hexatriene. Because a triene contains a pi system formed from six p-orbitals, a total of six π molecular orbitals results. These are shown in fig. 12.4 with the π orbital diagram of the ground state. Of these π_1 π_2 and π_3 are bonding molecular orbitals and Fig. and π_4* π_5* and π_6* are antibonding.

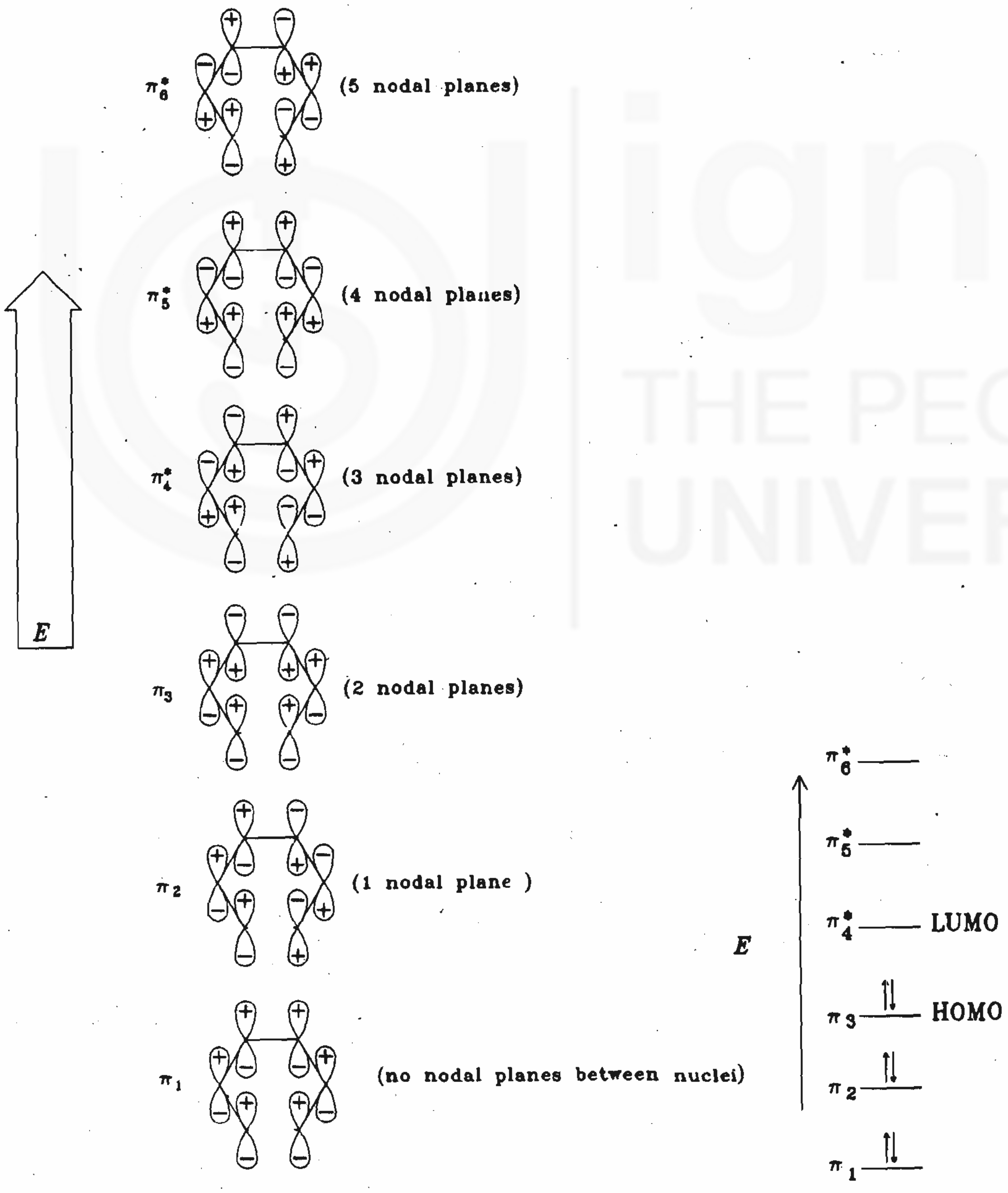


Fig. 12.4 : The bonding and antibonding π molecular orbitals of 1,3,5-hexatriene

We can now discuss the mechanism of pericyclic reactions, but before that try the following SAQ.

SAQ 1

Draw the orbital diagram for the lowest energy excited state of 1,3,5-hexatriene.

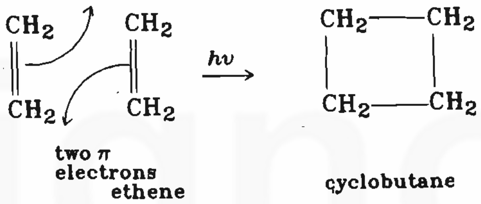
....

....

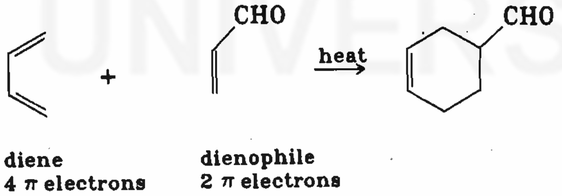
....

12.4 CYCLOADDITION REACTIONS

As said earlier, in a cycloaddition reaction two unsaturated molecules undergo an addition reaction to yield a cyclic product. For example, cyclisation of ethene to cyclobutane on irradiation with light.



The cycloaddition of ethene or any two simple alkenes is called a **[2+2] cycloaddition** as two pi electrons + two pi electrons are involved. The Diels-Alder reaction shown below is an example of a [4+2] cycloaddition. The diene here contains four π electrons and the dienophile two. The carbonyl pi electrons which are not used in bond formation in the reaction are not included in the number classification of this cycloaddition.

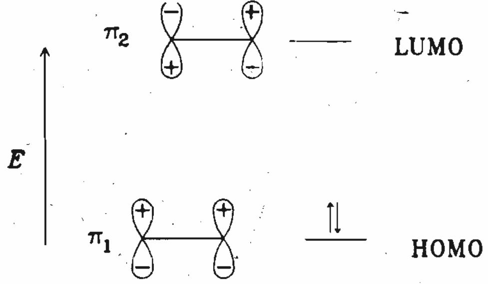


Cycloaddition reaction are concerted, stereospecific reactions. Any particular reaction is either thermal or photo-induced but not both. Let us try to analyse these reactions in terms of frontier orbital theory.

