UNIT 5 ADDITION TO CARBON-CARBON MULTIPLE BOND SYSTEM

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5.1 INTRODUCTION

In the last two units you have studied about substitution reactions. In this unit you will study addition reactions of carbon-carbon double bond and carbon-carbon triple bond.

The most characteristic way in which carbon-carbon double (alkenes) or carbon-carbon triple bonds (alkynes)reacts,is by addition to the multiple (double or triple) bonds. Alkenes consist of one σ bond and one π bond, while alkynes contain one σ bond and two π bonds. Since π bonds are weaker than σ bonds, most of the reactions would involve the breaking of the weak π bond(s).

Addition reactions at the carbon-carbon multiple bonds can be divided into three types:

- Electrophilic additions
- Free radical additions
- Concerted additions

In this unit we shall discuss each type of the addition reactions in detail.

Objectives

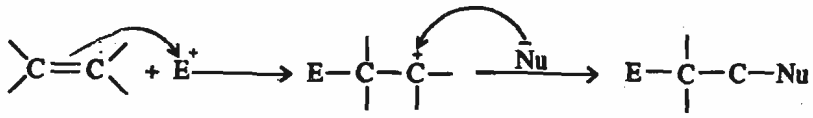
After studying this unit, you should be able to:

- list types of addition reactions,
- discuss the mechanism of electrophilic addition reactions,
- explain the 1, 2 and 1,4-addition of dienes,
- explain the mechanism of free radical addition reactions, and
- explain the mechanism of concerted addition reactions.

5.2 ELECTROPHILIC ADDITION REACTIONS

Most reactions of alkenes or alkynes occur when an electron-deficient substance (an electrophile) attacks the π bond. Most commonly the attacking reagents are acid, either a mineral acid or a Lewis acid, i.e., any species which is electron-deficient and seeks to share an electron pair of some other substance. By contrast, there is little tendency for a double or a triple bond to react with a base.

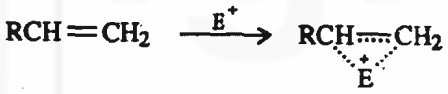
In addition reaction of an alkene, the π bond is broken and its pair of electrons are used in the formation of two new σ bonds. The sp^2 hydridised carbon atoms are rehybridised to sp^3 in the process. Compounds containing π bonds are usually of higher energy than those having σ bonds. Consequently, an addition reaction is usually an exothermic process.



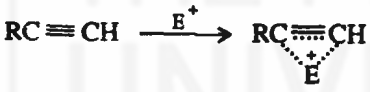
In the region of the double bond there is a cloud of π-electrons above and below the plane of the bonded atoms. The π electrons are loosely held by the nuclei and are thus easily available to electron seeking reagents. Such reagents are called electrophilic reagents or electrophiles and the reactions are called electrophilic addition reactions.

In general, alkynes undergo almost the same types of reactions as alkenes. Electron density around the carbon-carbon triple bond is higher than that around carbon-carbon double bond. So, we might expect alkynes to be more reactive towards electrophilic reagents than alkenes, but the reverse is true, i.e., alkenes are more reactive than alkynes. You may be surprised at this trend. To understand the reason, consider the nature of the carbon atoms of alkenes and alkynes. You may recall that in alkenes carbon atoms are sp^2 hydridised and in alkynes, these are *sp* hydridised. Since an *sp* hybridised carbon is more electronegative than an sp^2 hybridised carbon atom, the π electrons are more tightly held by the carbon nuclei in the former case and, hence, they are less easily available for combination with an electrophile. Thus, electrophilic addition at the *sp* hybridised carbon atoms in an alkyne should be less facile.

Another explanation may be attributed to the formation of highly strained unstable cyclic alkenyl cation from an alkyne as compared to strain-free alkyl cation formed from an alkene.



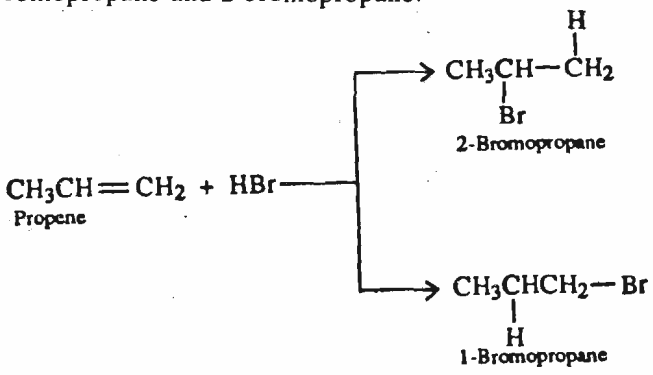
Alkyl cation



Both these factors may account for the diminished reactivity of alkynes towards electrophilic addition. Let us study some important electrophilic addition reactions of alkenes and alkynes.

5.2.1 Addition of Hydrogen Halides

Alkyl halide is formed when an alkene reacts with hydrogen halide. This reaction is known as **hydrohalogenation**. The order of reactivity of HX towards alkene is: HI > HBr > HCl > HF. In the case of a symmetrical alkene we get only one product but in case of unsymmetrical alkene we get two different products. Actually only one of the two products is formed in significant amount. For example, when HBr adds to an unsymmetrical alkene like propene, in principle, two products could be formed, i.e., 1-bromopropane and 2-bromopropane.



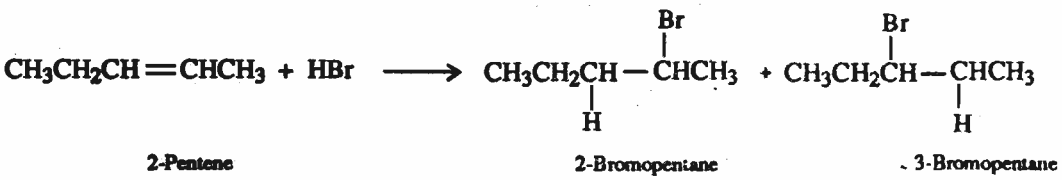
Propene

2-Bromopropane

1-Bromopropane

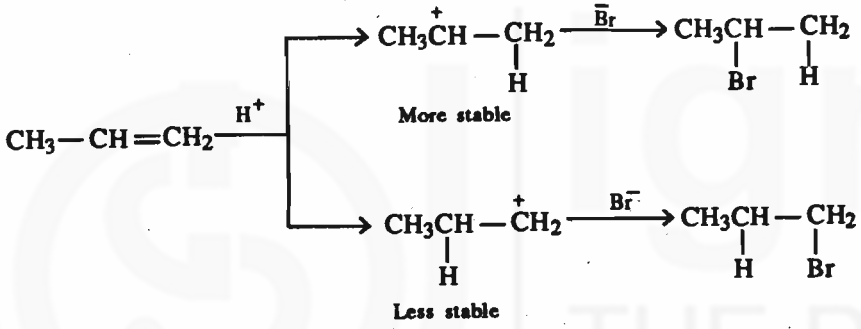
However, only one product, 2-bromopropane is produced. One would like to know why only one product is formed. A Russian chemist Valdimir Markownikoff studied this question in 1870 and made a generalisation based empirically on his observation. According to the rule named after him as, Markownikoff's rule, the addition of a hydrogen halide to an unsymmetrical alkene takes place in such a way that the negative part of the substrate goes to the carbon atom that contains lesser number of hydrogen atoms.

However, when both carbon atoms forming the double bond have the same number of hyrogen atoms in a unsymmetrical alkene, a mixture of products results. For example, when 2- pentene reacts with hydrogen bromide, it gives a mixute of 2-bromopentane and 3-bromopentane.

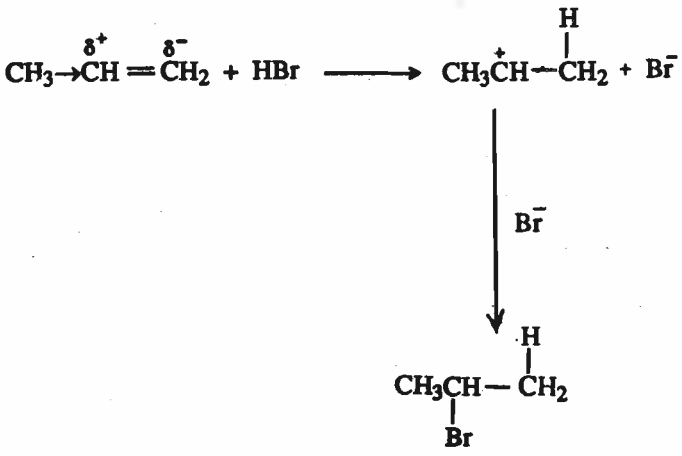


2-Pentene 2-Bromopentane 3-Bromopentane

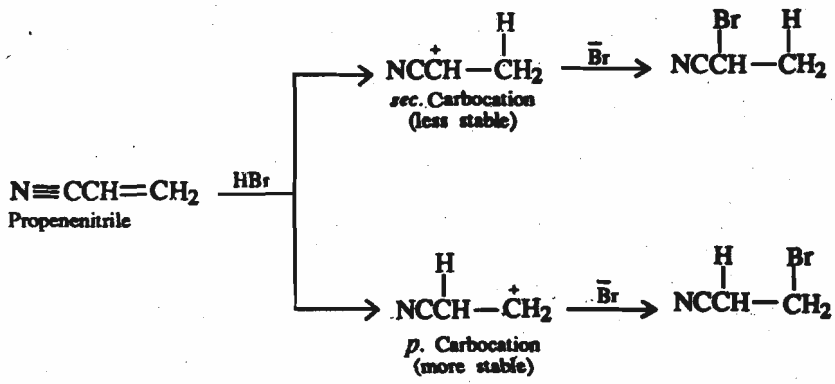
Markownikoff's rule can be explained on the basis of relative stabilities of the carbocations. In the first step i.e., the addition of H^+ to propene, there is a possibility of the formation of either primary or secondary carbocation. Since the secondary carbocation is more stable, it will form of 2-bromopropane.



We can also understand the Markownikoff's rule by considering the electronic effect of the substitutent on the double bond. For example in propene, due to +I effect of the methyl group, the π electrons are displaced towards the terminal carbon atom which acquires partial negative charge. So, the proton adds on the carbon atom farthest from the methyl group, and then the halide ion adds to the carbocation formed at the adjacent carbon atom.



Now consider another example, *viz.*, addition of HBr to propenenitrile. Addition of HBr to propenenitrile gives 1-bromopropanenitrile as the major product, which is obtained from the primary carbocation.



In the case of propene. 'rile, because of the strong electron withdrawing effect of the nitrile group, the secondary carbocation is less stable than primary carbocation. Further the carbocation is separated from the CN group by two carbon atoms and the destabilisation by the inductive effect is less.

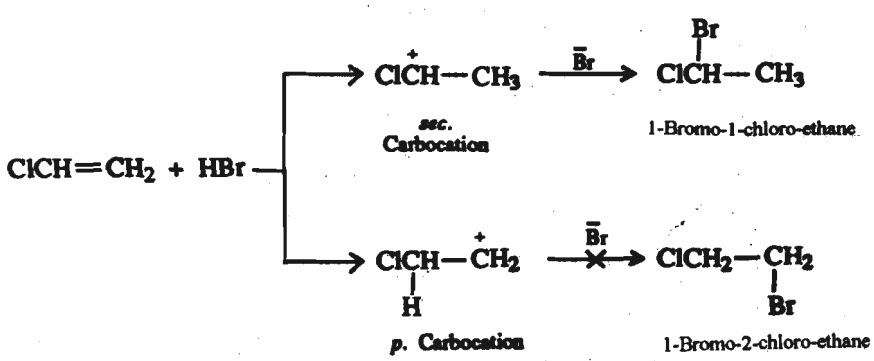
Thus, the Markownikoff's rule can be modified to the following statement — "In the addition of hydrogen halide to alkenes, the more stable carbocation is formed which then adds the negative ion to form the product." This rule is adequate to predict the orientation pattern of addition of unsymmetrical reagents to unsymmetrical alkenes. However, it may be emphasised that this rule is applicable only to the addition of electrophilic reagents.

The products formed from the addition of HBr to some substituted alkene are given in Table 5.1.

Table 5.1 : Orientation pattern addition HBr to substituted ethenes

	Alkene	Product
1.	$CH_3CH=CH_2$	$CH_3\underset{\underset{Br}{|}}{C}H-CH_3$
2.	$(CH_3)_2C=CH_2$	$(CH_3)_2\underset{\underset{Br}{|}}{C}-CH_3$
3.	$C_6H_5CH=CH_2$	$C_6H_5\underset{\underset{Br}{|}}{C}H-CH_3$
4.	$ClCH=CH_2$	$ClCH-CH_3$ (Br)
5.	$NCHC=CH_2$	$NCCH_2-CH_2Br$
6.	$(CH_3)_3N^+CH=CH_2$	$(CH_3)_3N^+CH_2-CH_2Br$
7.	$HOQCCH=CH_2$	$HOOCCH_2-CH_2Br$
8.	$F_3CCH=CH_2$	$F_3CCH_2-CH_2Br$

Entry 4 of Table 5.1 is of special interest and illustrates certain general features.

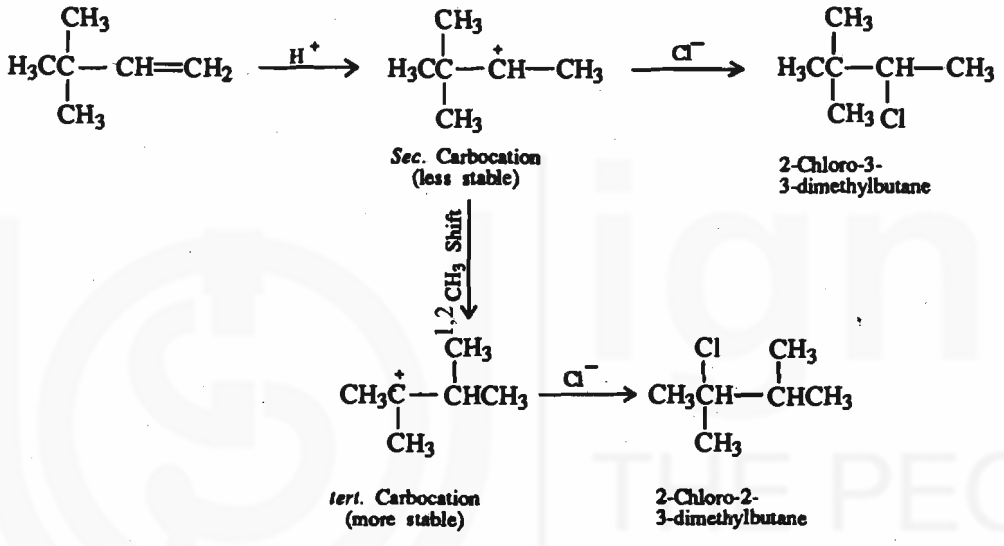


In chloroethene (and other haloethenes), the primary carbocation would be more stable due to inductive effect (similar to the addition of HBr to propenenitrile given earlier).

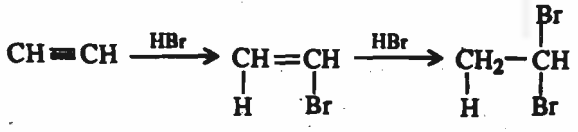
If this were the only effect in operation, the prodcut would be 1-bromo-2-chloroethane because its corresponding carbocation is more stable. There is, however, another effect arising from delocalisation of the lone pair on the chlorine atom with the vacant *p*-orbital of carbocation at C-2 (resonance effect) which stabilises the secondary carbocation. The question is, which of these effects predominates? Formation of 1-bromo-1-chloroethane implies that the lone apir effect apparently prevails over the inductive effect rendering secondary carbocation stabler than the primary carbocation.

Rearrangements take place in other electrophilic additions like hydration, halogenation, etc. also.

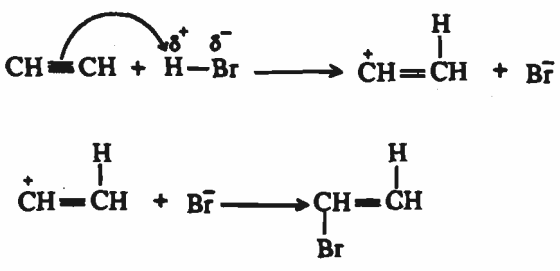
Rearrangement: Rearrangement is one of the characteristics of a carbocation. A carbocation formed, in an addition reaction of a hydrogen halide to an unsymmetrical alkene, often undergoes rearrangement (alkyl or hydride shift) to give a more stable carbocation. For example, addition of HCl to 3,3-dimethyl-1-butene gives two products, 2-chloro-3,3-dimethyl butane (normal product) and 2-chloro, 2,3-dimethylbutane (rearranged product) as shown in following scheme:



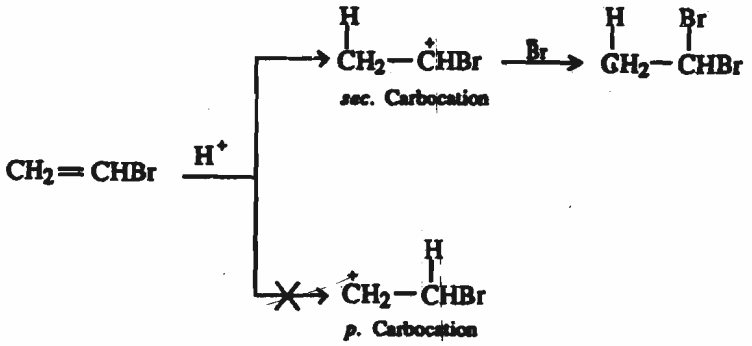
Alkynes also undergo hydrohalogenation. Like alkenes, the addition is in accordance with Markownikoff's rule. For example, ethyne reacts with hydrogen bromide to form first 1-bromoethene and then 1,1-dibromoethane.



The mechanism of the reaction is same as in the hydrohalogenation of alkenes. Addition of one molecule of HBr gives bromoethene.



Addition of another molecule of hydrogen bromide could give either secondary carbocation, or a primary carbocation. Since the former is more stable than the latte. the reaction proceeds via the former to form 1,1-dibromoethane, i.e.,



Because of the electron withdrawing nature of bromine atom, the availability of π electrons in 1-bromoethene is less than that in ethyne. Hence addition of HBr to 1-bromoethene is much slower than to ethyne.