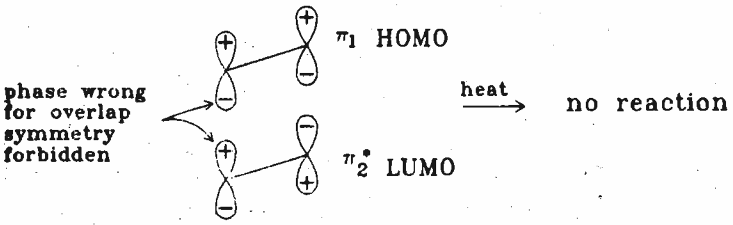
12.4.1 [2+2] Cycloadditions

[2+2] Cycloadditions proceed readily in the presence of light of proper wavelength but not when the mixture is heated. According to frontier orbital theory, this can be easily explained by assuming that the electrons "flow" from the HOMO of one molecule to LUMO of the other. For this the HOMO of one molecule must overlap with the LUMO of the second molecule. It cannot overlap with HOMO of the second molecule because this orbital is already occupied. Simultaneously with the merging of the π orbitals, these orbitals undergo rehybridisation to yield new sp^3 sigma bonds.

Let us consider [2+2] cycloaddition of ethene to give cyclobutane. As discussed above ethene has two π molecular orbitals π_1 and π_2*. In the ground state π_1 is the bonding orbital and the HOMO while π_2* is the antibonding orbital and LUMO.

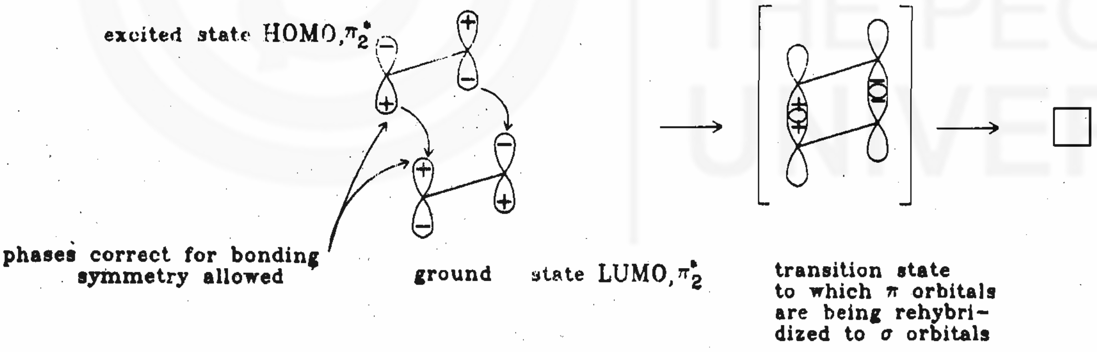


When ethene is heated, π electrons are not promoted but remain in the ground state. If you examine the phases of the ground state HOMO of ethene molecule and the LUMO of another ethene molecule, you can see why cyclisation does not occur by thermal induction.



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

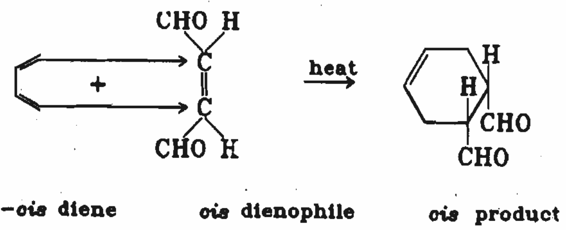
When ethene is irradiated with ultraviolet light, a π electron is promoted from π_1 to π_2* orbital in some, but not all molecules. This results in a mixture of the ground state and excited state ethene molecules. Now, if you examine the HOMO of an excited molecule and the LUMO of a ground state molecule you can see that the phases are correct for bonding. Such a reaction has a relatively low energy of activation and is said to be **symmetry-allowed.**



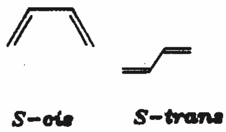
In general, thermally induced [2+2] cycloadditions are symmetry forbidden and photo-induced [2+2] cycloadditions are symmetry allowed. A symmetry forbidden reaction may take place under different conditions, but then the energy of activation is very high. This will not be a concerted reaction and may proceed stepwise through radical intermediate.

12.4.2 [4+2] Cycloadditions

The thermal [4+2] cycloaddition has been known for almost half a century as the Diels-Alder reaction. It has proved synthetically useful since it unites two carbon skeletons smoothly and stereospecifically. In Diels-Alder reaction, a six membered ring is formed by 1,4-addition of an olefinic unit to a conjugated diene. Diels Alder is a *cis* or *syn* addition, the diene must have *S*-cis conformation.

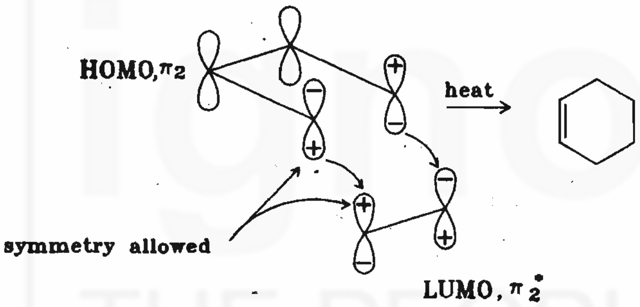


Here *S-cis* refers to the geometry around the single bond which determines the conformation. The two conformations of 1,3- butadiene are

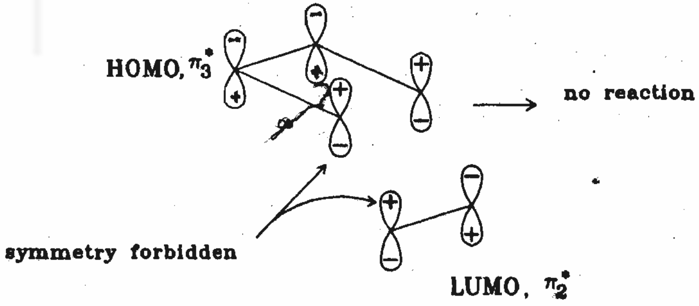


The dienes are activated by electron-donor substituents. For example, 1,3-butadine is less reactive than its mono, di or trimethyl derivatives. However, in the case of tetramethylbutadienes, steric hindrance decreases activity. The dienophile is activated by electron-withdrawing substituents like — COOH, — COOR, — CHO, — COR, — CN, —NO_2, etc. Some reactive dienes do not need activation as is illustrated by the dimerisation of cyclopentadiene.

You may like to know why experimental conditions for [2+2] cycloaddition are different from those for [4+2] cycloaddition, the former being a photo-induced process while the latter is induced thermally. To see why this is so, we would have to examine the HOMO-LUMO interactions of the *p*-orbitals that will form new sigma bonds in [4+2] cycloaddition. Let us first compare the HOMO-LUMO interactions for the ground state for a thermally induced reaction. We will use the simplest [4+2] system, the cycloaddition of 1,3-butadiene and ethene. In the thermally induced cycloaddition between these two reactants, we can visualise the pi electrons flowing from HOMO, π_2 of the diene (Fig. 12.3) to the LUMO π_2^* of the dienophile. You can see that orbitals that lead to cycloaddition are in phase. The reaction therefore is **symmetry allowed.**



Now let us see how things are if we try to photo induce the reaction. When the diene is excited by light, its HOMO becomes the π_3^* orbital (Fig 12.3). This molecular orbital cannot overlap with the LUMO of the dienophile because the two are not in-phase. The photo induced [4+2] cylisation, therefore, is **symmetry-forbidden.**



SAQ 2

(a) Explain why in [4+2] cycloaddition, diene is activated by electron donor substituents and dienophile by electron-withdrawing substituents.