SAQ 1

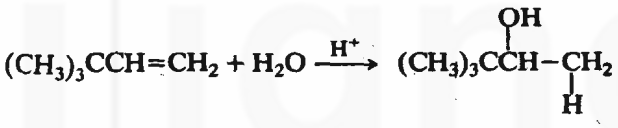
Predict the relative rates of the following alkenes towards HBr

a) $CH_3CH_2CH{=}CH_2$ b) $CH_2{=}CH_2$ c) $CH_3CH_2CH{=}C(CH_3)_2$

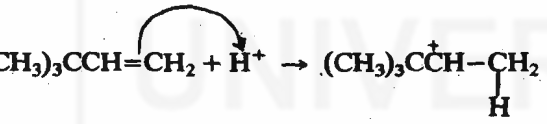
.....

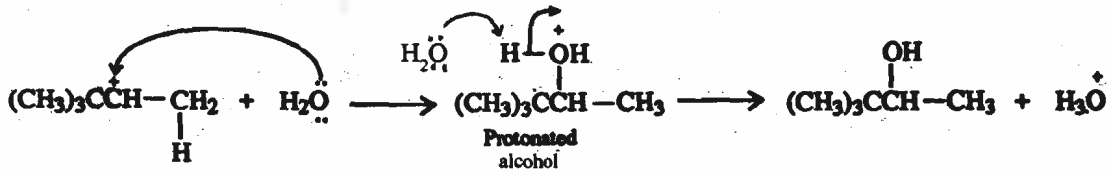
5.2.2 Addition of Water

In the presence of a mineral acid, water adds to the carbon-carbon double bond to give an alcohol. This reaction is called hydration of an alkene.

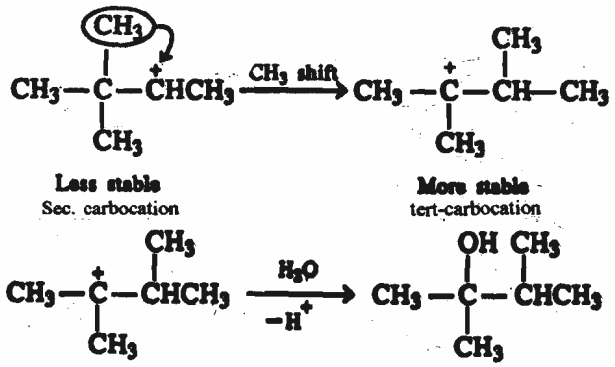


This reaction also follows Markownikoff's rule, a pattern with which we are now familiar. As expected, the reaction occurs in two steps. The alkene is first protonated to give a carbocation. Attack of the nucleophile (H_2O) on the carbocation, in the second step, and loss of a proton from the resulting adduct completes the reaction.

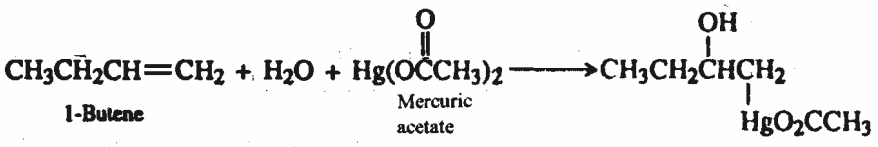


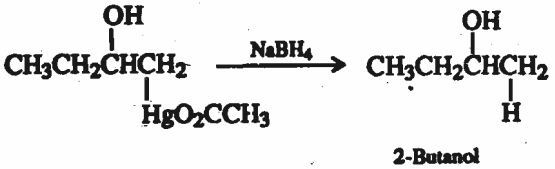


Because a carbocation is involved, rearrangement is possible. Carbocation can undergo a 1,2-shift of CH_3 group to yield the more stable carbocation, e.g.



Another method used to accomplish Markownikoff's hydration of an alkene is **oxymercuration-demercuration**. Alkene reacts with mercuric acetate in the presence of water to give hydroxy-mercurial compounds which on reduction accomplishes demercuration and produces an alcohol. The product of oxymercuration is usually reduced with sodium borohydride ($NaBH_4$). Oxymercuration-demercuration reaction usually gives a better yield of alcohols than acid catalysed hydration.

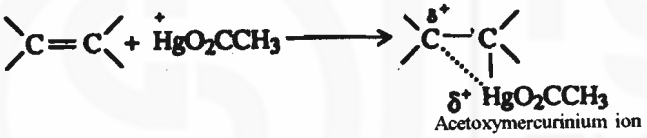




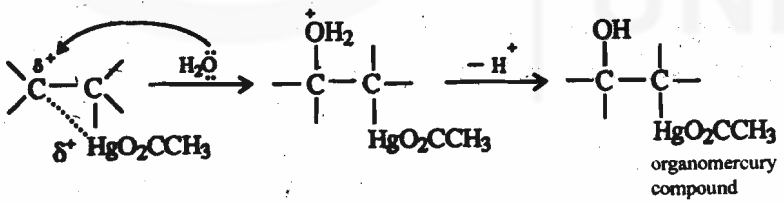
Mechanism: The mechanism of oxymercuration is very similar to that of hydrohalogenation. First mercuric acetate dissociate into $\overset{+}{H}gO_2CCH_3$ and $\bar{O}_2CCH_3$ e.g.,

$$Hg(O_2CCH_3)_2 \rightleftharpoons \overset{+}{H}gO_2CCH_3 + \bar{O}_2CCH_3$$

In the first step electrophile $\overset{+}{H}gO_2CCH_3$ attacks the carbon-carbon double bond and forms a cyclic intermediate called acetoxymercurinium ion.



In the next step nucleophile H_2O attacks on the partially positively charged carbon atom from the side opposite to mercury to give the stable organomercury compound. The organomercury compound on reduction with $NaBH_4$ gives alcohol. We will study about the reduction by $NaBH_4$ in Unit 8.



Oxymercuration is regiospecific and stereospecific (*anti* addition). The stereospecificity is attributed to formation of a cyclic intermediate.

Like alkenes addition of water to alkyne should give alcohol, e.g.,

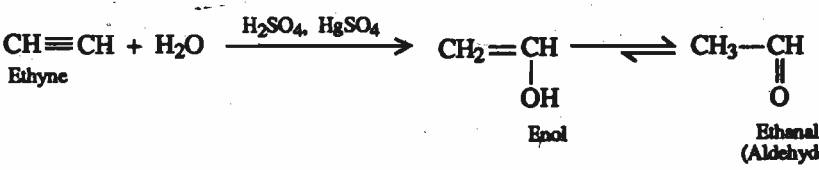
$$RC{\equiv}CR + H_2O \xrightarrow{H^+} RCH{=}\overset{OH}{C}R$$

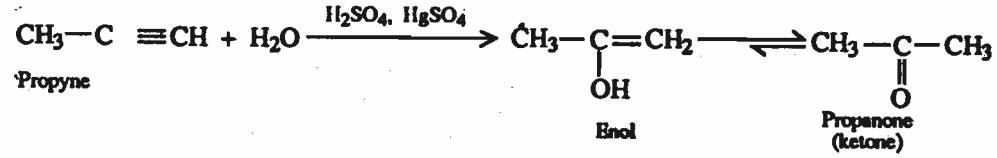
The alcohol produced by hydration of an alkyne, however, is of a special kind known as enol. As the name (en-ol) indicates it has OH group attached to a carbon atom forming a double bond. Infact enols are very unstable and generally undergo isomerization (tautomerism) to give either an aldehyde or a ketone.

$$RCH{=}\overset{OH}{C}R \rightleftharpoons RCH_2{-}\overset{O}{\overset{\|}{C}}R$$

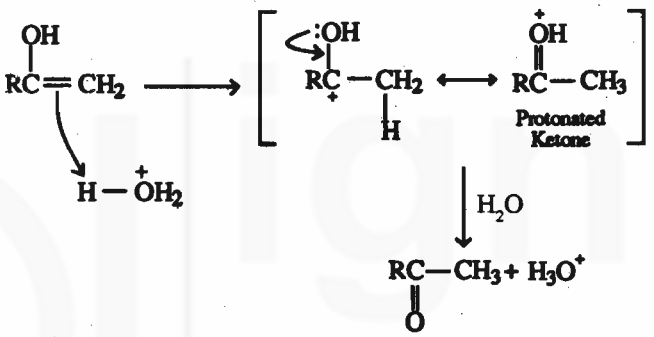
Keto-enol tautomerism does not require acid catalysis though acids expedite the equilibrium.

Enols are converted to aldehydes or ketones by prototropic shift, i.e., shift of a proton from oxygen to carbon. This phenomenon is known as **Keto-enol tautomerism**, and the individual compounds are known as **tautomers**. For example, when ethyne reacts with water, it gives ethanal, an aldehyde, while 1-propyne gives propanone a ketone, i.e.,

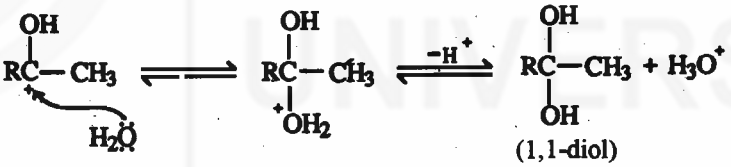




The enol is converted into aldehyde or ketone by a mechanism that is similar to hydration of a double bond. The enol double bond is protonated to give a carbocation. The carbocation in this example, as its resonance structures show, is a protonated ketone. Instead of adding water, this ion loses a proton to give ketone.

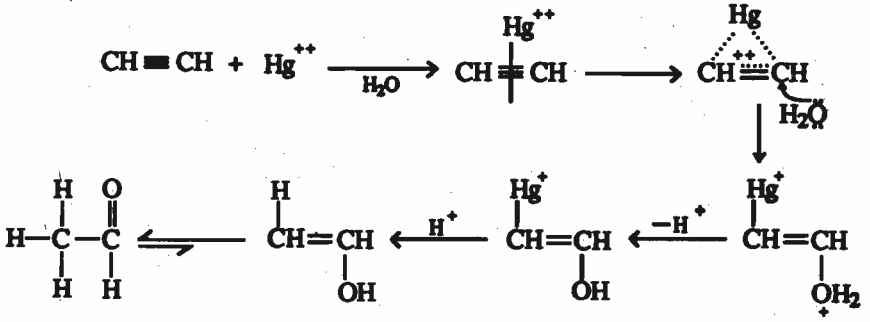


You may now ask why the carbocation is not attacked by a water molecule., i.e. ?



The answer is that this reaction is reversible and the equilibrium between the ketone and the corresponding diol in most cases favours ketone.

Alkynes cannot be hydrated as easily as simple alkenes, because of their lower reactivity towards electrophilic addition. However, in the presence of mercuric sulphate, a catalyst, hydration occurs readily. A possible explanation of the function of the catalyst is that Hg^{++} ion being of a large size, readily forms a bridged ion, a π complex, which then reacts as shown below:



SAQ 2

Predict the product(s) of the following reactions

a) $(CH_3)_3CCH=CH_2 + H_2O \xrightarrow{H^+}$

b) $CH_3CH_2CH=CH_2 + H_2O + Hg(OCCH_3)_2 \rightarrow \underset{\text{.....}}{A} \xrightarrow{NaBH_4} \underset{\text{.....}}{B}$

c) $CH_3C{\equiv}CH + H_2O \xrightarrow{H^+}$ .....

5.2.3 Addition of Halogen

Treatment of alkenes with halogens gives 1,2-dihalogenated alkanes or dihalides. Bromine and chlorine are effective electrophilies. This reaction is by far the best method of preparing vicinal dihalides, e.g.,

$$CH_2=CH_2 + Br_2 \xrightarrow{CCl_4} \underset{\text{1,2-Dibromoethane}}{CH_2(Br)-CH_2(Br)}$$

$$CH_3C(CH_3)=CH_2 + Cl_2 \xrightarrow{CCl_4} \underset{\text{1,2-Dichloro 2-methyl propane}}{CH_3C(CH_3)(Cl)-CH_2(Cl)}$$

Fluorine and iodine generally do not add to the carbon-carbon double bond or carbon-carbon triple bond. Fluorine undergoes explosive reaction with alkenes or alkynes, the reaction, therefore, require special techniques. Addition of iodine to alkene is a reversible reaction, i.e., the 1,2-diiodo product is unstable and loses I_2 to reform the alkene.

$$>C=C< + I_2 \rightleftharpoons >C(I)-C(I)<$$

These reactions are generally carried out in an inert solvent (e.g., CCl_4). Since at high temperature substitution products may be formed, hence these reactions are carried out at room temperature.

Like alkenes, alkynes also react with chlorine and bromine to yield tetrahaloalkanes. Two molecules of halogen add to the triple bond. A dihaloalkene is an intermediate and can be isolated using proper reaction conditions. Ethyne, for instance, on treatment with bromine water gives only 1,2-dibromoethene whereas with bromine alone, it forms 1,1,2,2-tetraboromoethane.

$$\underset{\text{Ethyne}}{HC{\equiv}CH} \xrightarrow{Br_2 \text{ water}} \underset{\text{1,2-Dibromoethene}}{HC(Br)=CH(Br)}$$

$$HC{\equiv}CH \xrightarrow{Br_2} \underset{\text{1,1,2,2,-Tetrabromoethane}}{HC(Br)_2-CH(Br)_2}$$

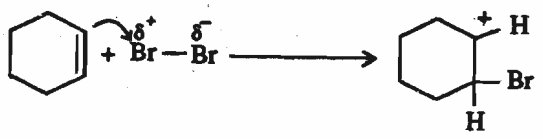
Addition of halogens to ethyne is stereoselective; the predominant product is the *trans* isomer.

$$HC{\equiv}CH + X_2 \longrightarrow \underset{\textit{trans} \text{ Product}}{H(X)C=C(X)H}$$

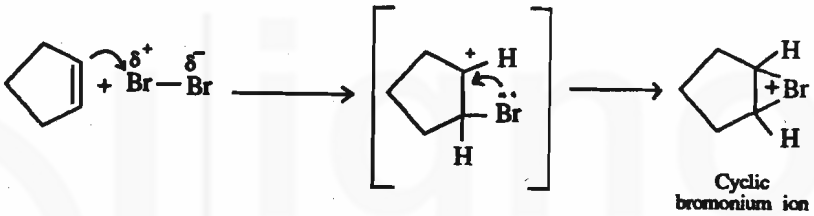
This reaction is very useful for detection of the carbon-carbon double bond. The test reagent (Br_2 in CCl_4) has a reddish brown colour of bromine while the dihalide is colourless. After addition of Br_2 to carbon-carbon double bond, rapid decolourisation occurs, which confirms the presence of carbon-carbon double bond.

Mechanism: Although bromine is non-polar, it is nevertheless highly polarisable. In the vicinity of carbon-carbon double bond, the bromine molecule becomes polarised and, hence, partial positive charge (δ^+) is developed on one bromine atom and partial negative (δ^-) charge is developed on the other bromine atom.

In the first step, the π electrons attack the positive end of the polarised bromine molecule, displacing bromide ion and forming carbocation.

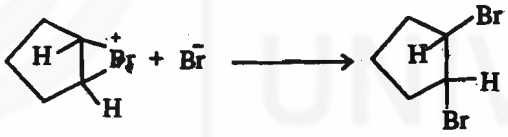


Immediately in the next step, $B\bar{r}$ attacks the carbocation to yield the additon product. Since carbocation is coplanar,, and sp^2 hybridised, $B\bar{r}$ can attack from both the sides to give a mixture of *cis* and *trans* products. However, only the *trans* product was observed. The explanation was suggested in 1937 by Kimball and Roberts who postulated that true reaction intermediate is not a carbocation but a cyclic bromonium ion.



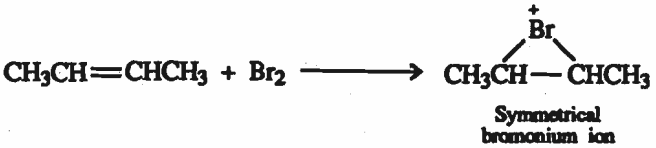
Cyclic bromonium ion

The bromide ion must attack from the rear side of the leaving group in the nucleophilic displacement reaction. Therefore, the bromide ion attacks exclusively on the side opposite to the bromonium ion to yield only the *trans* product. This is also known as *anti* addition.

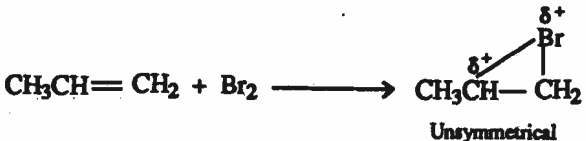


trans Product

Addition of Br_2 to a symmetrical alkene gives a symmetrical bromonium ion. However, addition of Br_2 to an unsymmetrical alkene gives an unsymmetrical bromonium ion, in which, most of the positive charge is carried on the more substituted carbon. i.e.,



Symmetrical bromonium ion

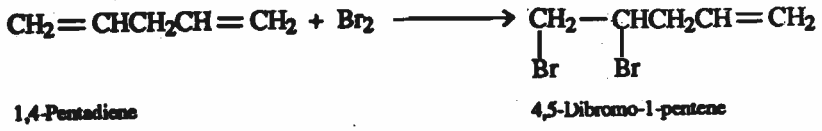


Unsymmetrical bromonium ion

In the symmetrical bromonium ion the attack by a nucleophile could take place at either carbon. However, in case of unsymmetrical bromonium ion the nucleophile will attack the more substituted carbon.

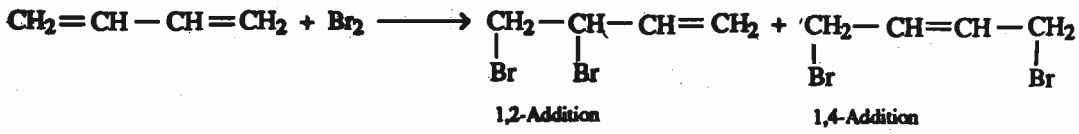
5.2.4 Addition to Conjugated Dienes

In isolated diene both the double bonds react independently, as though they are in different molecules. Reaction of an isolated diene say 1,4-pentadiene with bromine gives 4,5-dibromo-1-pentene.