(b) Predict whether a photo induced [4+2] cycloaddition would be possible if the dienophile instead of the diene were the excited reactant.

....

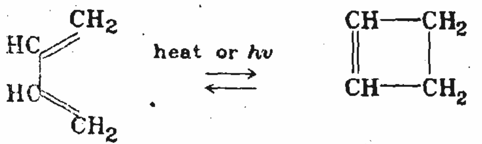
....

....

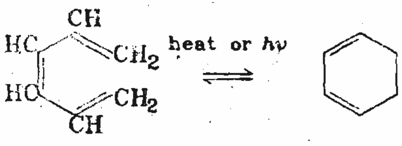
12.5 ELECTROCYCLIC REACTIONS

An electrocyclic reaction is the concerted inter-conversion of a conjugated polyene into a cycloalkene. Here we will discuss cyclisation. The reverse reaction, ring opening proceeds by the same mechanism, but in the reverse direction.

Electrocyclic reactions are induced either thermally or photochemically, for example.

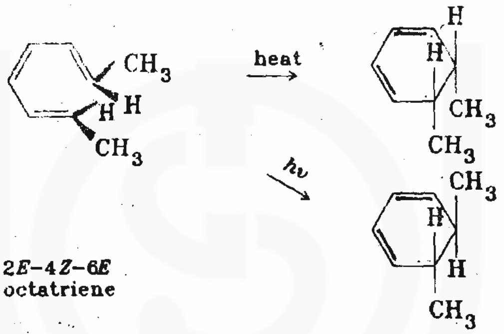


1,3-butadiene cyclobutene



1,3,5 hexatriene 1,3 - cyclohexadiene

However, the stereochemistry of the product depends on whether the reaction is thermally or photo-induced as the following example would show:



2*E*-4*Z*-6*E* octatriene

cis-5,6-dimethyl 1, 3, - cyclo hexene

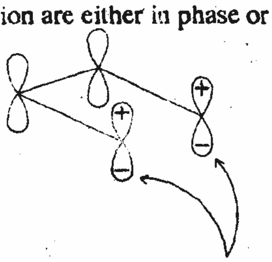
trans-5,6-dimethyl 1,3 cyclohexene

Let us study electrocyclic reactions of some systems.

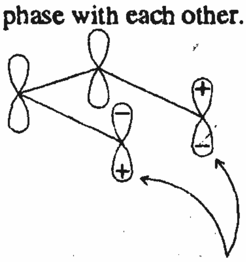
12.5.1 Cyclisation of 4*n* systems

1,3-Butadiene is the simplest polyene with 4*n* electrons. Interconversion of 1,3-butadiene and cyclobutene can be taken to illustrate the mechanism of such reactions. Since cyclobutenes are strained ring systems, the reverse reaction, ring opening is usually favoured. However, as said earlier, the mechanism for ring opening is just the reverse for ring closure.

1,3-Butadiene, like any conjugated polyene, yields cyclobutene by the end-to-end overlap of its *p* orbitals and simultaneous rehybridisation of the carbon atoms involved in bond formation. Now the two lobes of each *p*-orbital that will form the new sigma bond in cyclisation are either in phase or out of phase with each other.



in phase

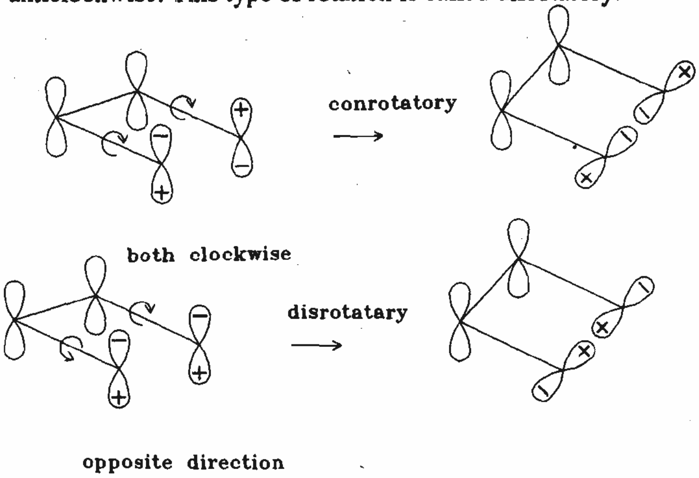


out of phase

In order that a new sigma bond can be formed, the existing C—C sigma bonds must rotate so that the *p*-orbitals can undergo end-to end overlap. The energy for the *pi*-bond breakage and bond rotation is supplied by heat or ultraviolet radiation used to induce the reaction. The pair of overlapping lobes of *p* orbitals must be in phase after rotation. There are two ways in which the existing C—C sigma bonds can rotate in order to bring the *p*-orbitals in phase for overlap.

- The two C— C sigma bonds can rotate in the same direction, either both clockwise or both counter-clockwise. This type of rotation is called conrotatory.

- The two C— C sigma bonds can rotate in the opposite directions, one clockwise and the other anticlockwise. This type of rotation is called disrotatory.



In the first of above examples, you can see that the phases of *p*-orbitals in the starting dienes are different. You may also note that when the *p*-orbitals are out of phase before rotation, conrotatory motion can bring them into phase for symmetry allowed overlap; and when the *p*-orbitals are in phase before rotation (second example) disrotatory motion is required. In other words, direction of rotation for symmetry allowed overlap depends on the phases of *p*-orbitals just prior to cyclisation. The phases of *p*-orbitals of the diene just prior to the reaction, in turn, depend on whether the molecule is in the ground state or in the excited state. Let us consider both these cases.

When 1,3-butadiene is heated, reaction takes place from the ground state. The electrons that are used for sigma bond formation are in the HOMO, π_2. If you refer to Fig. 12.3, you can see that the pertinent *p*-orbitals in this HOMO are out of phase with each other. So for the sigma bond to form, rotation must be conrotatory. Disrotatory motion would not bring lobes of *p*-orbitals in phase for overlap.

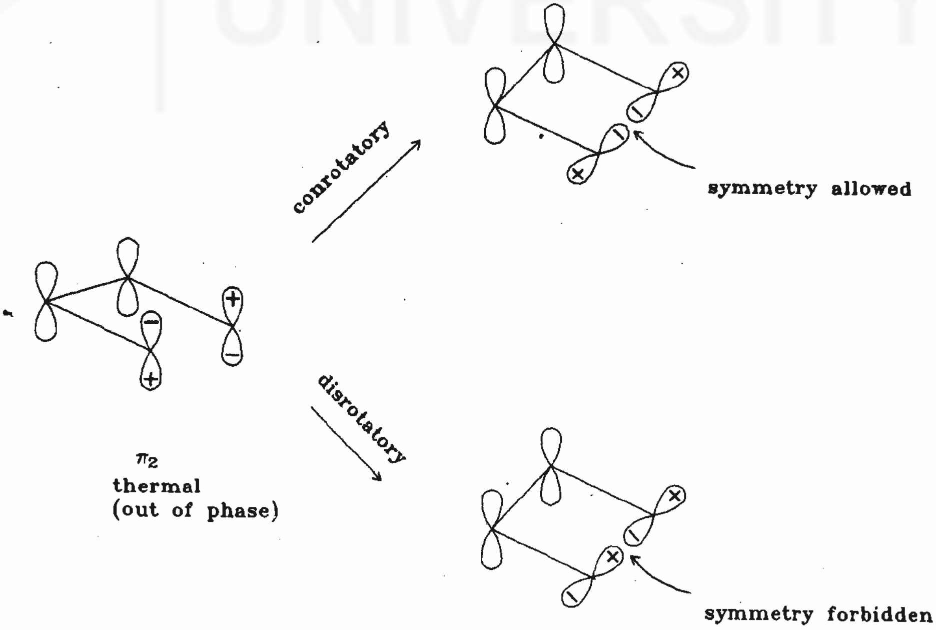
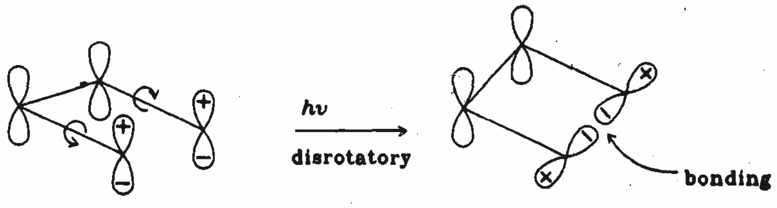


Photo induced cyclisation takes place in the excited state. Here HOMO is π_3*, in which phases of *p*-orbitals are in phase. Therefore, the rotation of C—C sigma bonds has to be disrotatory for a symmetry allowed reaction to take place.



π_3^*
photo
(in phase)

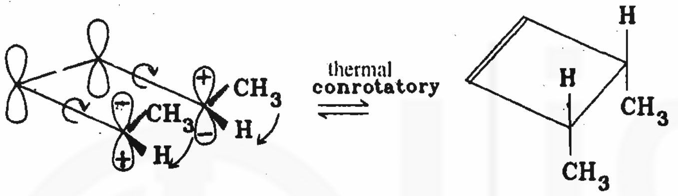
symmetry-allowed

Stereochemistry of a 4*n* cyclisation

We have said above that the stereochemistry of the product in electrocyclisation depends on whether the reaction is thermally or photo induced.

Let us see why. In order to study the stereochemistry of electrocyclisation of 4*n* systems we will take a substituted 1,3-butadiene. If (2*E*,4*Z*)- hexadiene is cyclised *cis*-dimethyl cyclobutene results from heating and the *trans* isomer from a photochemical reaction.

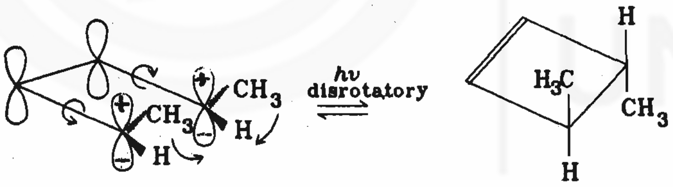
As you can deduce from the discussion above, in thermal cyclisation conrotatory motion is required for bond formation. So both methyl groups rotate in the same direction. As a result they are on the same side of the ring or *cis* in the product.



π_2

cis

In photochemical cyclisation, on the other hand, disrotatory motion would be required for bond formation. The two methyl groups rotate in opposite directions, one rotates up, the other down; with the result that they are trans in the product.

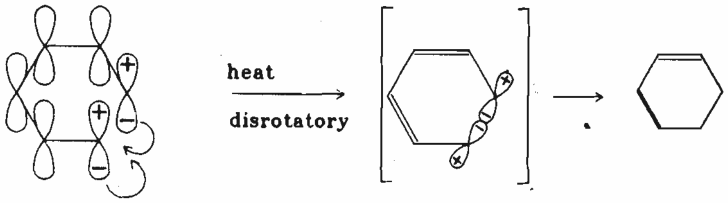


trans

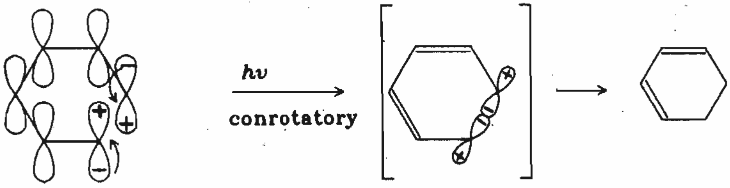
π_3^*

12.5.2 Cyclisation of (4*n*+2) Systems

A typical example can be cyclisation of 1,3,5-hexatriene to 1,3-cyclohexadiene. As you can see in Fig.12.4, the HOMO in the ground state is π_3. In this molecular orbital, the *p*-orbitals that form sigma bond are in phase so thermal cyclisation would proceed by disrotatory motion.



When 1,3,5-hexatriene is irradiated by ultraviolet light, one electron is promoted to π_4^*, which now becomes the HOMO. In this molecular orbital the *p*-orbitals are out of phase. Therefore, conrotatory motion would be necessary for bond formation.



So you can see that the symmetry allowed reactions of (4*n*+2) systems are just opposite to those of 4*n* systems. Table 12.1 gives a summary of types of motions expected in thermal and photo induced reactions in these two systems.

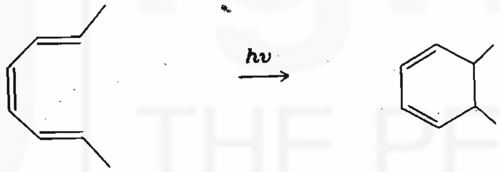
Table 12.1: Types of electrocyclic reactions

Number of Pi Electrons	Reaction	Motion
4*n*	thermal	conrotatory
4*n*	photochemical	disrotatory
(4*n* + 2)	thermal	disrotatory
(4*n* + 2)	photochemical	conrotatory

SAQ 3

(a) Would you expect (2*E*,4*E*)-hexadiene to yield *cis* or *trans* 3,4-dimethyl butene in a photo induced reactions.

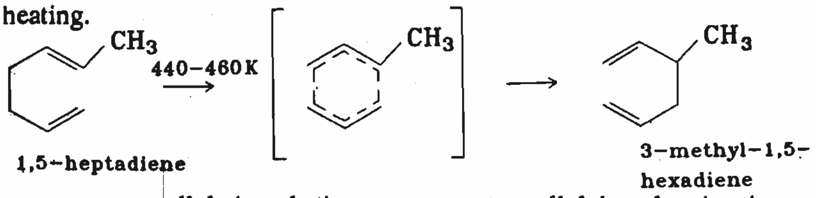
(b) Predict the stereochemistry of the product in the following reaction.