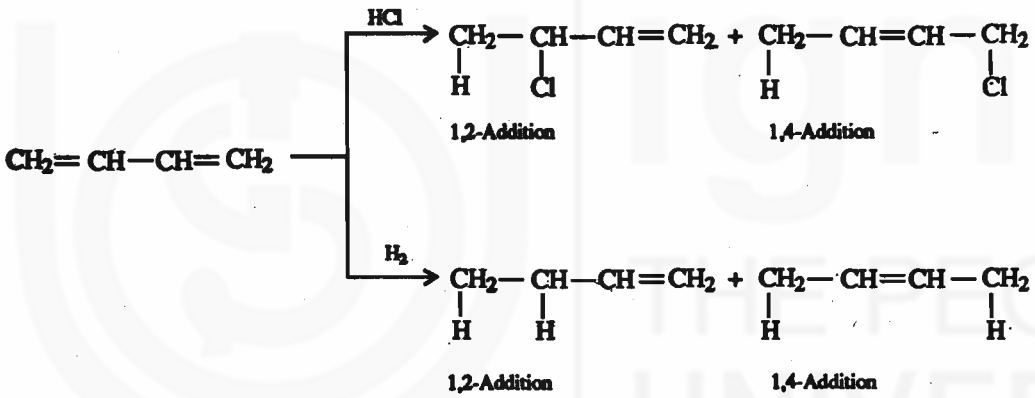
1,4-Pentadiene — 4,5-Dibromo-1-pentene

Conjugated dienes behave differently from isolated dienes. Conjugated dienes undergo normal as well as unexpected addition reactions. When a conjugated diene, say 1,3-butadiene is treated with bromine, two dibromo derivatives are obtained. One of these is the expected 3,4-dibromo-1-butene due to 1,3-butadiene. The first step the unexpected 1,4-dibromo-2-butene due to 1,4-addition (major product).



1,2-Addition — 1,4-Addition

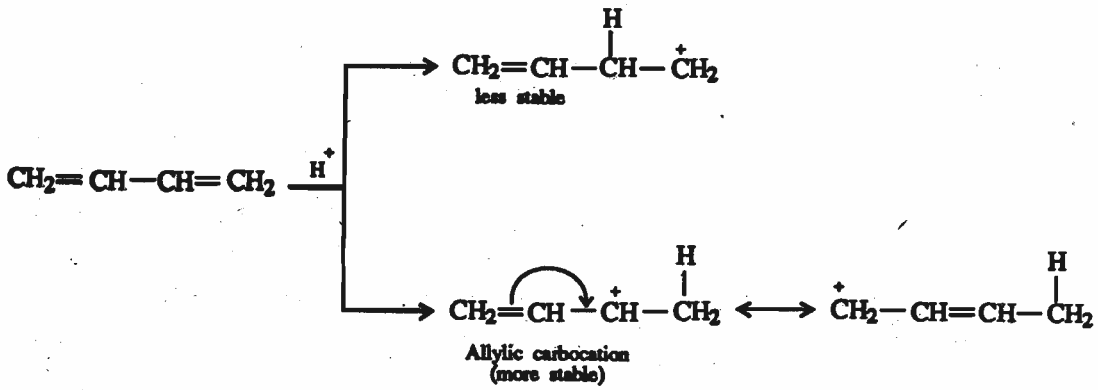
Similarly reactions of HCl and H_2 with conjugated diene provide not only 1,2-addition product but also 1,4-addition product, e.g.



1,2-Addition — 1,4-Addition

1,2-Addition — 1,4-Addition

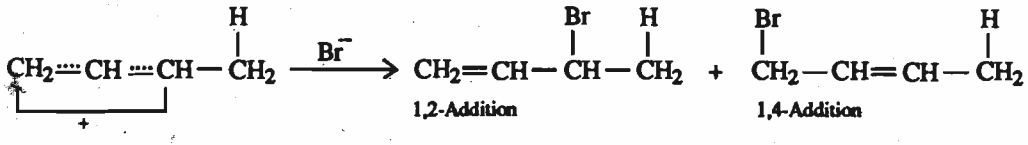
Addition at 1,2-position is understandable but how can we account for the products that are obtained due to 1,4-addition. To understand this, let us examine the mechanism of the addition of hydrogen bromide to 1,3-butadiene. The first step involves the formation of carbocation. Hydrogen may attach itself to either C_1 or C_2. The addition of the hydrogen at C_2 would give rise to a unstable primary localised carbocation. But the addition at C_1 results in the formation of resonance stabilised allylication. This also explain the enhanced reactivity of dienes over isolated double bonds.



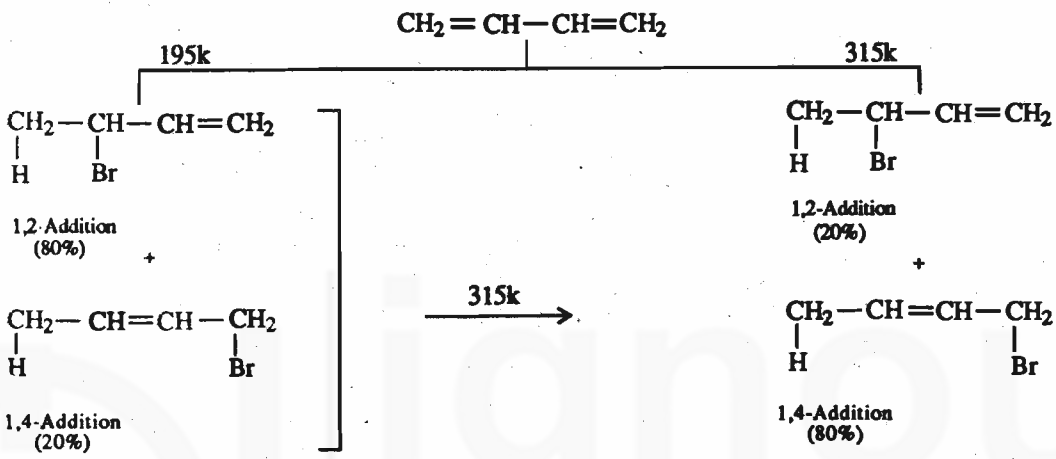
less stable

Allylic carbocation (more stable)

In the second step Br^- can attack at either C_1 or C_3 since both share the positive charge. Thus a mixture of 1,2- and 1,4-addition products is obtained.

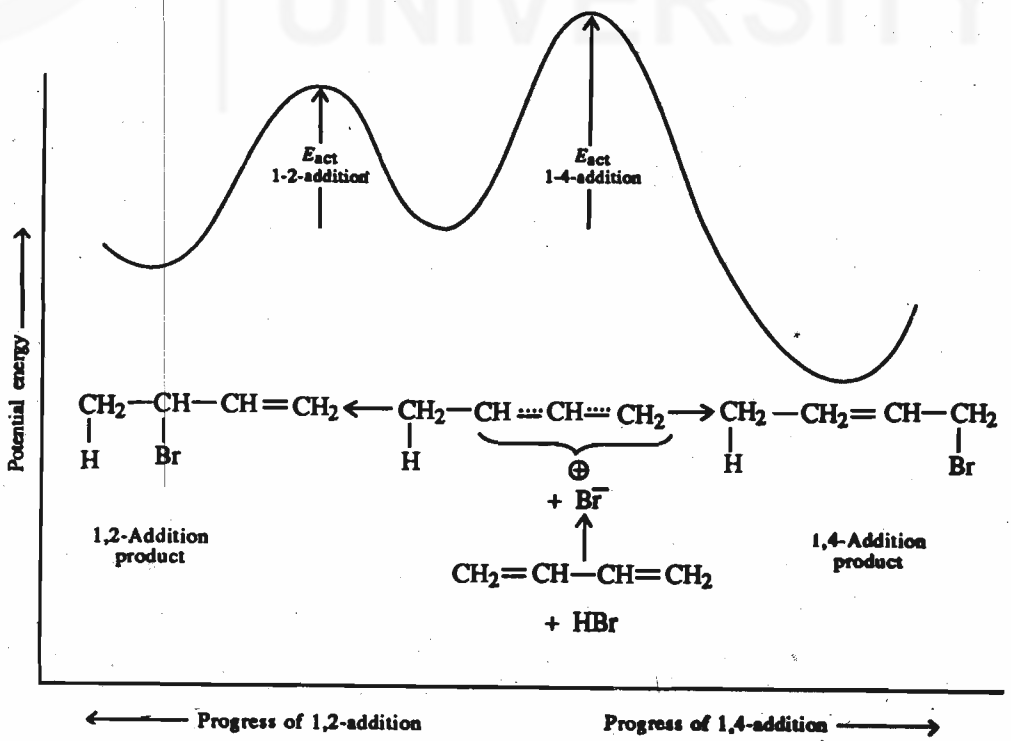


Now one can ask whether these two products are formed in equal amounts or in different ratio. It is interesting to note that the product composition in these reactions varies at different temperature. To understand this take the example of addition of HBr to 1,3-butadiene. HBr when added to 1,3-butadiene at low temperature (195 K), the 1,2-product (80%) predominates over 1,4-product (20%). While at higher temperature (5 K) the 1,4-product (80%) predominates over 1,2-product (20%). At intermediate temperature, a mixtures of intermediate composition are obtained.



It has also been observed that warming 1,2-product to 315 K with a trace of acid results in an equilibrium mixture in which 1,4-product predominates.

How can we explain these observations? Let us examine the reaction by drawing a potential energy diagram (Fig. 5.1). At low temperature, the addition of HBr to 1,3-butadiene gives 80% 1,2-product. This shows that 1,2-addition has the low energy of activation (E_{act}) and thus, the 1,2-product is formed faster than the 1,4-product. The relative rates of the reaction control the product ratio.



At higher temperature, a greater percentage of molecules can reach the higher-energy state, and the more stable, 1,4-product predominates. At higher temperature, the relative stabilities of the products control the product ratio. Thus, we can say 1,2-product is kinetically controlled while the 1,4-product is thermodynamically controlled.

Formation of 1,4-product can also be explained on the basis of electrometic effect. Butadiene can undergo the electromieric effect in two stages.

i) $CH_2=CH-CH=\overset{\curvearrowright}{C}H_2 \longrightarrow CH_2=CH-\overset{+}{C}H-\bar{C}H_2$

ii) $CH_2=\overset{\curvearrowright}{CH}-CH=\overset{\curvearrowright}{C}H_2 \longrightarrow \overset{+}{C}H_2-CH=CH-\bar{C}H_2$

Second ionic species is more stable as the charges are further apart in this as compared with the first. In an ionising solvent the addition of Br_2 takes place in the second species to give 1,4-addition product.

$$\overset{+}{C}H_2-CH=CH-\bar{C}H_2 + Br-Br \longrightarrow \overset{+}{C}H_2-CH=CH-\underset{Br}{CH_2} + \bar{B}r$$

$$\overset{+}{C}H_2-CH=CH-\underset{Br}{CH_2} \xrightarrow{Br^-} \underset{Br}{CH_2}-CH=CH-\underset{Br}{CH_2}$$

SAQ 3

Fill in the blanks:

a) When a conjugated diene is treated with halogen it gaves normal ..... product and unexpected ..... product.

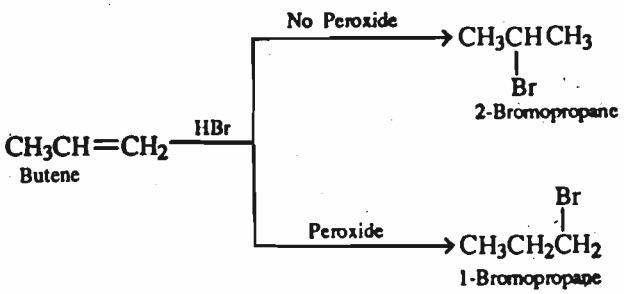
b) Addition of H^+ to 1,3-butadiene gives ..... carbocation and ..... carbocation.

c) When HBr is added to 1,3-butadiene at low temperature ..... predominate and at high temperature ..... predominates.

d) In the addition of HBr to conjugated diene the ..... is kinetically controlled and the ..... is thermodynamically controlled.

5.3 FREE RADICAL ADDITION REACTIONS

The above discussion may give you the impression that addition of hydrogen halides to unsaturated hydrocarbons always gives Markownikoff's product. But it is not so. After extensive study of the mechanism of addition of HBr to different alkenes, it was found by Kharasch and Mayo that in the presence of a peroxide the product obtained was contrary to Markownikoff's rule. Such additions are sometimes referred to as anti-Markownikoff additions. Since the orientation is reversed in the persence of a peroxide, this is also known as the peroxide effect. For example, the addition of hydrogen bromide to propene in the presence of peroxides gives 1-bromopropane rather than 2-bromopropane. However, this effect is not observed with HCI or HI.

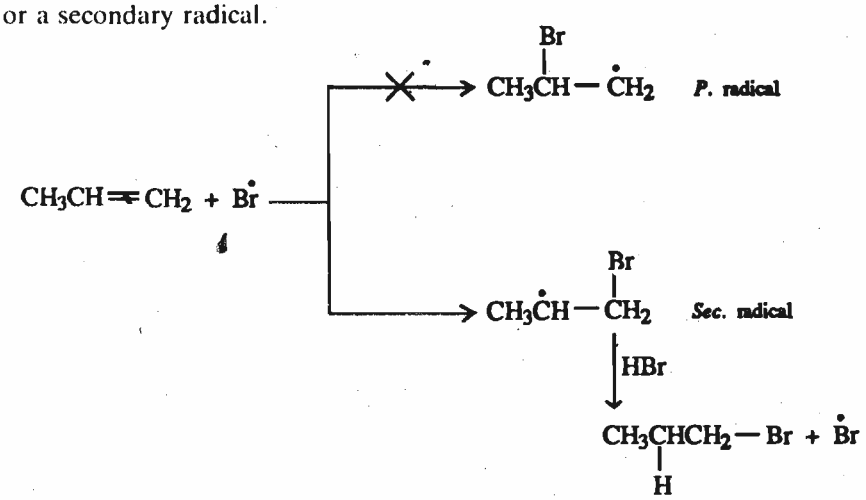


The intermediate in the peroxide catalysed reaction is a free radical and not a carbocation. The function of peroxide is to generate the free radical

$$(RCO_2)_2 \longrightarrow 2R\dot{C}O_2 \longrightarrow 2\dot{R} + 2CO_2$$

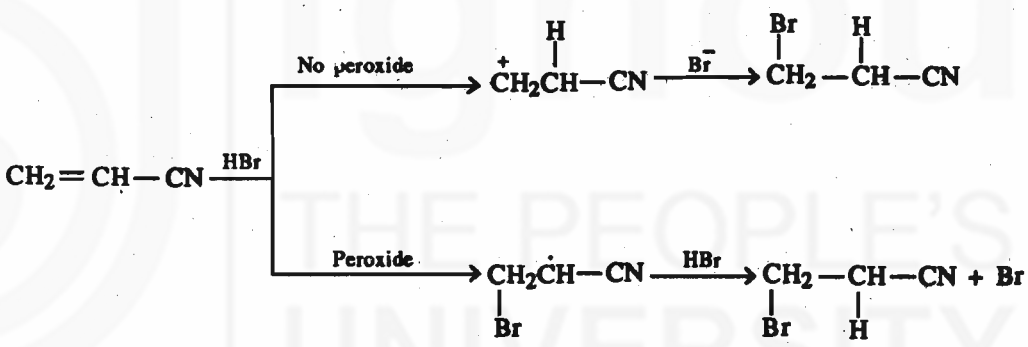
$$\dot{R} + HBr \longrightarrow RH + \dot{B}r$$

Bromine radical can add to either of the two carbon atoms producing either a primary or a secondary radical.



The bromine radical prefers to react at the terminal carbon to give a secondary radical because, the secondary radical is more stable than a primary radical. The orientation of addition of the free radical is controlled on the principle that it takes place in a manner such that the more stable radical, of the possible alternatives, is generated. Consequently, the final product of reaction of HBr is (in presence of peroxide) generally the one with bromine attached to the less substituted carbon atom.

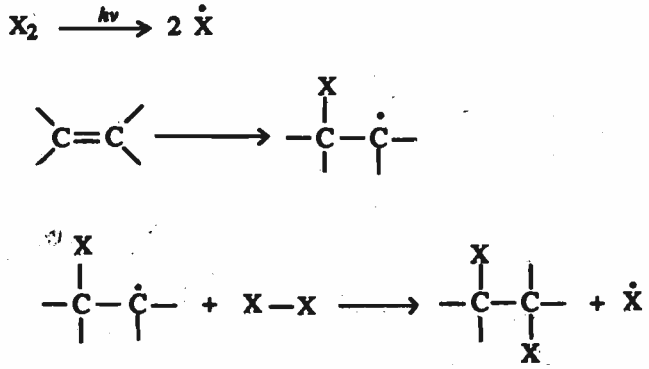
Now let us take the example of propenenitrile. How would propenenitrile react with HBr in the presence of peroxides? Reaction of propenenitrile with HBr both in the presence as well as and in the absence of peroxide yields 1-bromopropanenitrile



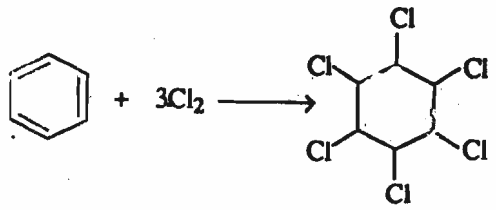
We see that the same product is formed by an entirely different mechanisms. On the basis of the principles discussed above, it is possible to predict the direction of orientation in either case.

Now let us see what is the stereochemistry of free radical addition?. In most of the reported cases, it is *trans*. 1-Bromocyclohexene reacts with HBr in the presence of peroxide to give *cis* 1,2-dibromocyclohexane, in which the two components of the addendum, viz., H and Br have *trans* stereochemistry.

In section 5.2.3 you have studied the halogenation of alkene by ionic mechanism. Halogenation of alkenes can also be carried in the presence of light or peroxides, which follows free radical mechanism as shown below:



An industrial process involving addition of free radicals across double bonds is the reaction of chlorine with benzene in presence of light. Of the theoretically possible eight isomers only three, viz., α, β and γ are formed in substantial amounts. It is well known that the γ-isomer, called gammexane is a potent insecticide.



In this process chlorine radical is formed by homolytic fission of Cl_2.

You will study free radical addition reactions in more detail in Unit 10.

SAQ 4

Complete the following reactions

a) $CH_3C{=}CH_2 + HBr \xrightarrow{\text{Peroxide}}$ .....

b) $CH_2{=}CHCN + HBr \xrightarrow{\text{Peroxide}}$ .....

c) $CH_2{=}CHCN + HBr \longrightarrow$ ....

5.4 CONCERTED ADDITION REACTIONS

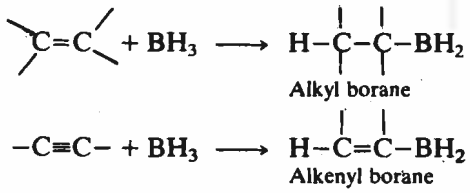
In contrast to electrophilic addition reaction there are group of reagents which react with double bond from the same face of the double bond. These do not involve highly charged intermediates like carbocation. These are known as concerted addition reactions. Some important examples of concerted addition reactions are discussed below.

5.4.1 Hydroboration

Organoboranes were discovered in the 1950s by Herbert C. Brown, who was awarded a Nobel Prize in 1979 for his work with organoboron compounds.

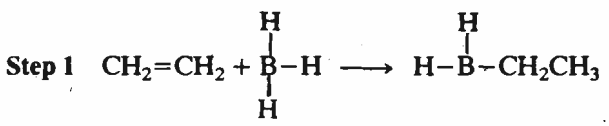
Hydroboration is a reaction in which diborane, $(BH_3)_2$ adds to a carbon-carbon double bond or carbon-carbon triple bond to yield an organoborane. A new carbon-hydrogen bond and a new carbon-boron bond are formed.

Addition of borane to alkenes gives alkyl boranes while addition of borane to an alkyne gives alkenyl borane.

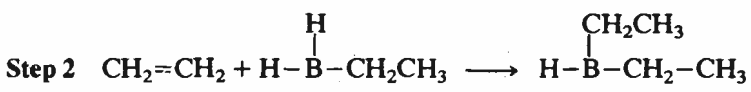


This reaction is very facile and requires only a few seconds for completion at 275 K and gives organoboranes in quantitative yield in ether solvents.

The addition takes place in a stepwise fashion via successive addition of each boron hydrogen bond to the alkene. The sequence of reaction is called **hydroboration**.



Borane (BH_3) itself is unknown but its dimer, diborane (B_2H_6) behaves as if it were the hypothetical monomer.



Step 3 $CH_2=CH_2 + H-B(CH_2CH_3)_2 \longrightarrow B(CH_2CH_3)_3$

Triethyl borane

Sometimes the hydroboration reaction is described as *anti*-Markownikoff's addition. This is true only in a literal sense, because in this reaction hydrogen is the electronegative portion of the molecule instead of being the electropositive portion as in other cases.

$$CH_3CH=CH_2 \longrightarrow CH_3CH(H)-CH_2(BH_2)$$

As shown above, hydrogen (as a hydride ion, $\bar{H}$) goes to the more substituted carbon atom. The result appears to be *anti*-Markownikoff's addition.

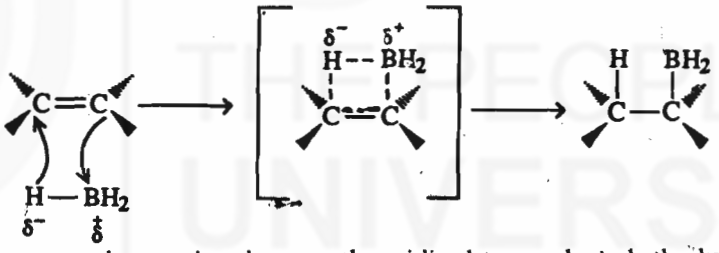
The ease of reaction decreases with the increase in the alkyl substituents on the double bond, e.g., trisubstituted alkenes form dialkylboranes and tetrasubstituted alkenes yield only monoalkylboranes.

$$(CH_3)_2C=CHCH_3 \xrightarrow{(BH_3)_2} (CH_3)_2CH-CH(CH_3)-BH-CH(CH_3)-CH(CH_3)_2$$

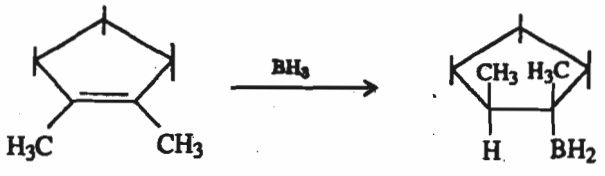
$$(CH_3)_2C=C(CH_3)_2 \xrightarrow{(BH_3)_2} (CH_3)_2CH-C(CH_3)_2-BH_2$$

Stereochemistry

In hydroboration the boron and the hydride ion add to the two carbon atoms of the double bond simultaneously. This means that B and H must add from the same side of the double bond. Such addition reactions are called *cis*-additions or *syn*-additions.



When an organoborane is subsequently oxidised to an alcohol, the hydroxyl group ends up in the same position as the boron atom that it has replaced, that is, with the retention of configuration at that carbon.

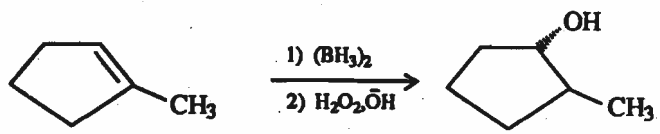


The organoboranes are versatile compounds capable of undergoing a variety of chemical transformations. Some important reactions of organoboranes are given below:

i) One of the most important reactions of organoboranes is H_2O_2 oxidation. Oxidation of an organoborane by alkaline H_2O_2 gives the corresponding alcohol. It appears as if water had been added to the double bond in an *anti*-Markownikoff's manner.

$$3\,CH_3CH_2CH=CH_2 \xrightarrow{BH_3} (CH_3CH_2CH_2CH_2)_3B \xrightarrow{H_2O_2,\ \bar{O}H} 3\,CH_3CH_2CH_2CH_2OH$$

1-Butanol

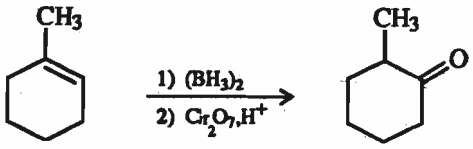


$$CH_3C{\equiv}CCH_3 \xrightarrow{(BH_3)_2} CH_3\overset{>B\ H}{\overset{|}{C}}{=}\overset{|}{C}CH_3 \xrightarrow{H_2O_2,\ \bar{O}H}$$

$$CH_3\overset{OH}{\overset{|}{C}}{=}\overset{H}{\overset{|}{C}}CH_3 \rightleftharpoons CH_3\overset{O}{\overset{\|}{C}}CH_2CH_3$$

2-Butanone

ii) Oxidation of organoboranes with chromic acid yields carbonyl compounds.

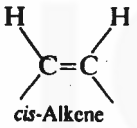


iii) Organoboranes are readily cleared to alkanes by treating with carboxylic acid. Thus, the acid-hydrolysis of organoboranes provides a useful method for carrying out hydrogenation of alkenes and also of alkynes.

$$3\,CH_3CH{=}CH_2 \xrightarrow{(BH_3)_2} (CH_3CH_2CH_2)_3B \xrightarrow{3\,CH_3COOH} 3\,CH_3CH_2CH_3$$

1-Propene — Propane

$$-C{\equiv}C- \xrightarrow[2.\ CH_3COOH]{1.\ (BH_3)_2}$$



cis-Alkene

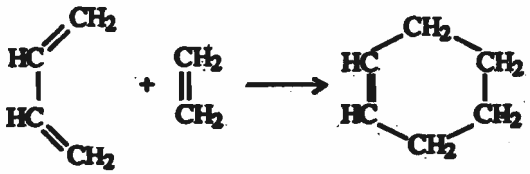
iv) Reaction of trialkyl boranes with alkaline silver nitrate solution induces a coupling reaction and hence provides a method for the synthesis of higher alkanes.

$$2[(CH_3)_2CHCH_2]_3B \xrightarrow[275\ K]{AgNO_3/NaOH} 3CH_3\overset{CH_3}{\overset{|}{C}}HCH_2CH_2\overset{CH_3}{\overset{|}{C}}HCH_3$$

2,5-Dimethylhexane

5.4.2 Diels-Alder Reaction

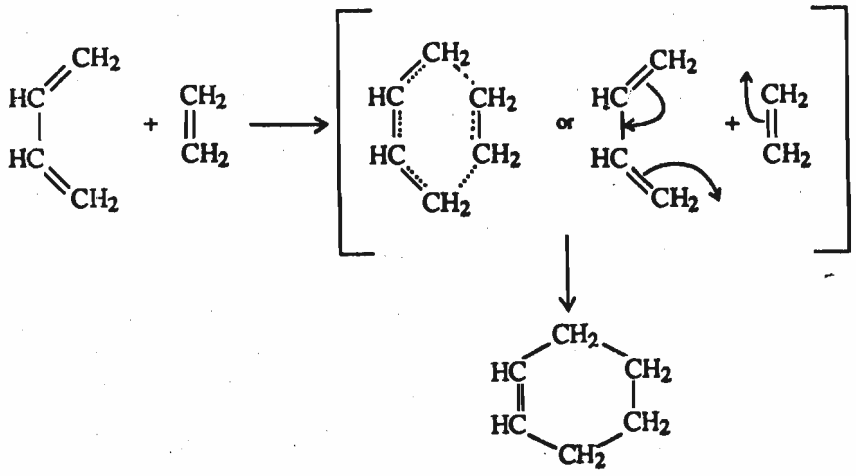
In Diels-Alder reaction, a conjugated diene is treated with certain unsaturated compounds called the dienophiles (diene-lover), to yield an adduct. This is a 1,4-addition of an alkene to a conjugated diene. This reaction is named after the German chemists Otto Diels and Kurt Alder. It is an exceedingly useful reaction used for synthesising cyclic systems. The simplest Diels-Alder reaction is the reaction of 1,3-butadiene and ethene to yield cyclohexene, i.e.,



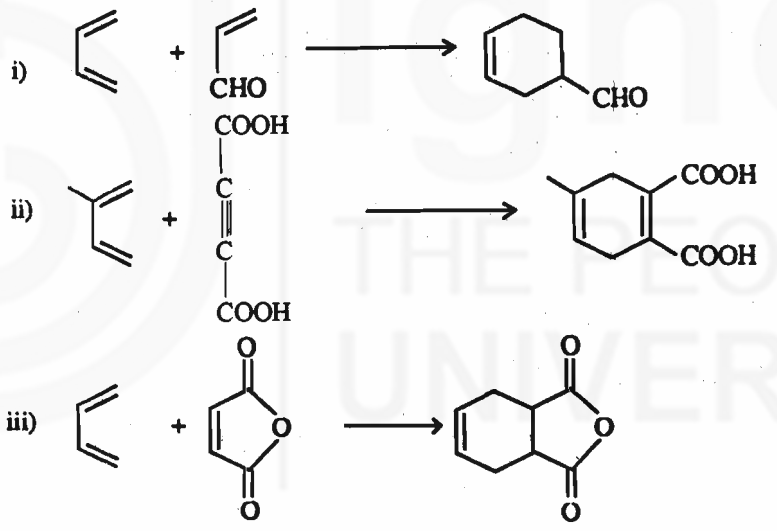
This is very slow reaction and occurs only under the conditions of heat and pressure. However, this reaction takes place most rapidly giving high yields if the alkene component contains electron withdrawing groups or the diene has electron donating groups.

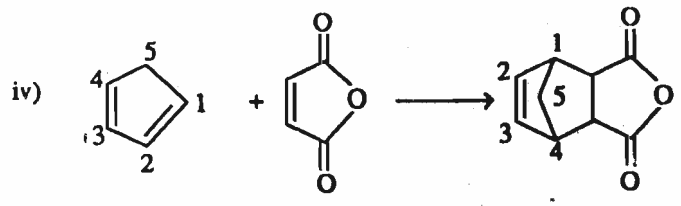
The reaction has a wide scope because also compounds containing multiple bonds other than carbon-carbon double bond may be used. When cyclic dienes are used in the Diels-Alder reaction, bicyclic adducts result. An especially important cyclic diene is cyclopentadiene.

Mechanism: The mechanism of Diels-Alder reaction is quite different from all others we have studied. It is neither a polar reaction nor a free radical reaction, rather it is concerted (one step) pericyclic process. Both new carbon-carbon single bonds and the new π bond are formed simultaneously, just as the three π bonds in the starting materials break. The concerted nature of the transformation can be shown as a delocalised transition state in which all six π electrons are indicated by dotted line or by the electron pushing technique.

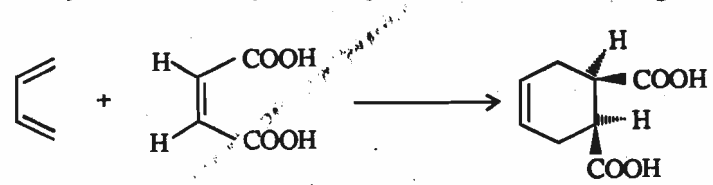


Some important examples of Diels-Alder reaction are given below:

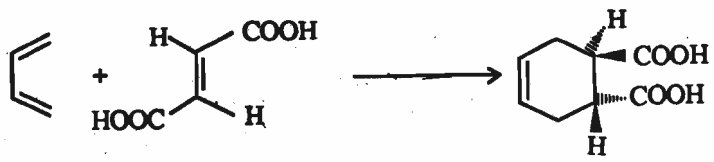




Another important feature of the Diels-Alder reaction is that it is stereospecific.. The stereochemistry of the starting dienophile is maintained during the reaction. For example, maleic acid gives a *cis* product and fumaric acid gives a *trans* product, e.g.,



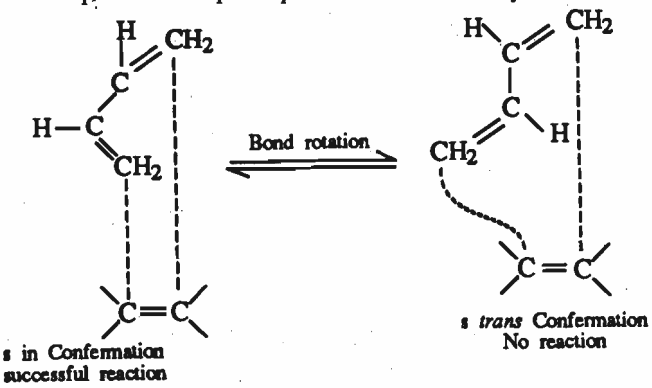
Maleic acid *cis* Acid



Fumaric acid

trans Acid

To undergo the Diels-Alder reaction, a diene must be able to adopt a *s-cis* geometry (*cis-like* about the single bond) only. The carbon atoms 1 and 4 of the diene in *s-cis* conformation are close enough to react through a cyclic transition state to give a new ring. In the alternative *s-trans* geometry, the ends of the diene are too far apart to overlap the dienophile *p*-orbitals effectively.

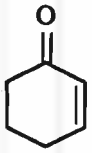
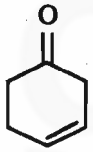


s in Confermation successful reaction

s *trans* Confermation No reaction

SAQ 5

Which of the following alkenes would you expect to be good Diels-Alder dienophiles?

a) $CH = CHNO_2$ b)  c)  d) 

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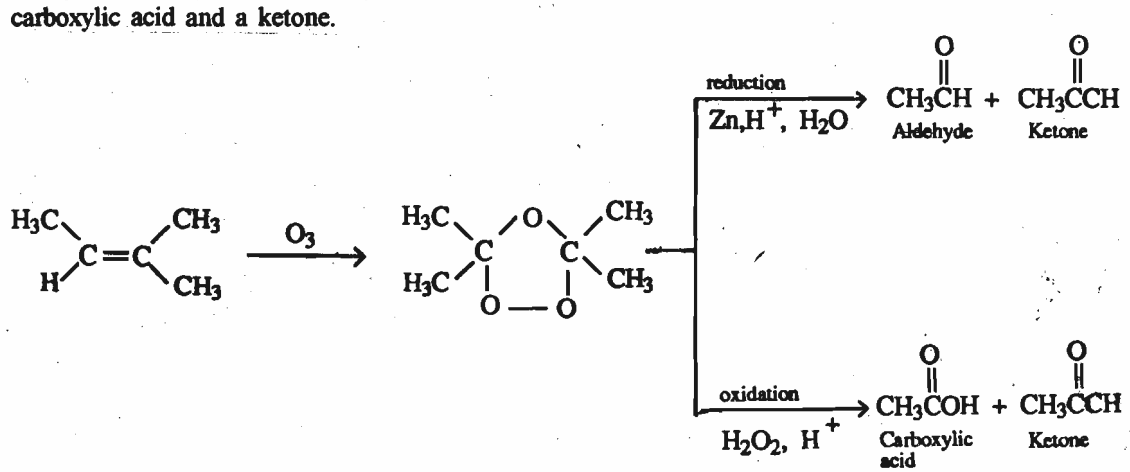
5.4.3 Ozonolysis

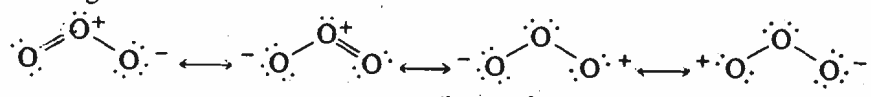
In all the reactions of alkenes and alkynes studied so far, the carbon skeleton of the starting material has been left intact. We have seen the conversion of the carbon-carbon double bond into new functional groups (halide, alcohol, etc.) by addition different reagents, but the carbon skeleton has not been broken. Ozonolysis is a cleavage reaction, in which the double bond is completely altered or broken and the alkene molecule is converted into two smaller molecules.

$$>C=C< + O_3 \longrightarrow >C=O + O=C<$$

Ozonolysis consists of two separate reactions, first is the oxidation of the alkene or alkyne by ozone to give an ozonide; and the second is either oxidation or reduction of the ozonide to yield the cleavage products. For example reductive ozonolysis of 2-methyl-2-butene yields an aldehyde and a ketone, while oxidative ozonolysis give a carboxylic acid and a ketone.