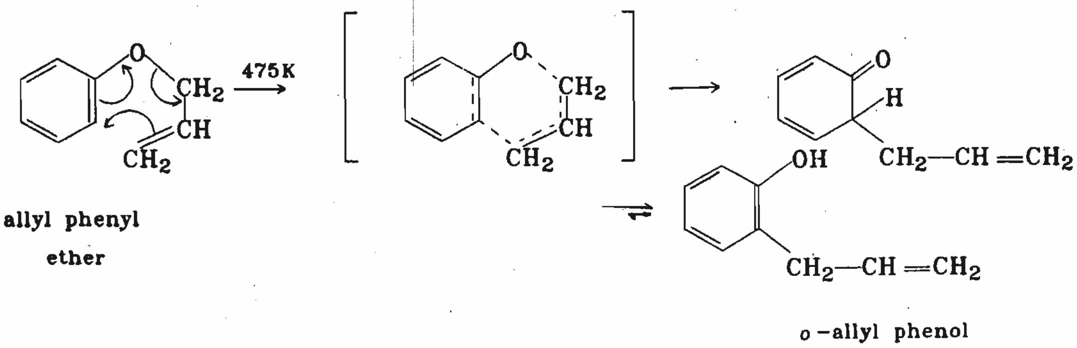
12.6 SIGMATROPIC REARRANGEMENTS

A sigmatropic rearrangement is a concerted intramolecular shift of an atom or a group of atoms. Cope and Claisen rearrangements are the two well known examples of sigmatropic rearrangements.

A typical example of Cope rearrangement is 1,5-heptadiene rearranging to 3-methyl-1,5-hexadiene on heating.



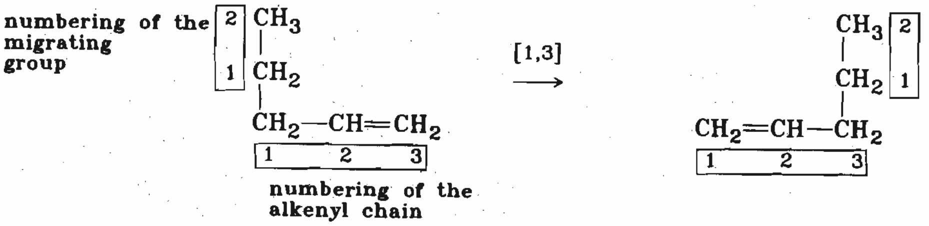
In Claisen rearrangement an allyl phenyl ether rearranges to *o*-allylphenol on heating.



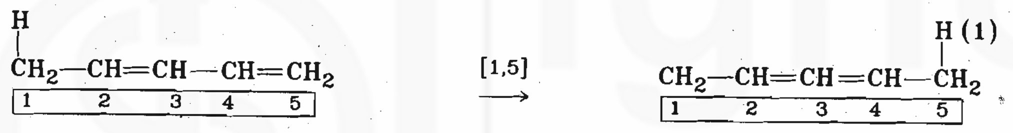
In Claisen rearrangement, the allyl group migrates to the *ortho* position. However, if both *ortho* positions are filled, *para* migration takes place, but never *meta*. There is no reaction when both *ortho* and the *para* positions are fiflled. Further, experiments with compounds labelled with ^{14}C have shown that *ortho* migration is always accompanied by an allylic shift where as in *para* migration there is never an allylic shift.

12.6.1 Classification of Sigmatropic Rearrangements

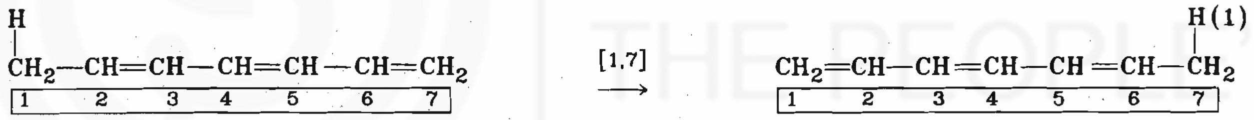
The method of classification of sigmatropic rearrangements differs from cycloadditions and electrocyclic reactions. Whereas in the latter two types of reactions, classification is based on the number of electrons involved in the cyclic transition state, the sigmatropic rearrangements are classified by a double numbering system that refers to the relative position of the atoms involved in the migration. This is best explained by taking a few examples.



As you can see both the alkenyl chain and the migrating group are numbered starting at the position of their original attachment. This may not be a carbon atom. Also these numbers are not related to nomenclature numbers. In the above example atom 1 of the migrating group ends up on atom 3 of the alkenyl chain, so this rearrangement is classified as [1,3] sigmatropic rearrangement. Examples of [1,5] and [1,7] sigmatropic rearrangements are given below. In both cases the migrating group is H.

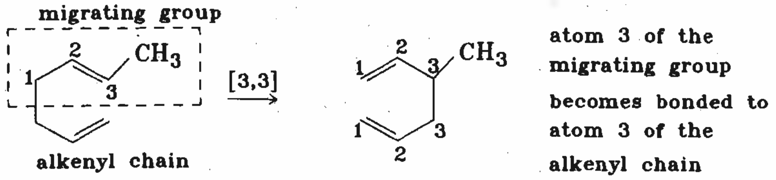
i) 

$$\overset{\text{H}}{\underset{1}{\text{CH}_2}}\text{—}\underset{2}{\text{CH}}\text{=}\underset{3}{\text{CH}}\text{—}\underset{4}{\text{CH}}\text{=}\underset{5}{\text{CH}_2} \xrightarrow{[1,5]} \underset{1}{\text{CH}_2}\text{—}\underset{2}{\text{CH}}\text{=}\underset{3}{\text{CH}}\text{=}\underset{4}{\text{CH}}\text{—}\overset{\text{H (1)}}{\underset{5}{\text{CH}_2}}$$

ii) 

$$\overset{\text{H}}{\underset{1}{\text{CH}_2}}\text{—}\underset{2}{\text{CH}}\text{=}\underset{3}{\text{CH}}\text{—}\underset{4}{\text{CH}}\text{=}\underset{5}{\text{CH}}\text{—}\underset{6}{\text{CH}}\text{=}\underset{7}{\text{CH}_2} \xrightarrow{[1,7]} \underset{1}{\text{CH}_2}\text{=}\underset{2}{\text{CH}}\text{—}\underset{3}{\text{CH}}\text{=}\underset{4}{\text{CH}}\text{—}\underset{5}{\text{CH}}\text{=}\underset{6}{\text{CH}}\text{—}\overset{\text{H(1)}}{\underset{7}{\text{CH}_2}}$$

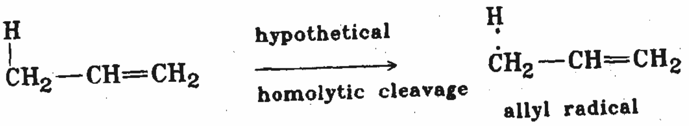
[1,3] sigmatropic rearrangements are relatively rare, while [1,5] sigmatropic rearrangements are fairly common. First atom of the migrating group may not always become bonded to the alkenyl chain. In the example of Cope rearrangement given above, atom 3 of the migrating group becomes bonded to atom 3 of the alkenyl chain. So this is an example of [3,3] sigmatropic rearrangement.