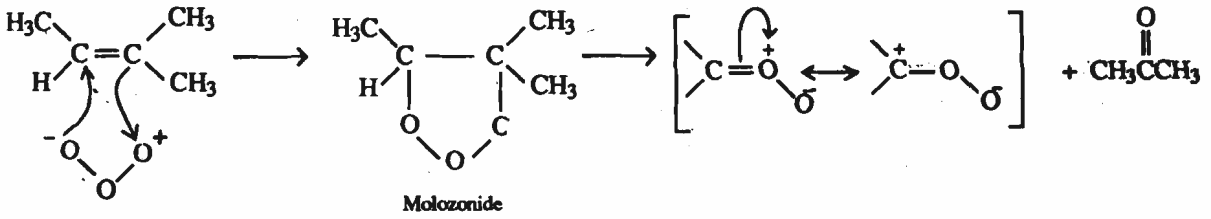


Mechanism : Ozone can be represented as resonance hybrid of the following contributing structure:

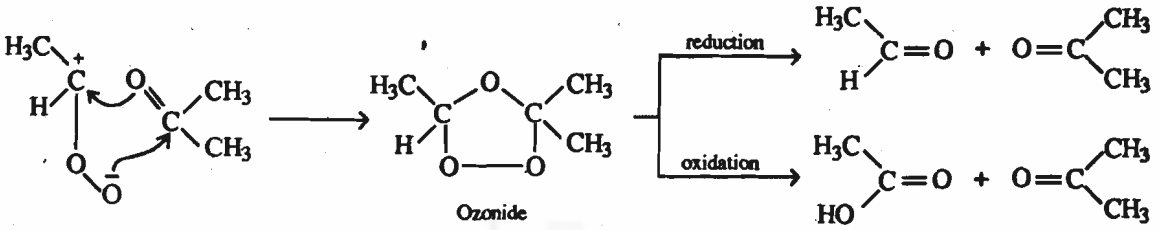


resonance contributors of ozone

The first step consists of a 1,3-dipolar addition of ozone to the double bond forming a molozonide. The molozonide, being unstable, subsequently decomposes into fragments. Recombination of these fragments in an alternative way yields an ozonide.

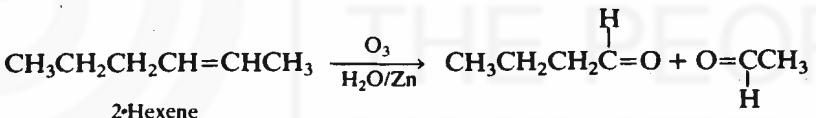


Molozonide

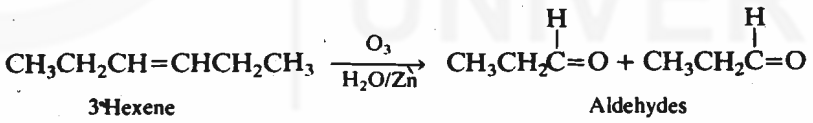


Ozonide

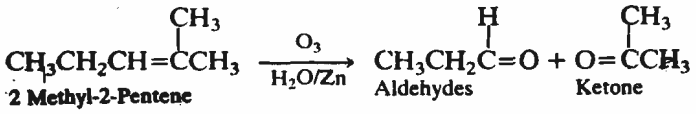
Low molecular-weight ozonides are highly explosive and are, therefore, not isolated. Instead, ozonides are usually further treated with either a reducing agent such as zinc metal in ethanoic acid or an oxidising agent, such as hydrogen peroxide to yield cleaved products. The overall reaction is known as ozonolysis. Knowing the number and arrangement of cabon atoms in those cleaved products, one can locate the position of the double bond in the original alkene. Some examples of ozonolysis are given below:



2-Hexene — Aldehydes



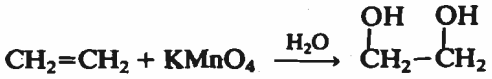
3-Hexene — Aldehydes

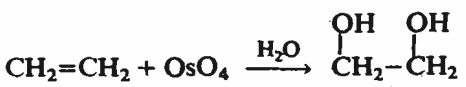


2 Methyl-2-Pentene — Aldehydes — Ketone

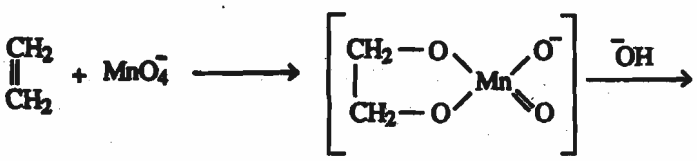
5.4.4 Hydroxylation

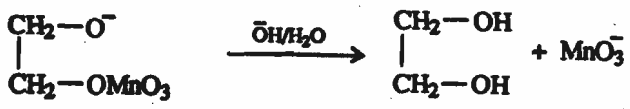
Alkenes are readily hydroxylated, (i.e., addition of hydroxyl groups) to form a dihydroxy compound (diol) known as gycols. The most popular reagent used to convert an alkene into diol is cold alkaline aqueous solution of potassium permanganate ($KMnO_4$) or osmium tetroxide (OsO_4). The yield with $KMnO_4$ is quite low as compared to OsO_4, but the use of OsO_4 is limited because it is both expensive and toxic.

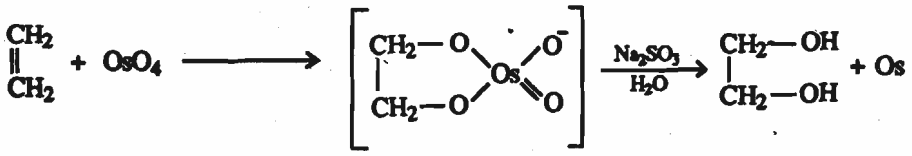




Both of these hydroxylation reactions occur with *syn,* rather than *anti* stereochemistry and yield *cis* diol. Both the permanganate and the OsO_4 oxidation processes proceed *via* cyclic intermediates.







Oxidation of alkenes (disappearance of pink colour) by cold aq. (neutral or slightly alkaline) permanganate is regarded as a test for the presence of an olefinic bond (Baeyer test).

5.5 SUMMARY

- Addition reaction of carbon-carbon multiple bonds can be divided into three main groups i.e., electrophilic addition, free radical addition and concerted addition.
- Alkenes undergo electrophilic addition more readily than alkynes.
- Alkenes react with hydrogen halides to give alkyl halides.
- Unsymmetrical alkenes on reaction with a hydrogen halide undergo Markownikoff's addition.
- Alkenes react with water to give alcohols, while alkynes give enols. Alcohols can also be obtained by oxymercuration and demercuration.
- Treatment of alkenes with halogens give 1,2-dihalogenated alkanes and that of alkynes give tetrahaloalkanes.
- When conjugated dienes are treated with hydrogen or halogens or hydrogen halide, two addition products are obtained. One is 1,2-addition product and the other is 1,4-addition product.
- Addition of HBr in the presence of peroxide gives *anti*-Markownikoff's product. This reaction occurs via free radical mechanism.
- Reaction of propenenitrile with HBr both in presence of peroxide and in the absence of peroxide yields the same product.
- Borane adds to an alkene or an alkyne to give organoborane, which undergoes a variety of chemical transformations.

5.6 TERMINAL QUESTIONS

1) Predict the products of the following:
   a) $CH_3CH_2CH{=}CHCH_3 + HBr \longrightarrow .... + ...$
   b) $NCCH{=}CH_2 + HBr \longrightarrow ....$

c) $ClCH{=}CH_2 + HBr \longrightarrow$ ....

d) $(CH_3)_3CCH{=}CH_2 + HBr \longrightarrow$ .... + ...

2) Fill in the following blanks:

a) Addition of H_2O to unsymmetrical alkene follows ..... rule.

b) Carbocation can undergo a 1,2-shift of H or R to yield more stable .....

c) Oxymercuration-demercuration of alkene gives .....

d) Alkyne reacts with halogen to give .....

3) Why are alkenes more reactive than alkynes towards electrophilic reactions?

4) A, B and C are isomeric heptenes. On ozonolysis A gives ethanal and pentanal, B gives propanone and butanone and C gives ethanal and pentan-3-one. Give the structure formulae of A, B and C.

5.7 ANSWERS

Self-assessment Questions

1) The alkene which forms most stable carbocation has fastest reaction. Thus the rate of reaction towards HBr addition is:

$CH_2{=}CH_2 < CH_3CH_2CH{=}CH_2 < (CH_3)_2C{=}CHCH_2CH_3$

2) a) $(CH_3)_3\overset{OH}{\overset{|}{C}}H-\underset{H}{\overset{|}{C}}H_2 + (CH_3)_2\overset{OH}{\overset{|}{C}}H-\underset{CH_3\ H}{\overset{|}{C}}H_2$

b) A = $CH_3CH_2\overset{OH}{\overset{|}{C}}H-\underset{HgO_2CCH_3}{\overset{|}{C}}H_2$, B = $CH_3CH_2\overset{OH}{\overset{|}{C}}H-\underset{H}{\overset{|}{C}}H_2$

c) $CH_3\overset{OH}{\overset{|}{C}}{=}CH_2 \rightleftharpoons CH_3\overset{O}{\overset{\|}{C}}CH_3$

3) a) 1,2-addition, 1,4-addition

b) primary, secondary

c) 1,2-product, 1,4-product

d) 1,2-product, 1,4-product

4) a) $CH_3\overset{CH_3}{\overset{|}{C}}H-\underset{H}{\overset{|}{C}}H_2-Br$

b) $CH_2\overset{Br}{\overset{|}{C}}HCN$ (H)

c) $CH_2\overset{Br}{\overset{|}{C}}HCN$ (H)

5) Alkenes (a) and (c) are good dienophiles

1) a) $CH_3CH_2\underset{\underset{H}{|}}{\overset{\overset{Br}{|}}{C}}HCHCH_3 + CH_3CH_2\underset{\underset{Br}{|}}{\overset{\overset{H}{|}}{C}}HCHCH_3$

b) $NC\overset{\overset{H}{|}}{C}H\underset{\underset{Br}{|}}{C}H_2$

c) $Cl\overset{\overset{H}{|}}{C}H\underset{\underset{Br}{|}}{C}H_2$

d) $CH_3\overset{\overset{CH_3}{|}}{\underset{\underset{CH_3}{|}}{C}}\overset{\overset{H}{|}}{\underset{\underset{Br}{|}}{C}}HCH_2 + CH_3\overset{\overset{Br}{|}}{\underset{\underset{CH_3}{|}}{C}}\overset{\overset{CH_3}{|}}{\underset{\underset{H}{|}}{C}}HCH_2$

2) a) Markownikeff's
   b) carbocation
   c) alcohol
   d) tetrahaloalkane.

3) Since an *sp* hybridised carbon is more electronegative than sp^2 hybridised carbon, π electrons in alkynes are less easily available for combination with electrophile. Therefore alkynes are less reactive than alkene.

4) >C=O group is introduced at >C=C< after fission, hence:

compound A = $CH_3CH{=}CHCH_2CH_2CH_2CH_3$

compound B = $CH_3\overset{\overset{CH_3}{|}}{C}{=}\overset{\overset{CH_3}{|}}{C}-CH_2CH_3$

compound C = $CH_3CH{=}\underset{\underset{CH_2CH_3}{|}}{C}CH_2CH_3$

UNIT 6 NUCLEOPHILIC ADDITION TO CARBONYL COMPOUNDS

Structure

6.1 Introduction
Objectives
6.2 Nature of the Carbonyl Group
6.3 Kind of Carbonyl Compounds
6.4 Reactivity of Carbonyl Compounds
6.5 Reactions of Carbonyl Compounds
Reaction with Hydrogen Cyanide
Reaction with Sodium Hydrogen Sulphite
Reaction with Water
Reaction with Alcohol
Reaction with Amines
Reaction with Grignard Reagents
Wittig Reaction
Aldol Condensation
Reactions Related to Aldol Condensation
Cannizzaro Reaction
Michael Addition
6.6 Summary
6.7 Terminal Questions
6.8 Answers

6.1 INTRODUCTION

In Unit 5 you have studied the addition reactions of carbon-carbon multiple bonded systems. In this unit we shall discuss the nucleophilic addition reactions of aldehydes and ketones. Both aldehyde and ketone contain the carbonyl group, >C=O and are often referred to collectively as carbonyl compounds. The remarkable reactivity of the carbonyl group makes the chemistry of aldehydes and ketones the backbone of synthetic organic chemistry. The double bond between the carbon and oxygen atoms in these compounds serves as a model for the reactions of many other functional groups containing π bonds between dissimilar atoms. Although the reactions of carbonyl compounds are quite simple their synthetic utility is enormous. In this unit we shall study the important nucleophilic reactions of aldehydes and ketones.

Objectives

After studying this unit, you should be able to:

- describe the structure of carbonyl group, and explain its polarity,
- explain the relative reactivity of aldehydes and ketones,
- discuss the general mechanism of nucleophilic addition to carbonyl compounds,
- discuss the different reactions of aldehydes and ketones.

6.2 NATURE OF THE CARBONYL GROUP

A carbonyl group consists of a carbon doubly bonded to an oxygen atom (Fig. 6.1). The carbonyl double bond is similar in many respects to the carbon-carbon double bond of an alkene. Like carbon-carbon double bond of alkene, carbon-oxygen double bond of a carbonyl compound consists of one σ bond and one π bond. The

carbonyl carbon atom is sp^2 hybridised and forms three σ bonds (two C-H bonds and one C-O bond) and an unhybridized *p* orbital is left on the carbon atom. The σ bond is formed by overlap of sp^2 hybrid orbitals and a π bond is formed with oxygen by overlap of *p*-orbitals. Carbonyl compounds are planar and have bond angles of approximately 120°.

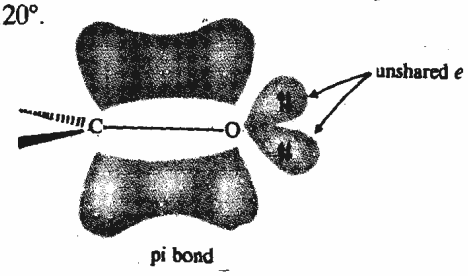


Fig. 6.1: Bonding in carbonyl compound.

Unlike carbon-carbon double bond, carbon-oxygen double bond is polar. This is because of the higher electronegativity of oxygen relative to carbon. The π electrons of the carbon-oxygen double bond get shifted towards the oxygen atom and the bond gets polarised. This electron imbalance in the π bond makes the carbon atom **electron-deficient** as a result the carbonyl group as a whole has an electron withdrawing effect. Thus, the carbonyl group has two active centres, viz.,

$$\overset{\delta^+}{>}C=\overset{\delta^-}{O}$$

- The carbon carrying partial positive charge, called electrophilic or cationoid centre. This can be attacked by nucleophilic reagents.
- The oxygen carrying partial negative charge, called nucleophilic or anionoid centre. This can be attacked by electrophilic reagents.

6.3 KIND OF CARBONYL COMPOUNDS

Carbonyl compounds can be classified into two groups, based on the kind of reactions they undergo.

i) Aldehydes and ketones
ii) Carboxylic acids and their derivatives, e.g., esters, acid chlorides, acid anhydrides and amides.

In aldehydes and ketones, the acyl units (RCO) are bonded to H and R, respectively. These substituents cannot serve as leaving groups. Therefore, the chemistry of these compounds is similar. The acyl units in carboxylic acids and their derivatives are bonded to substituents like oxygen, halogen or nitrogen that can serve as leaving groups. Hence, the chemistry of aldehydes and ketones is different from that of carboxylic acids and their derivatives.

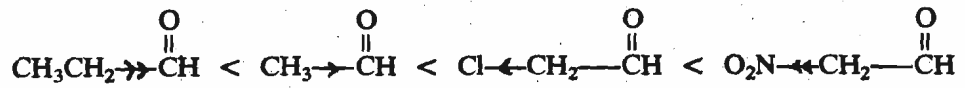
In this unit we shall discuss only the nucleophilic addition to aldehydes and ketones.

Before going into details of the reactions of carbonyl compounds, let us study the relative reactivity of aldehydes and ketones.

6.4 REACTIVITY OF CARBONYL COMPOUNDS

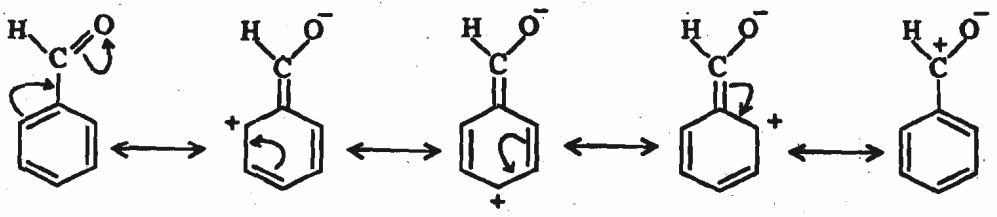
You have studied in Unit 1 that a nucleophilic addition reaction involves addition of a nucleophile to the partially positively charged carbon atom of the carbonyl group. The relative reactivities of aldehydes and ketones in nucleophilic addition reactions may be attributed partly to the extent of polarisation of the carbonyl carbon. The rate determining step involves the attack of nucleophile at the positively charged carbon atom. Therefore, the reactivity of the carbonyl group depends upon the magnitude of the positive charge on the carbonyl carbon. Thus, a greater positive charge means higher reactivity. If this partial positive charge is dispersed throughout the molecule then the carbonyl compound is less reactive. Electron withdrawing substituents at the carbonyl carbon, which increase its positive charge, increase its reactivity towards nucleophilic addition reactions. Similarly, electron donating substituents decrease its positive character and hence decrease the reactivity towards nucleophilic addition reaction.

You know that alkyl groups have electron releasing effect. Therefore, ketones, which contain two alkyl groups, are less reactive than aldehydes. Further chloroethanal, which contains the electron withdrawing chlorine atom, is more reactive than ethanal. Similarly, nitroethanal, where NO_2 group has stronger electron withdrawing character than chlorine is more reactive than chloroethanal. Thus the order of reactivity is:



Aromatic aldehydes or ketones are less reactive than aliphatic aldehydes and ketones. This can be attributed to resonance interaction between the carbonyl group and the aromatic ring.

The result of this interaction is a weakening of the positive charge on the carbonyl carbon atom through dispersal of the charge within the ring.

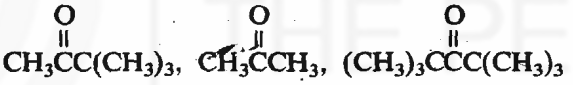


Steric factor also plays an important role in the relative reactivity of aldehydes and ketones. A bulky group in the vicinity of the carbonyl carbon presents greater steric hindrance than the smaller hydrogen atom to the approaching nucleophile.

With the above general ideas, it will be easier to study the reactions of aldehydes and ketones which we will take up in the next section.

SAQ 1

Considering the steric factor, arrange the following compounds in the order of their reactivity.