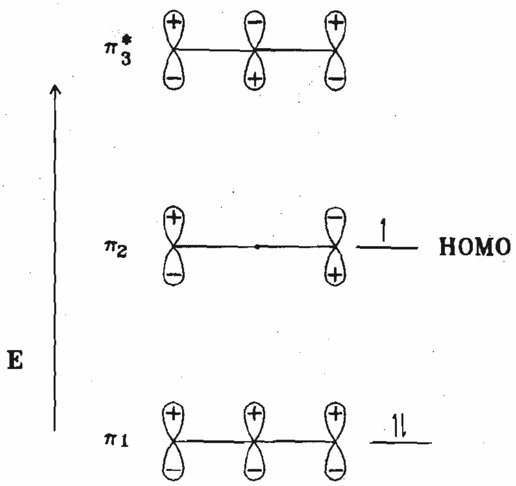
12.6.2 Mechanism of Sigmatropic Rearrangements

We can use frontier orbital method for analysing the mechanism of sigmatropic rearrangements also. For the purpose of analysing the orbitals, it is assumed that the sigma bond connecting the migrating group to its original position undergoes homolytic cleavage to yield two radicals. You must bear in mind that this is not how the reaction takes place. The reaction is concerted. The assumption is made to allow an easy analysis of the molecular orbitals.

Let us first take the case of a [1,3] sigmatropic rearrangement. The products of the hypothetical cleavage are a hydrogen atom and an allyl radical which contains three pi electrons and so three π molecular orbitals.

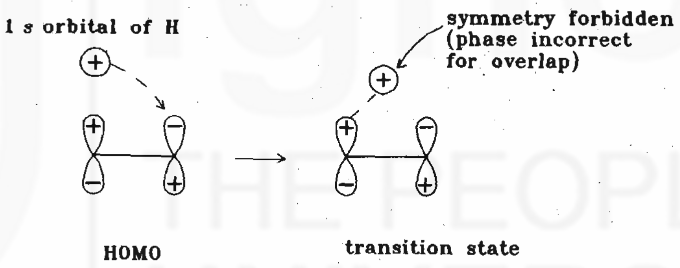


$$\overset{H}{C}H_2-CH{=}CH_2 \xrightarrow[\text{homolytic cleavage}]{\text{hypothetical}} \overset{H}{\dot{C}}H_2-CH{=}CH_2$$



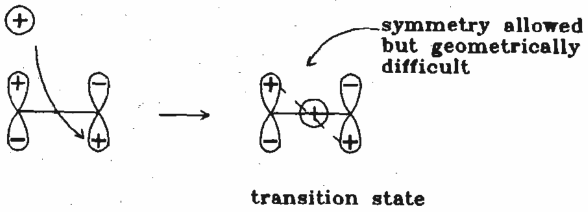
There are two modes in which H can shift. In one case the migrating group remains on the same side of the alkenyl chain, such a migrating is called **suprafacial.** In the other the migrating group migrates to the opposite face of the orbital system, this is known as **antarafacial.**

If you examine the HOMO of the allyl radical in a [1,3] sigmatropic shift, you can see that suprafacial migration is symmetry forbidden though it may be geometrically feasible.



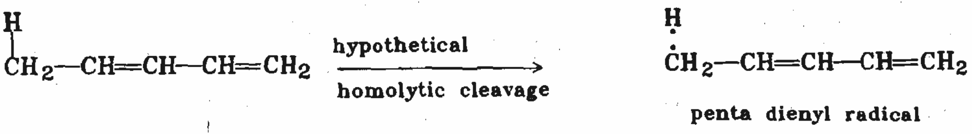
suprafacial shift

Let us see what happens in the case of antarafacial shift. You can see that this is symmetry allowed but geometrically unfavourable. This leads to the conclusion that [1,3] sigmatropic rearrangements should not occur readily. As mentioned above, it has been found in practice that they are rare.



antarafacial shift

By contrast [1,5] sigmatropic shifts are quite common. If we assume a homolytic bond cleavage for the purpose of analysis, we have to consider π molecular orbitals of pentadienyl radical which has five π electrons and hence five molecular orbitals shown in Fig 12.5.



$$\overset{H}{C}H_2-CH{=}CH-CH{=}CH_2 \xrightarrow[\text{homolytic cleavage}]{\text{hypothetical}} \overset{H}{\dot{C}}H_2-CH{=}CH-CH{=}CH_2$$

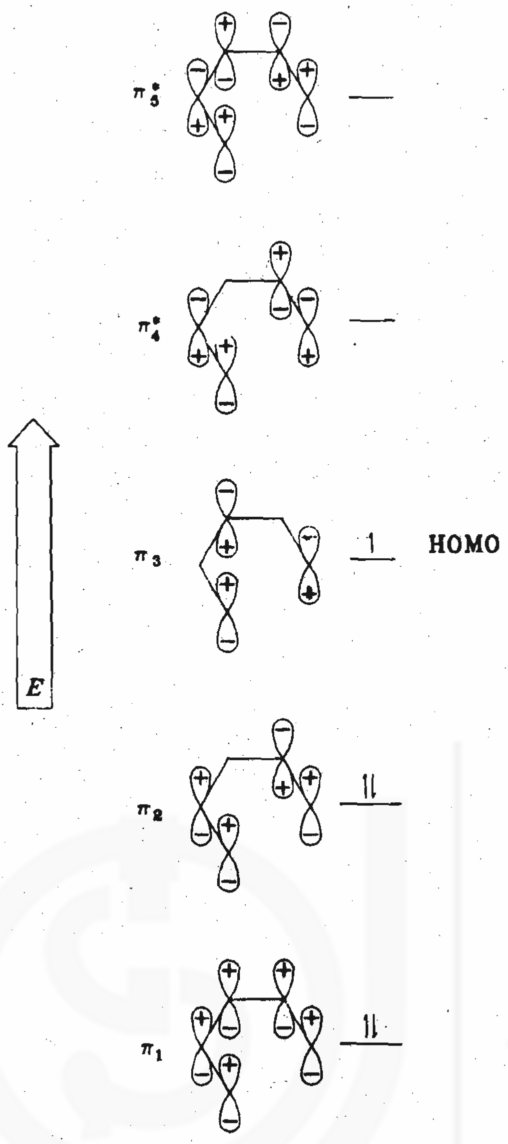
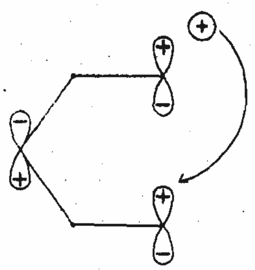


Fig 12.5 : The five π molecular orbitals of the pentadienyl radical

Considering π_3, the HOMO of this radical, we can see that suprafacial [1,5] shift is both symmetry allowed and geometrically favourable, which makes it facile.



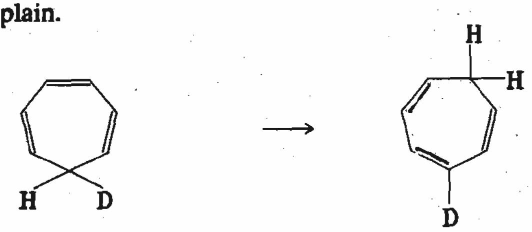
1,5 suprafacial shift
symmetry allowed
geometrically favourable

rotate through 90°

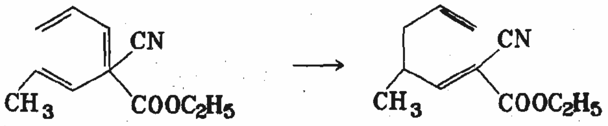
SAQ 4

Which of the following sigmatropic rearrngements would proceed readily and which slowly? Explain.

a)



b)



12.7 SUMMARY

In this unit we have discussed pericyclic reactions. These reactions are thermal or photo induced concerted reactions with cyclic transition sates. Pericyclic reactions have been classified into,

- Cycloaddition reactions
- Electrocyclic reactions
- Sigmatropic rearrangements

In this unit we have used the frontier orbital method for analysing the mechanism of these reactions, according to which the electrons are assumed to flow from the HOMO of one molecule to LUMO of the other. If these orbitals are in phase, the reaction is symmetry allowed. If the orbitals are not in phase the reaction is symmetry forbidden.

Cycloaddition reactions of 4*n* and (4*n*+2) systems have been discussed. It has been shown by analysis of the frontier orbitals in the ground state and the excited state that cycloadditions of 4*n* systems would be photo induced while those of (4*n*+2) thermally induced.

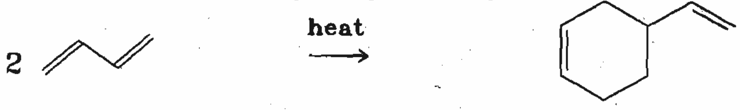
Electrocylic reactions of 4*n* and (4*n*+2) systems have been discussed next. Here *p*-orbital components of the HOMO undergo end-to-end overlap to form new sigma bonds. For this they must undergo conrotatory or disrotatory motion which in turn determines the stereochemistry of the product. Rationale for the stereochemistry of the products obtained in thermal and photochemical reactions has been established on this basis.

Sigmatropic rearrangements are concerted intramolecular rearrangements. These occur suprafacially or antarafacially depending on the phases of interacting orbitals in the HOMO of the hypothetical radical system. The facility of [1,3] and [1,5] sigmatropic shifts has been analysed in terms of orbital symmetry and geometry of the transition state.

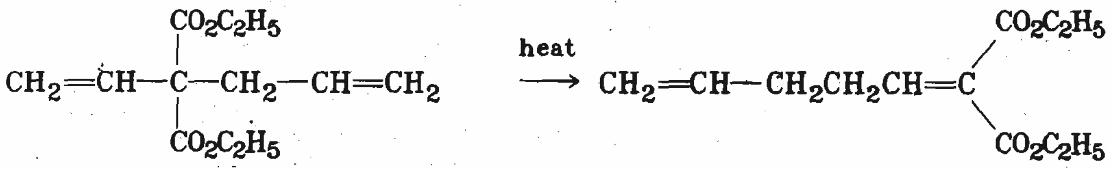
12.8 TERMINAL QUESTIONS

1) Identify each of the following reactions as a cycloaddition, an electrocyclisation reaction or a sigmatropic rearrangement.

a)

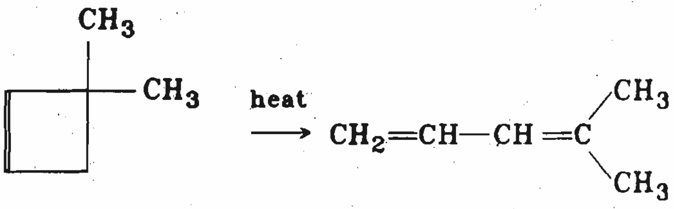


b)

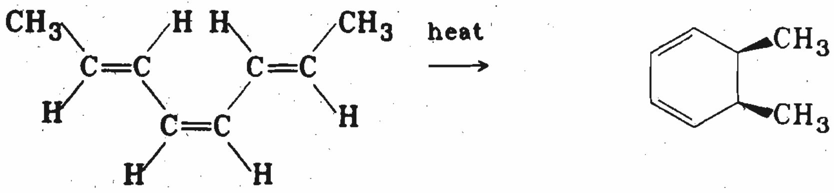


$$CH_2{=}CH{-}C(CO_2C_2H_5)_2{-}CH_2{-}CH{=}CH_2 \xrightarrow{\text{heat}} CH_2{=}CH{-}CH_2CH_2CH{=}C(CO_2C_2H_5)_2$$

c)



d)

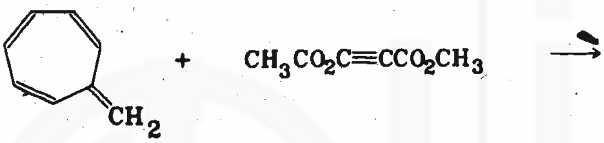


2) Draw the π orbital diagram for the lowest energy excited state of 1,3,5-hexatriene and indicate the HOMO.

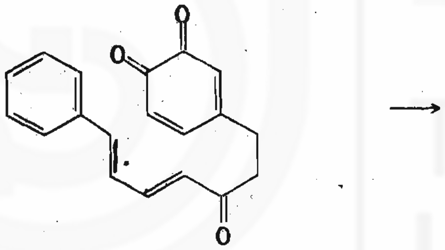
3) What would be the products in the following cyclo addition reactions. Classify each as [2+2] or [4+2] cyclo addition.

a) $2CH_2{=}C{=}CH_2 \longrightarrow$

b)



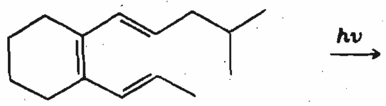
c)



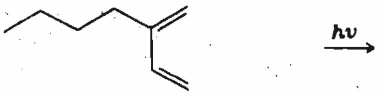
4) Specify which type of rotatory motion, conrotatory or disrotatory would each of the following undergo in an electrocyclisation reaction. Also indicate the product formed.

a)

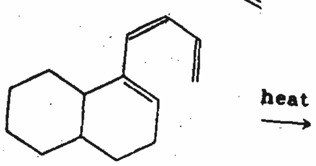
b)



c)

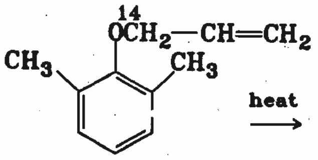


d)

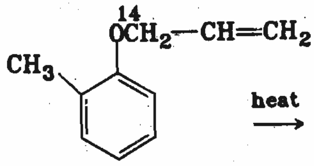


5) Predict the products in the following:

a)