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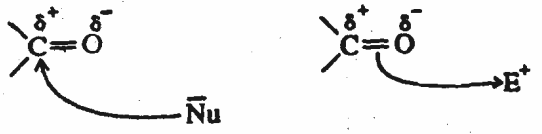
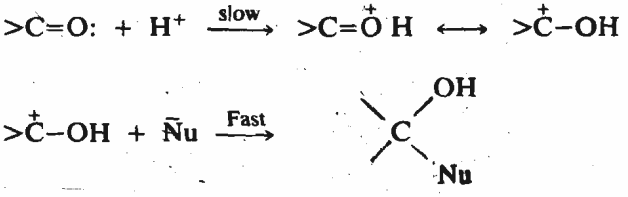
6.5 REACTIONS OF CARBONYL COMPOUNDS

Theoretically a carbonyl compound may be attacked either by a nucleophile or by an electrophile. Addition of the negative nucleophilic part of the reagent to the carbon atom or addition of the positive electrophilic part to the oxygen atom would give the same product ultimately.

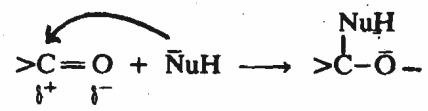


The addition reaction of carbonyl compounds, therefore, can theoretically proceed by the following two mechanism.

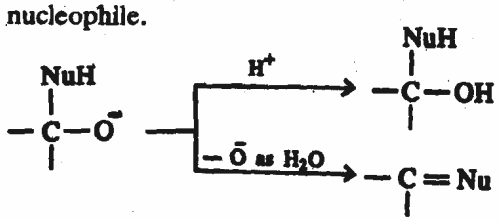
Mechanism I: In the first mechanism, the proton adds to the carbonyl oxygen in the first step (slow step). This further increases the electrophilic nature of the carbonyl carbon. In the next step (fast step) the nucleophile attacks the carbocation.



Mechanism II: In the second type of mechanism nucleophile attacks the polarised carbonyl carbon in the first step and forms an anionic intermediate.



This intermediate can undergo either protonation to form an alcohol, or it might expel oxygen as water to form a new double bond between carbon and the nucleophile.

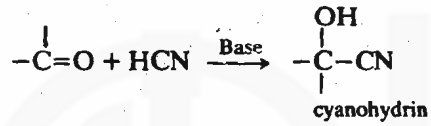


An acid catalysed reaction should follow mechanism I and the base catalysed mechanism II.

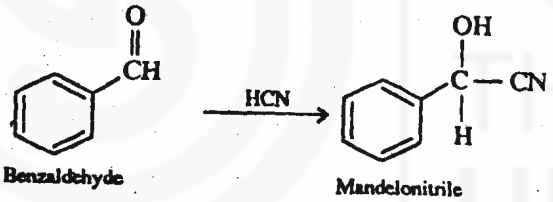
Now let us study some important reactions of aldehydes or ketones.

6.5.1 Reaction with Hydrogen Cyanide

Hydrogen cyanide (hydrocyanic acid) adds to the carbonyl compounds in aqueous solution or with anhydrous liquid HCN in the presence of catalytic amounts of an organic base to give cyanohydrins. Cyanohydrins are hydroxy nitriles.



For example, benzaldehyde gives the cyanohydrin (mandelonitrile) in 88% yield on treatment with HCN.

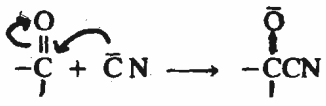


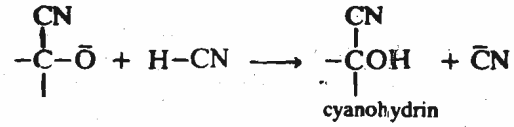
The reaction occurs very slowly when pure HCN is used, but becomes fast when a trace amount of base or cyanide ion is added. The function of the base is to increase the concentration of cyanide ion.

The reaction is reversible and the position of equilibrium depends on the usual steric and electronic factors that govern nucleophilic addition to carbonyl groups. Aldehydes and unhindered ketones give good yields of cyanohydrin.

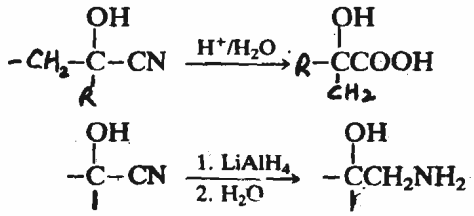
HCN is a very poisonous substance, it is not used directly in cyanohydrin formation. The reaction is carried out by mixing the carbonyl compound with aqueous sodium cyanide and then slowly acidifying the solution by a mineral acid.

Mechanism: In the first step, the cyanide ion attacks the carbonyl carbon to form an alkoxide ion intermediate. The alkoxide ion is basic and rapidly removes a proton from HCN present and generates a cyanide ion, in the second step.



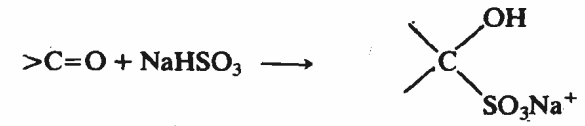


Cyanohydrins are also useful synthetic intermediates. An important consequence of the reaction is that one more carbon atom is added to the carbon chain. The cyano group may be converted to a carboxylic acid, by hyrdolysis, or to a primary amine by reduction.

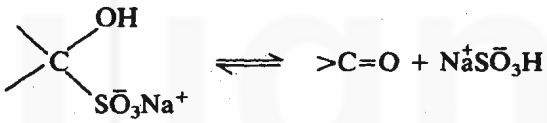


6.5.2 Reaction with Sodium Hydrogen Sulphite

Most of the aldehydes, some ketones (generally methyl ketone) and unhindered cyclic ketones react with sodium hydrogen sulphite (sodium bisulphite) to give a crystaline hydrogen sulphite adduct.



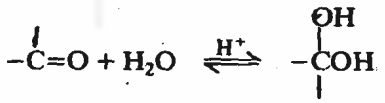
Ketones with bulky groups fail to add sodium hydrogen sulphite. On heating with dilute acid or aqueous sodium carbonate, bisulphite compound regenerates the carbonyl compound.



This reaction is often used for separation and purification of aldehydes and ketones from non-carbonyl compounds. When such a mixture is treated with sodium hydrogen sulphite, the aldehyde or ketone is converted into crystalline hydrogen sulphite adduct which can be separated. The crystalline adduct can be converted back into aldehyde or ketone.

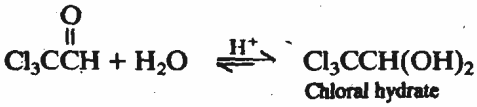
6.5.3 Reaction with Water

Aldehydes and ketones react with water to form 1,1-diols, (geninal-diols) or hydrates. Hydrogen becomes bonded to the negatively polarised carbonyl oxygen and hydroxyl group to the positively polarised carbon. This reaction is reversible and the hydrate formed is generally too unstable to be isolated.

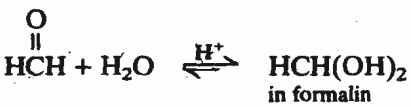


Geminal diol

Stable hydrates are known in a few cases but they are rather exceptions, e.g., chloral hydrate or in formalin:



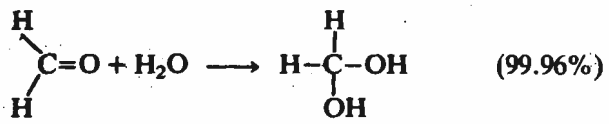
Chloral hydrate



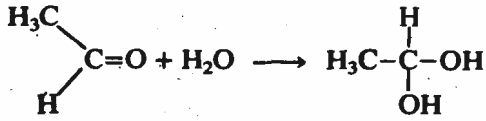
in formalin

The rate of reaction depends on the nature of the carbonyl group and is influenced by the combination of electronic and steric effects.

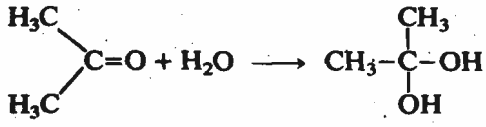
With increase of alkyl substitution on the carbonyl group, the reactivity of carbonyl compounds decreases, when treated with water under similar conditions. For example,



(99.96%)



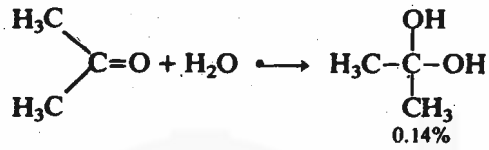
(58%)



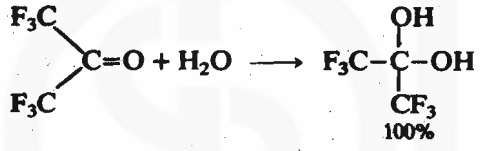
(0.14%)

Methanal has no alkyl substituents to stabilise its carbonyl group and is converted almost completely to the corresponding diol (99.96%). The carbonyl group of ethanal is stabilised by one alkyl substituent and the carbonyl of propanone by two. Ethanal gives 58% while propanone gives only 0.14% of diols.

Reactivity of carbonyl compounds increases when electron-withdrawing groups are attached to the carbonyl carbon. For example, in contrast to the almost negligible hydration of propanone, the hexafluoropropanone is completely hydrated.



0.14%



100%

Now let us consider the steric effect on the rate of reactions. Let us examine the geminal diol products. The carbon atom that bears two hydroxyl group is sp^3 hybridised. Its substituents are more crowded than they are in the starting aldehyde or ketone. Increased crowding can be better tolerated when the substituents are hydrogen than when they are alkyl groups. Diol of methanal is least crowded and hence formed in large amount. Diol of propanone on the other hand is more crowded, therefore, formed in a lesser amount. Finally, the amount of diol of ethanal is formed between the above two limits.

As the electronic and steric effects combine hydration of aldehydes becomes more favourable than that of ketones.

SAQ 2

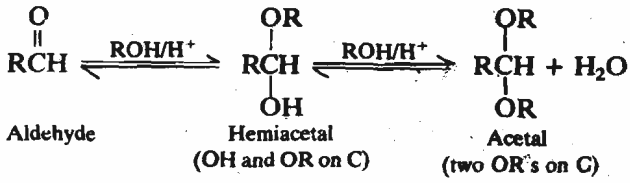
Which of the following compounds do you predict would form stable hydrates and why?

.....

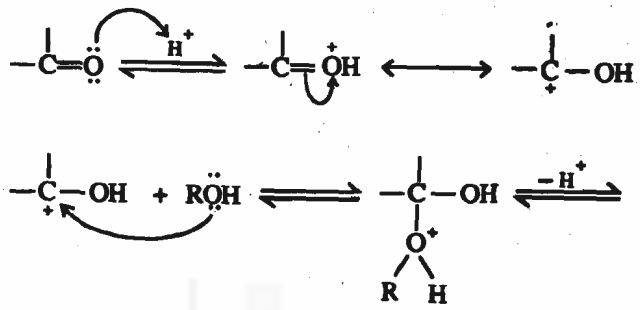
6.5.4 Reaction with Alcohol

Like water, an alcohol can undergo addition reaction with carbonyl group in the presence of an acid catalyst. It is also a reversible reaction. In most cases, the equilibrium lies to the aldehyde or ketone side. Addition of one molecule of an

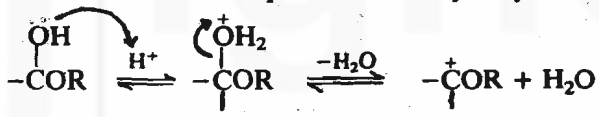
alcohol to an aldehyde or ketone gives **hemiacetal** or **hemiketal**, respectively. On the other hand, reaction of two molecules of alcohol to an aldehyde or a ketone, with the loss of water, give **acetal** or **ketal**, respectively. Unlike hydrates, acetals and ketals are quite stable and can be isolated.



Mechanism: The mechanism of formation of hemiacetal is analogous to that of the acid catalysed hydration of an aldehyde.

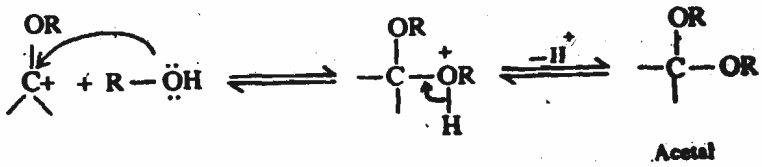


In the mechanism for acetal formation from the hemiacetal, again protonation and deprotonation, along with loss of water, are the major reaction steps. First protonation of hemiacetal take place followed by dehydration to give a carbocation.

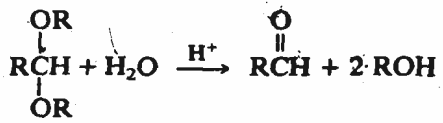


The carbocation is stabilised by electron release from its oxygen substituent to yield oxonium ion.

Attack by a second molecule of alcohol forms the protonated acetal which on deprotonation gives acetal.



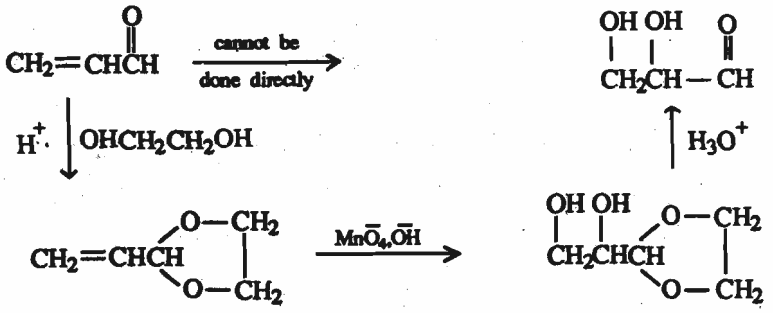
An acetal can be hydrolysed back into parent aldehyde and alcohol upon treatment with aqueous mineral acid even at room temperature.



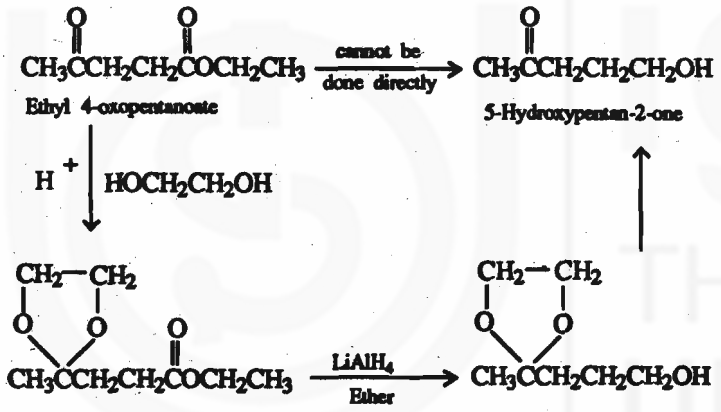
The mechanism is just the reverse of that for the formation of the acetal.

Now you will see how acetal formation and hydrolysis have been applied to synthetic organic chemistry as a means of carbonyl group protection. In some chemical reactions one functional group may interfere with intended reaction elsewhere in a complex molecule. We can often circumvent the problem in such cases by first

protecting the interfering functional group, carrying out the desired reaction, and then removing the protecting group. For example, if we wish to oxidise propenal to 2,3-dihydroxypropanal, there is an interference of the carbonyl group, since both the double bond (C=C and C=0) would be oxidised. But after converting the carbonyl group to an acetal, we can oxidise a carbon-carbon double bond in the molecule without oxidising the carbonyl group.



Since acetal formation is a reversible reaction it can be cleaved by hydrolysis to regenerate the carbonyl group. Thus, 2,3-dihydroxypropanal is obtained. Similarly take another example, conversion of ethyl 4-oxopentanoate to, 5-hydroxypentan-2-one. We can not reduce the ester group directly by $LiAlH_4$ as both the carbonyl groups would be reduced simultaneously. If we first protect the ketone by forming an acetal, subsequent ester reduction proceed normally and acetal can be cleaved to get back ketone.



SAQ 3

Consider the acid-catalysed reaction of ethanal with methanol. Write structural formulas for,

a) **The hemiacetal intermediate**
b) **The carbocation intermediate**
c) **The acetal product.**

.....

.....

.....

6.5.5 Reaction with Amines

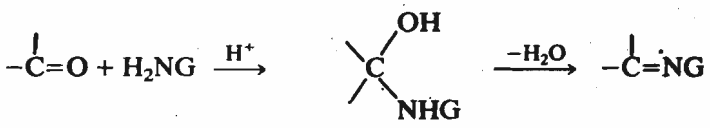
Reactions of carbonyl compounds with amine can be classified into the following two categories.

- Reaction with primary amines,
- Reaction with secondary amines.

Reaction with primary amines

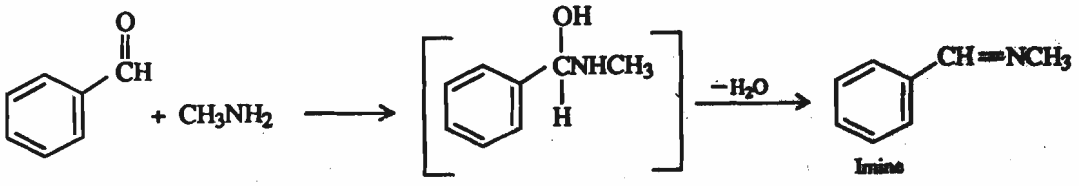
In the presence of an acid catalyst a primary amine adds to carbonyl compounds to give an imine (compounds with C=N group). In this reaction the initial addition of H^+ is followed by an attack of H_2NG. Subsequent dehydration forms a

carbon-nitrogen double bond. The net result is substitution of oxygen by another group. Primary amines react with aldehydes or ketones to form corresponding N-alkyl or N-aryl substituted imines, which contain C=N group.

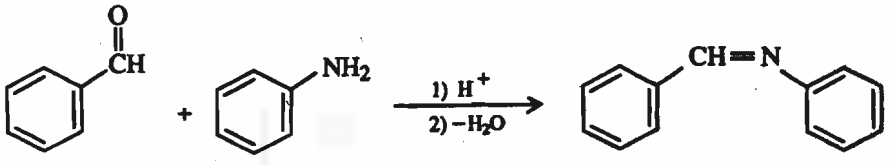


G = various groups N-substituted

The unsubstituted imines, obtained by reaction with NH_3, are very unstable; while substituted imines, formed form RNH_2, are more stable. Substituted imines are also called **Schiff bases**.