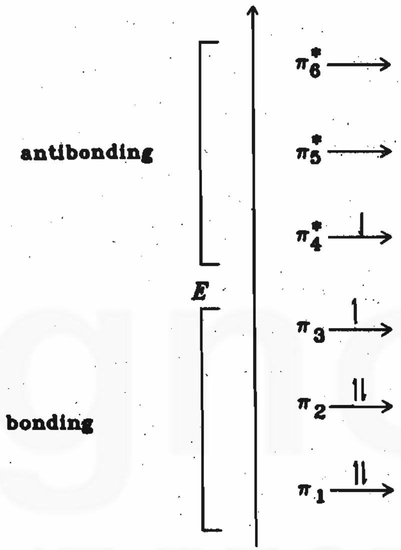
b)



12.9 ANSWERS

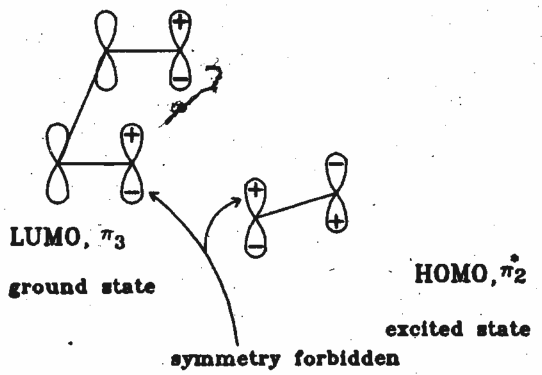
Self-assessment Questions

1)

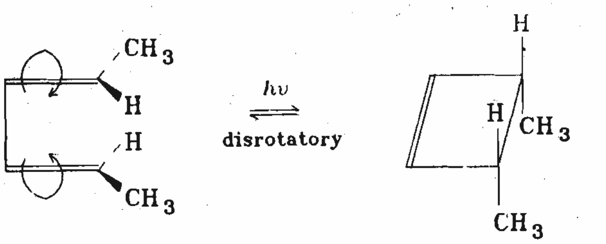


2) a) The reaction visualises π electrons flowing from HOMO, π_2 of the diene to the LUMO π_2^* of the dienophile. Therefore, a high electron density in the former and a low electron density in the latter would favour the reaction.

b) Photoinduced (4+2) cycloaddition is not possible in this case. Because LUMO π_2 of the diene is not in phase with HOMO π_2^* of the dienophile reaction would be symmetry forbidden.



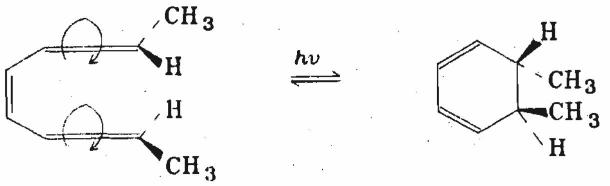
3) a) 2,4-Hexadiene is a 4*n* polyene. Therefore, the photochemical electrocyclic reaction takes place by disrotatory motion. The product would be *cis*-3,4-dimethyl cyclobutene.



2*E*,4*E*-hexadiene

cis-3,4-dimethyl cyclobutene

b) 1,3,5-Hexatriene is a (4n+2) polyene. Photochemical electrocyclic reaction would involve conrotatory motion to give the *trans* product.



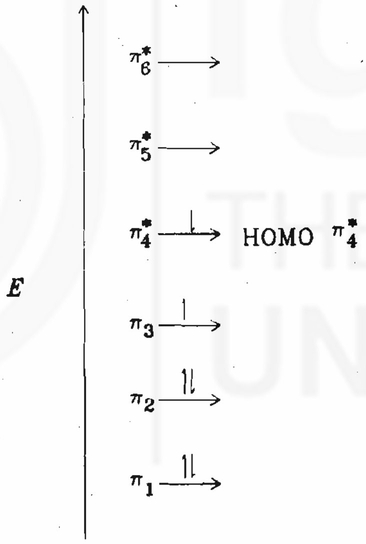
trans-5,6-dimethyl cyclohexa-1,3-diene

4) Both would proceed readily (a) by [1,5] sigmatropic shift and (b) by [3,3] sigmatropic shift.

Terminal Questions

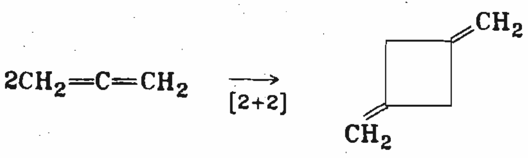
1) a) cyclo addition
   b) sigmatropic rearrangement
   c) electrocyclic reaction
   d) electrocyclic reaction

2)

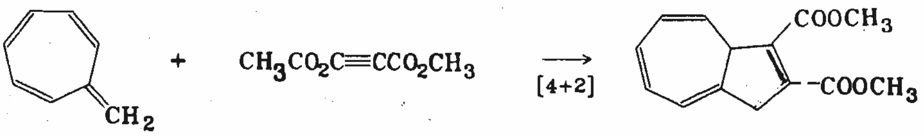


3)

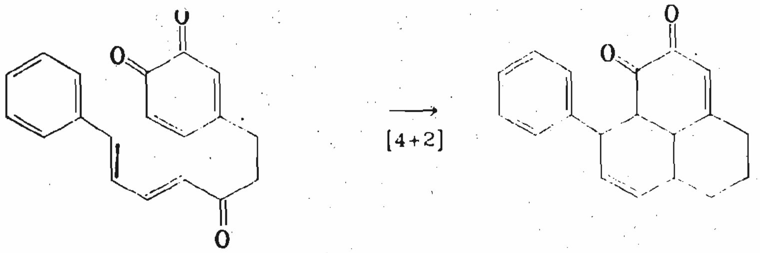
a)



b)

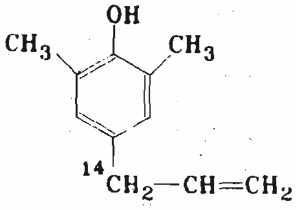


c)

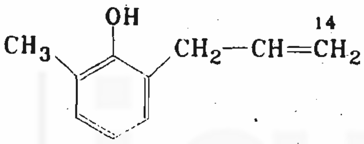


4) a) [4*n*] thermal reaction would involve conrotatory motion.
   b) [4*n*+2] photochemical reaction would involve conrotatory motion.
   c) [4*n*] photochemical reaction would involve disrotatory motion.
   d) [4n+2] thermal raection would involve disrotatory motion.

5) a)



b)



Further Readings

1) *Organic Chemistry,* 6th edition; by R.T. Morrison and R.N. Boyd; Prentice-Hall of India Pvt. Ltd.

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3) *Organic Chemistry,* Vol.I and II; by S.M. Mukherji, S.P. Singh and R.P. Kapoor; Wiley Eastern Ltd.

4) *Text Book of Organic Chemistry,* 24th edition; by P.L. Soni and H.M. Chawla: Sultan Chand & Sons.

5) *Text Book of Organic Chemistry,* 2nd edition; by Llyod N. Ferguson; Affiliated East West Press Pvt. Ltd.

6) *Reaction Mechanism and Reagent in Organic Chemistry,* 2nd edition, by Gurdeep R. Chatwal; Himalaya Publishing House.

7) *Reaction Mechanism in Organic Chemistry,* by S.M. Mukharji, S.P. Singh, The Macmillan Company of India Limited.

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