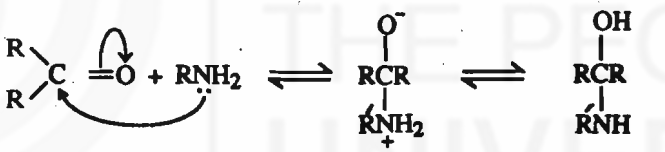


Imine



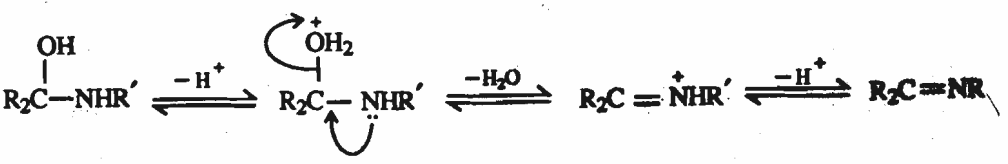
Imine

Mechanism: Formation of a Schiff base is a two step reaction. In the first step, the nucleophile (RNH_2) adds to the partially positive carbonyl carbon. This step is followed by proton shift from nitrogen to oxygen to give an intermediate called carbinolamine;



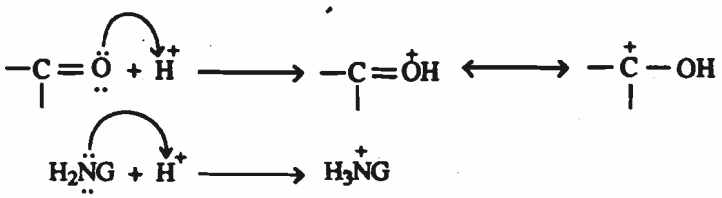
Carbinolamine

In the second step, the carbinolamine eliminates water and gives the imine.



Both the addition and the elimination steps of the reaction are sensitive to acid catalysis. Hence careful control of pH is essential. The rate of reaction is increased by an increase in acidity but beyond a certain limit, the rate decreases with further increase of acidity.

You can ask why is this so? This is because, these reactions are catalysed by acids, thus, protonation of the carbonyl compound as well as the reagent can take place.



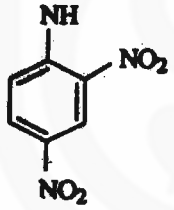
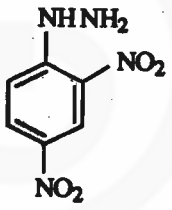
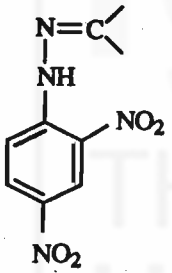
The first step of the reaction is the addition of the amine to the carbonyl group. In strongly acid medium, the concentration of the amine becomes very low because we get $G\overset{+}{N}H_3$ in excess amounts. In other words, the rate of the first step decreases with increase in acidity as $G\overset{+}{N}H3$ is a poor nucleophile than GNH_2.

The second step involves the elimination of water. In acidic medium concentration of the protonated carbinolamine increases with the increasing acid concentration. (Remember $-\overset{+}{O}H_2$ is a better leaving group than $-OH$).

An increase in acidity causes step 2 to go faster, but step 1 to go slower, while decreasing acidity causes step 1 to go faster but step 2 to go slower. Between these two extremes is the optimum pH (~ 3–4), at which the rate of the over all reaction is the greatest. At this pH, some of the amine is protonated, but some are free to initiate the nucleophilic addition. At this pH, too, enough acid is present so that elimination of water in the second step can proceed at a reasonable rate.

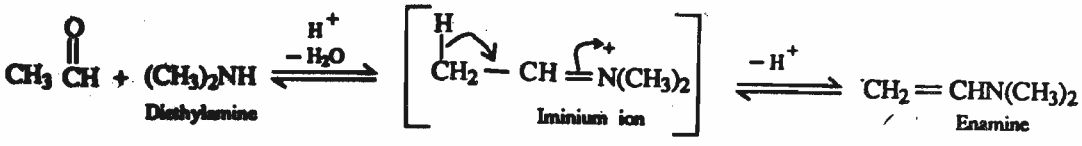
The names of reactants with different G, general condensation products and their class is given in Table 6.1. Many of these products are crystalline solids with sharp melting points. For this reason they are frequently employed for the preparation of aldehyde and ketone derivatives needed for identification.

Table 6.1 : Reaction of ammonia derivatives

G	Ammonia derivative	Product	Class of Product
$-RAr$ alkyl/aryl	$RNH_2/ArNH_2$ amine	$>C=NR/C=NAr$ N substituted imine	imine (Schiff base)
$-OH$	NH_2OH hydroxylamine	$>C=NOH$ oxime	Oxime
$-NH_2$	H_2NNH_2 hydrazine	$>C=NNH_2$ hydrazone	hydrazone
		 2,4-dinitrophenyl hydrazone	substituted hydrazone
$-NHCONH_2$	$H_2NNHCONH_2$ semicarbazide	$>C=NNHCONH_2$ semicarbazone	semicarbazone

Reaction with Secondary Amines

Aldehydes and ketones with an α-hydrogen react with secondary amines to yield **iminium ions**, which undergo further reaction to give **enamines** (vinylamines).



Since there is no proton remaining on nitrogen of this intermediate iminium ion, the imine formation cannot occur. Instead an enamine is formed by loss of a proton from a carbon atom β to the nitrogen. This results in the formation of a double bond between α and β carbon atoms.

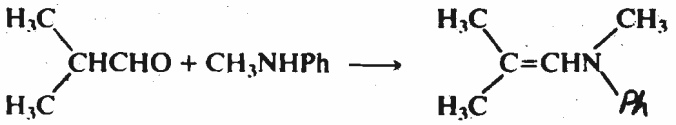
Like imine formation, enamine formation is reversible, and enamines can be converted back to the corresponding carbonyl compounds.

You must have noticed from the above that the mechanism of enamine formation is similar to the mechanism of imine formation. Reaction of aldehydes or ketones with primary and secondary amine may appear different but they are quite similar. Both

are typical examples of nucleophilic addition reaction in which the initially formed tetrahedral intermediate is not stable. Instead, the carbonyl oxygen is eliminated and a new carbon-nucleophile double bond is formed. You can practice this reaction by solving the following SAQ.

SAQ 4

Write the mechanism of the following reaction,



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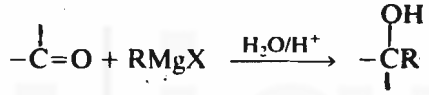
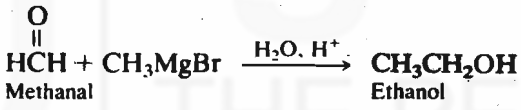
6.5.6 Reaction with Grignard Reagents

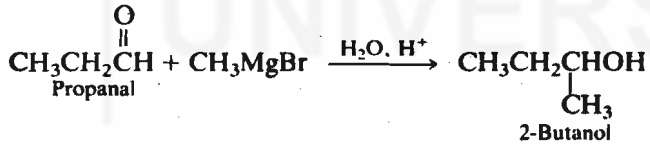
Developments in chemistry in the past 3-4 decades, has unravelled a large number of reactions of Grignard reagents with carbonyl group. The reaction of Grignard reagent with aldehydes or ketones gives alcohols. This is the most important method for preparaing alcohols.



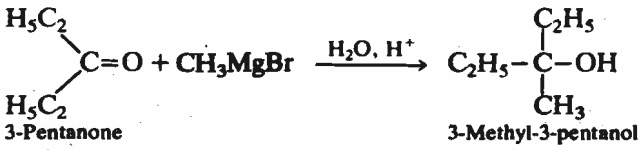
A large number of alcohols can be obtained from Grignard reactions depending upon the reagents used. For example, a Grignard reagent reacts with methanal to give a primary alcohol.



Reactions of Grignard reagent with other aldehyde except methanal yields a secondary alcohol. For example:

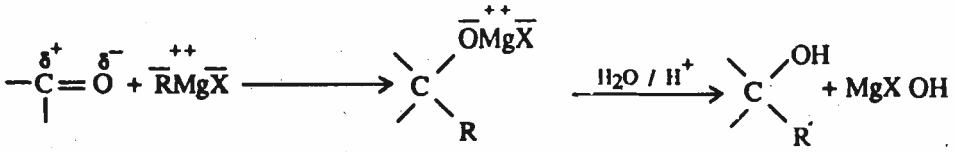


Similarly, reaction with ketones yields tertiary alcohols.

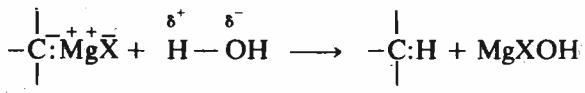


Mechanism: Analysing the charge distribution in the Grignard reagent, we find that since the magnesium bears the positive charge, the hydrocarbon portion of the reagent must have a negative charge and, therefore, should be a very powerful nucleophile.

When a Grignard reagent is mixed with an aldehyde or a ketone, the negative hydrocarbon group quickly attacks the positive carbonyl carbon and provides the two electrons needed for the new carbon-carbon bond. The π electrons are displaced by the oxygen, forming the alcohol salt which is hydrolysed to an alcohol with water in acidic medium.

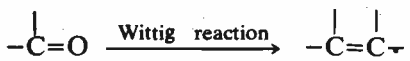


Note that the hydrocarbon portion of a Grignard reagent acts essentially as a carbanion. It is for this reason that Grignard reactions must be performed in dry ether. Even traces of moisture can neutralise the reagent.

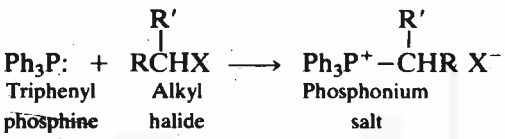


6.5.7 Wittig Reaction

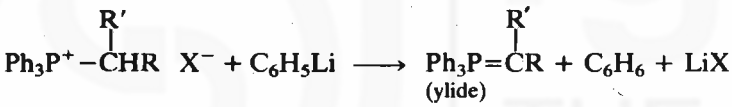
In 1954, George Wittig reported a method of synthesising alkenes from carbonyl compounds. This reaction is applicable to aldehydes and ketones and leads to replacement of carbonyl oxygen by the group =CRR′ (where R and R′ are hydrogen or alkyl group).



There are two main steps in Wittig reaction. In the first step, the nucleophilic reagent triphenylphosphine reacts with a primary or secondary alkyl halide to give a phosphonium salt.

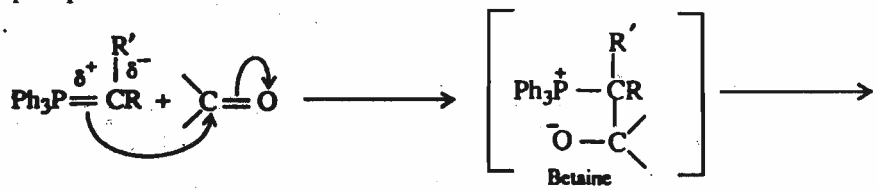


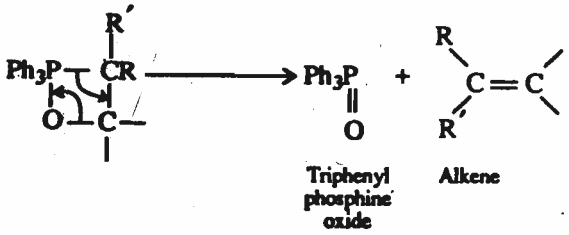
This phosphonium salt further reacts with a strong base, which abstracts a weakly acidic α-hydrogen to give alkylidene triphenylphosphorane (a phosphorus ylide) commonly known as the **Wittig reagent**.



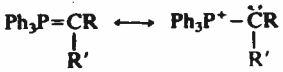
The resulting phosphorus ylide attacks the carbonyl carbon to form a dipolar intermediate called a **betaine**, which often undergoes elimination spontaneously to yield an alkene.

Mechanism: Mechanism of Wittig reaction has been the subject of much discussion, but evidence is now strongly in favour of the formation of an intermediate betaine. This betaine intermediate is unstable and rapidly fragments, probably by way of a second intermediate containing a four-membered ring, to an alkene and triphenylphosphine oxide.





The phosphorus ylides have a hybrid structure and it is the negative charge on carbon that is responsible for their characteristic reactions.

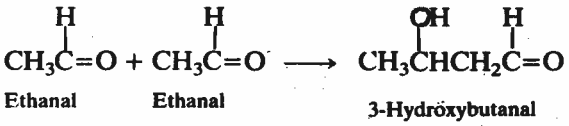


The great value of Wittig reaction is that pure alkenes of known structures can be prepared. The position at which the double bond is introduced is never in doubt. The double bond is formed between the carbonyl carbon of the aldehyde or ketone and the negatively charged carbon of the ylide.

Wittig reaction is so important that it can be used commercially for the preparation of β-carotene, a yellow food-colouring agent. Wittig reaction is versatile, the alkyl halide used to prepare the ylide may be methyl, primary or secondary but not tertiary. The alkyl halide can also contain any other functionality such as a double bond or alkenyl groups.

6.5.8 Aldol Condensation

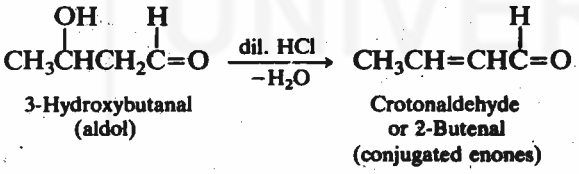
In the presence of a dilute base, such as aqueous NaOH, two or more molecules of an aldehyde or a ketone, containing an α-hydrogen may combine to form a β-hydroxyaldehyde or β-hydroxyketone, a compound containing alcoholic and aldehydic or ketonic groups, respectively. This reaction is called aldol condensation. The product results from addition of one molecule of the carbonyl compounds to a second molecule in such a way that the α-carbon of the first is attached to the carbonyl carbon of the second. For example, reaction between the two ethanal molecules.



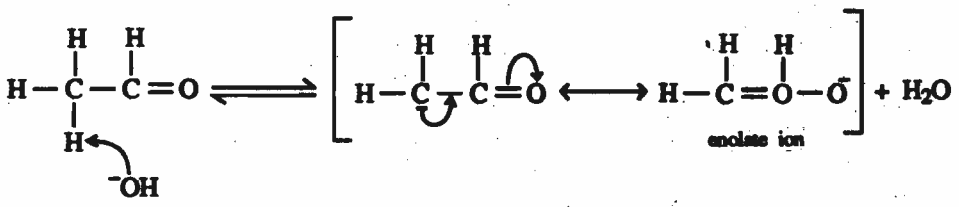
The starting aldehyde in an aldol condensation must contain an α-hydrogen. If the aldehyde or ketone does not contain an α-hydrogen, a simple aldol condensation cannot take place.

Since the β-hydroxyaldehyde has a carbonyl carbon with α-hydrogen it can undergo further reaction to give trimers or tetramers. For simplicity we will show only the dimerisation product.

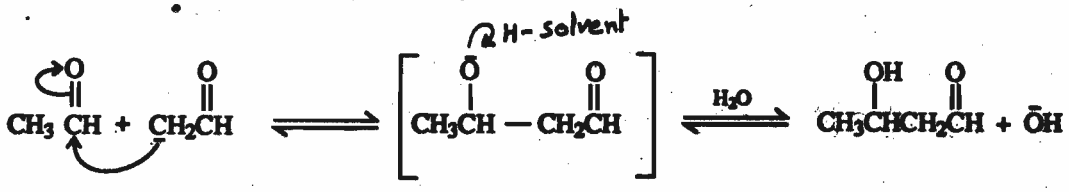
Aldol condensations are reversible reactions. The condensation product (a β-hydroxy carbonyl compound) loses a water molecule to form unsaturated aldehydes or ketones, (conjugated enones), e.g.,



Mechanism: Aldol condensation is a two step process. In the first step, the base abstracts a proton from the α-carbon of the aldehyde to form enolate ion.



In the next step, the enolate ion attacks the carbonyl carbon of another aldehyde molecule to form an alkoxide ion, which abstracts a proton from water to yield the β-hydroxyaldehyde, regenerating $\bar{O}H$.



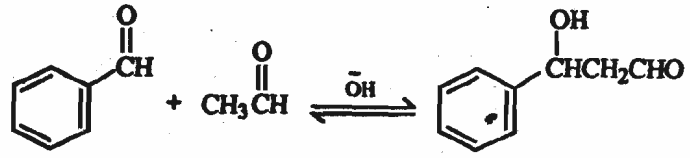
Alcohols generally do not undergo dehydration by dilute acid or base. However, aldol products undergo dehydration because in this case the double bond is in conjugation with the carbonyl group in the product.

Crossed aldol condensation

As mentioned above, an aldehyde without α-hydrogen does not undergo aldol condensation. However, if such an aldehyde is mixed with an aldehyde that does have an α-hydrogen, aldol condensation can occur. Aldol condensation between the two different carbonyl compounds is called crossed aldol condensation which is of two types:

In type one, both the carbonyl compounds have α-hydrogen atoms. In these cases a mixture of four possible products may be formed. Because of the formation of such a mixture, this type of reaction is commercially of no use.

In type two, one of the carbonyl compound does not have an α-hydrogen, e.g.,



Benzaldehyde (No α-hydrogen) Ethanal

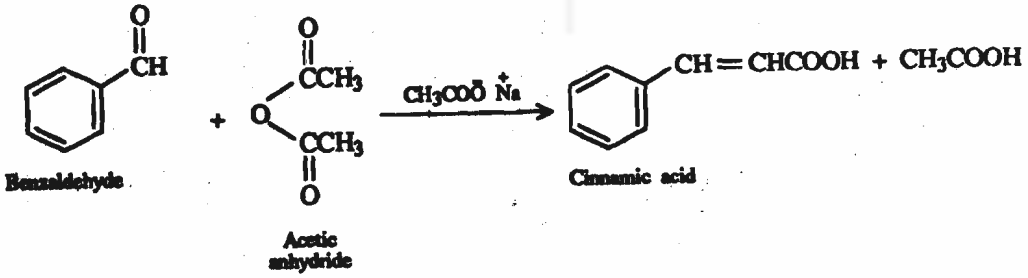
Methyl ketones can be used successfully in crossed aldol condensation with aldehydes that contain no α-hydrogen.

6.5.9 Reactions Related to Aldol Condensation

There are many reactions that are closely related to aldol condensation. At first glance each of these reactions may seem quite different from others. But a close examination of these reactions shows, that like aldol condensation each of these involves an attack by a carbanion formed from one molecule on the carbonyl group of another. Some such reaction are given below:

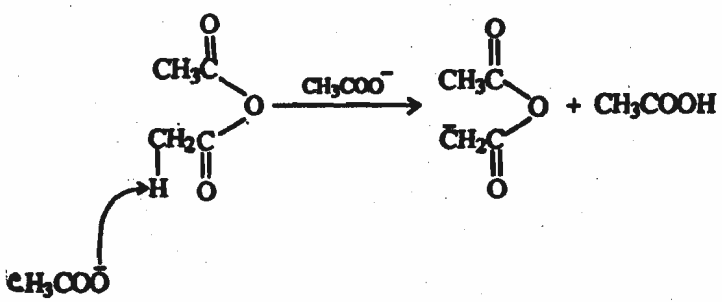
Perkin condensation

Perkin condensation is a reaction in which an aromatic aldehyde combines with anhydride of an aliphatic acid (having atleast two α-hydrogen atoms) in the presence of salt of the same acid to yield an α, β-unsaturated acid. In this reaction the catalyst used is generally the salt of the carboxylic acid related to the anhydride but it may be replaced by some other bases such as sodium carbonate, pyridine, etc. For example, benzaldehyde when heated with acetic anhydride in the presence of anhydrous sodium acetate gives cinnamic acid.

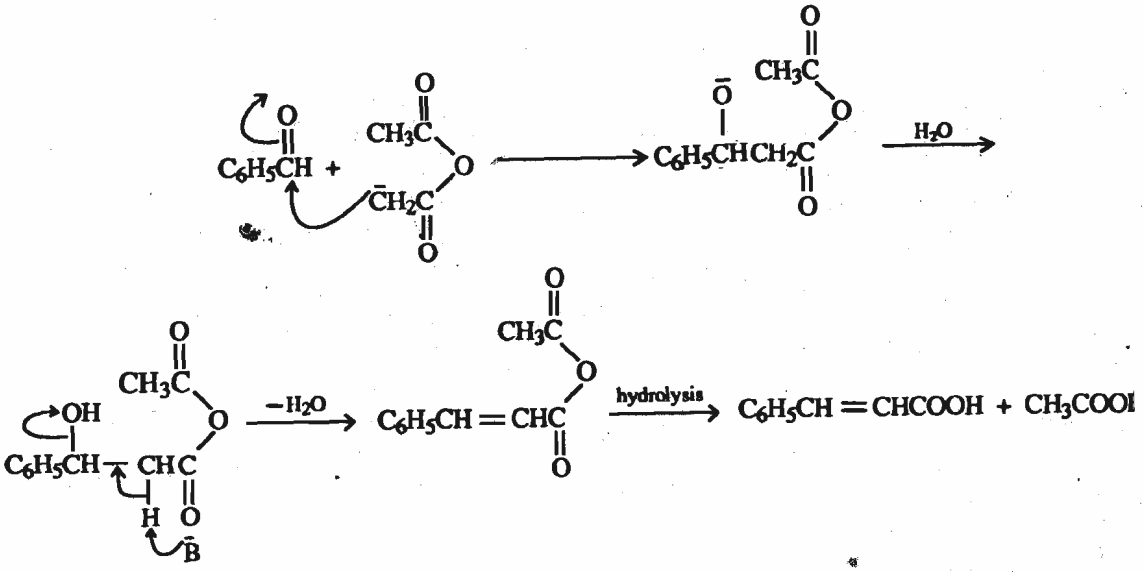


Benzaldehyde Acetic anhydride Cinnamic acid

Mechanism: First the base abstracts the α-hydrogen from the anhydride to form a carbanion.



In the next step, the resultant carbanion attacks the carbonyl carbon of the other molecule to form an anion which takes up a proton to form a hydroxy compound.

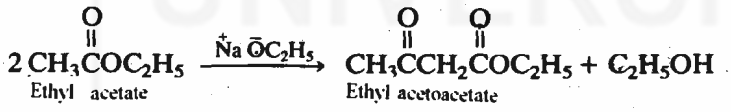


The hydroxy compound first undergoes dehydration to give an unsaturated anhydride which gets hydrolysed forming the α, β-unsaturated acid.

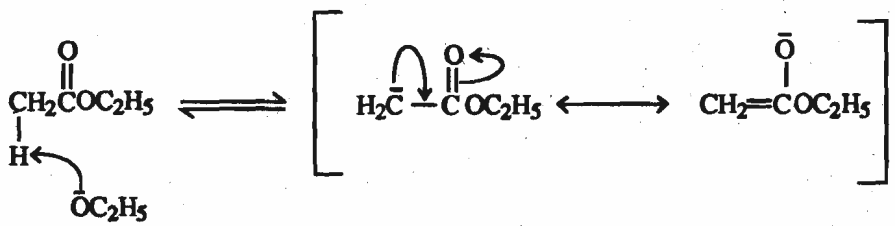
It must be noted that aliphatic aldehydes do not undergo Perkin reaction.

Claisen condensation

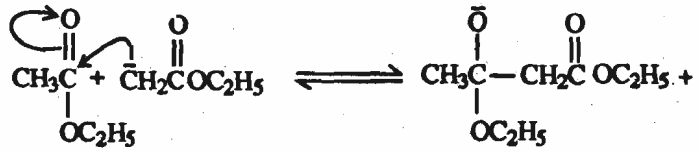
Claisen condensation is a reaction of esters having an α-hydrogen. When these esters are treated with a base such as sodium ethoxide, a reversible self-condensation reaction occurs to yield a β-keto ester. The ester condensation is similar to an aldol condensation; the difference is that the −OR group of an ester can act as a leaving group. The result is, therefore, substitution, whereas the aldol condensation is an addition reaction. For example, ethyl acetate when treated with sodium ethoxide yields ethyl acetoacetate, a β-keto ester.



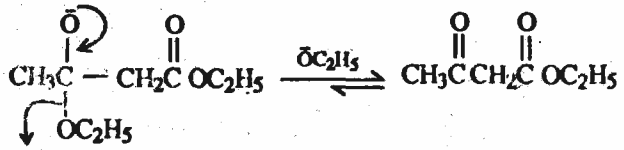
Mechanism: At first, the base abstracts an acidic α-hydrogen from an ester to form a carbanion or ester enolate ion,



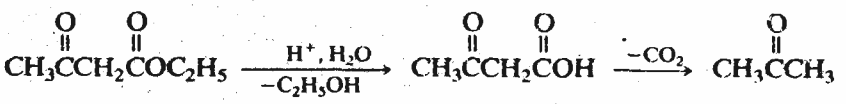
This carbanion adds to the carbonyl carbon of the second molecule of the ester, forming the intermediate anion,



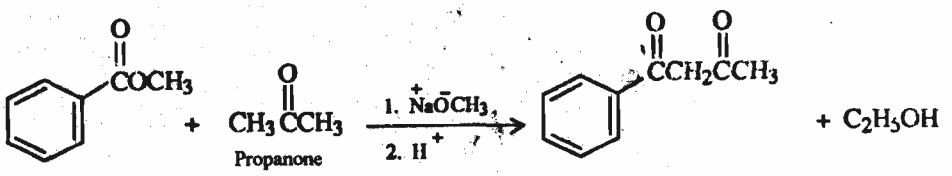
This intermediate anion is unstable. It expels ethoxide ion to yield ethylacetoacetate,



A β-keto ester can be hydrolysed by heating in acidic solution in which decarboxylation of the β-keto acid may occur.



Two different esters can also be used in Claisen condensation. The Claisen condensation between two different esters, both having an α-hydrogen is called **Crossed Claisen Condensation**. However, this type of reaction is not of synthetic importance, because in this case a mixture of products is obtained which is difficult to separate.



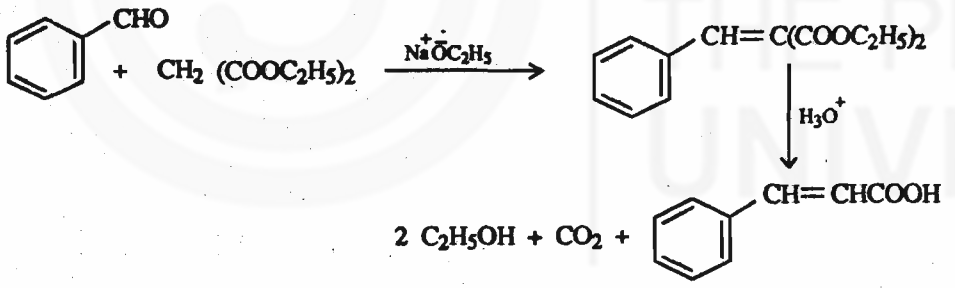
Methyl benzoate

Propanone

1-Phenyl-1-3-butanedione

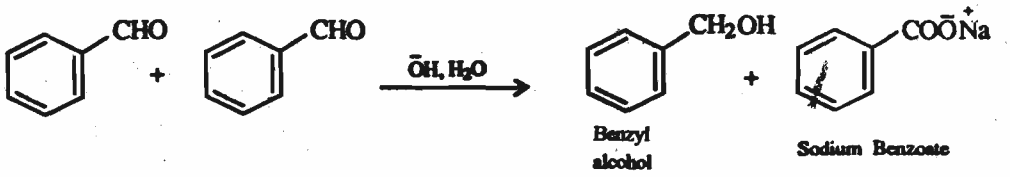
Knoevenagel condensation

Knoevenagel condensation is a reaction of aldehydes and many ketones with a compound that has a hydrogen α to two activating groups (such as C=O or C≡N) in presence of base. For example, benzaldehyde can condense with diethyl malonate to yield α, β-unsaturated diester,



6.5.10 Cannizzaro Reaction

In contrast to aldol condensation this reaction takes place when aldehydes having no α-hydrogen is treated with concentrated alkali or any other strong base. It undergoes self oxidation-reduction reaction and yields a mixture of an alcohol and a salt of the corresponding carboxylic acid. This reaction is known as **Cannizzaro reaction**. For example.



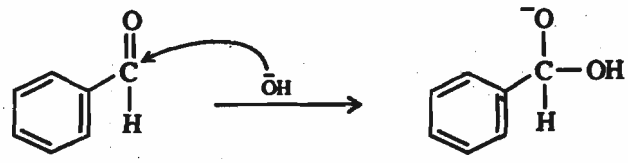
Benzyl alcohol

Sodium Benzoate

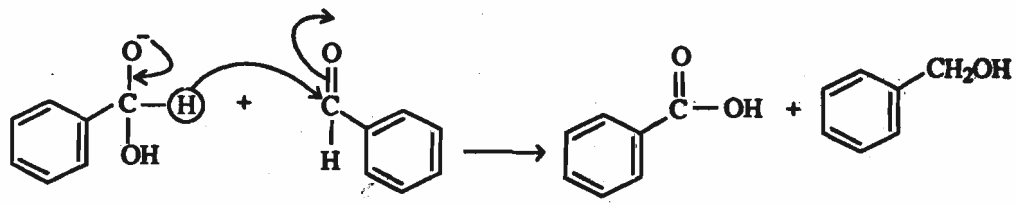
Methanal Methanol Sodium formate

Cannizzaro reaction is shown by all aromatic aldehydes and aliphatic aldehydes which do not contain α-hydrogen, e.g., methanal, trimethylethanal, etc. In general, a mixture of two different aldehydes undergoes a Cannizzaro reaction to give all possible products and is referred to as crossed Cannizzaro reaction.

Mechanism: The first step in the Cannizzaro reaction involves a nucleophillic attack of hydroxide ion on the carbonyl carbon of aldehyde to give an anion.

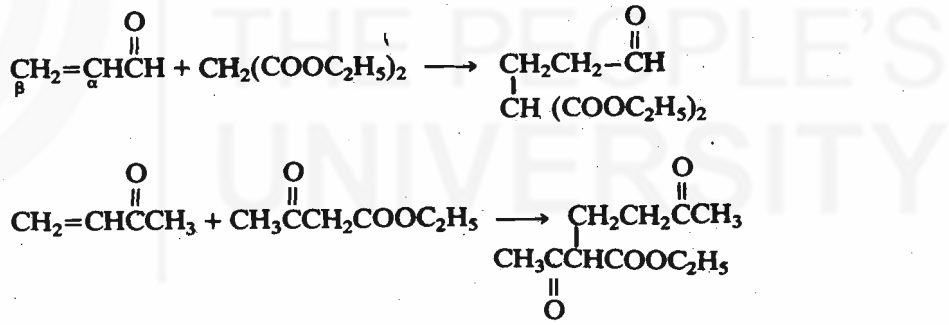


In the second step, transfer of a hydride ion from the tetrahedral intermediate to the second molecule of aldehyde takes place. The net result is that one molecule of aldehyde undergoes hydroxyl substitution for hydride and is thereby oxidised, whereas, a second molecule of aldehyde accepts the hydride and hence, is reduced to an alcohol.

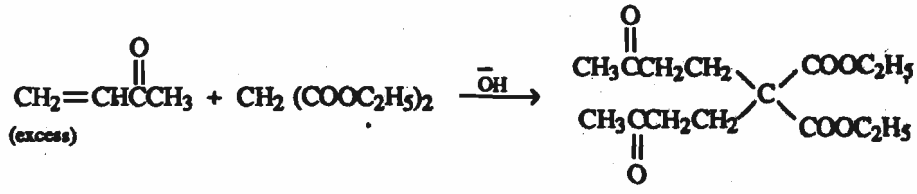


6.5.11 Michael Addition

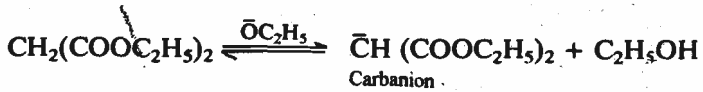
Nucleophiles and carbanions generally do not add to isolated carbon-carbon double bonds. However, when an electron withdrawing group like C=O is present in conjugation with a carbon-carbon double bond, carbanions add to the conjugated system at the site of electron deficiency, i.e., the β-carbon atom. Such addition reactions are known as **Michael addition**. In other words, addition of active methylene compounds to carbon-carbon double bond of α, β-unsaturated carbonyl compounds in the presence of basic catalyst is known as Michael addition. The following examples are illustrative:



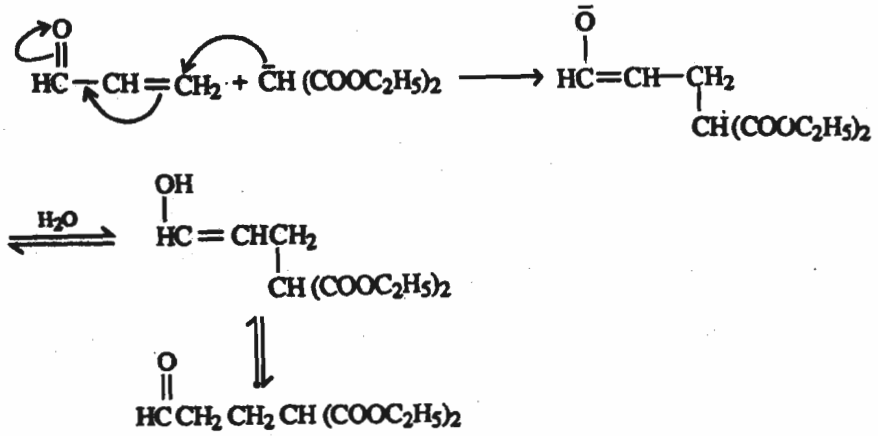
If an excess of the α, β-unsaturated carbonyl compound is used, it is possible to achieve dialkylation.



Mechanism: We take here the condensation of ethyl malonate with propenal as an example. In the first step of Michael reaction the base removes an α-hydrogen atom from ethyl malonate to generate the corresponding carbanion (enolate anion).



In the next step the carbanion attacks at the β-carbon atom of propenal to give the more stable enolate which abstracts a proton from the solvent to yield the final product.



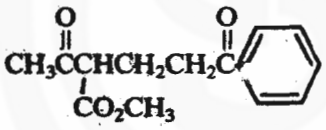
In general the compound from which carbanion is generated must have an acidic hydrogen, so that the carbanion can be obtained easily. Such a compound is usually one that contain a $-CH_2-$ or $>CH-$ group flanked by two electron withdrawing groups on either side.

Michael addition is a general reaction and is not limited to conjugated aldehyde and ketone. Conjugated esters, nitriles, amides and nitro compounds can also undergo Michael addition. For example:

$N{\equiv}CCH{=}CH_2 + CH_2(COOC_2H_5) \longrightarrow N{\equiv}CCH_2CH_2{-}CH(COOC_2H_5)_2$

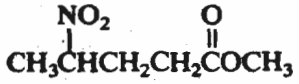
SAQ 5

How can the following compounds be prepared using Michael reaction?

a) 

b) 

c) $(CH_3O_2C)_2CHCH_2CH_2CN$

d) 

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6.6 SUMMARY

- Aldehydes and ketones have carbonyl (C=O) group. The carbonyl carbon atom is sp^2 hybridized and form three σ bonds. It has an unhybridized p orbital which forms a π bond.
- Due to higher electronegativity difference between the carbon and oxygen, the carbon-oxygen double bond (>C=O) is polarised, and, hence, it can undergo electrophilic attack at oxygen or nucleophilic attack at carbon.

- Carbonyl compounds can be classified into two groups: (a) aldehyde and ketone and (b) carboxylic acid and their derivatives.
- Electron withdrawing substituents at the carbonyl carbon increase its reactivity while electron donating substituents decrease its reactivity in nucleophilic addition reactions.
- Bulky groups, substituted at carbonyl carbon, present greater steric hindrance to the approaching nucleophile.
- HCN adds to the carbonyl compounds in the presence of a basic catalyst to give cyanohydrins.
- Most of the aldehydes and and some ketones react with sodium hydrogen sulphite to give hydrogen sulphite adducts.
- The addition of one molecule of an alcohol to an aldehyde or ketone gives a hemiacetal or a hemiketal, respectively. On the other hand, the reaction of two molecules of alcohol to an aldehyde or a ketone, with the loss of water, gives acetal or ketal, respectively.
- Since acetal formation is a reversible reaction it can serve as a protecting group for carbonyl compounds.
- Primary amines react with aldehydes or ketones to form the corresponding N-alkyl or N-aryl substituted imines. This reaction is sensitive to acid catalysis. Therefore, a careful control of pH is essential. Secondary amines react with aldehydes or ketone to give enamines.
- Reactions of Grignard reagents with aldehydes or ketones gives alcohols.
- Two or more molecules of aldehydes or ketones, containing α-hydrogens may combine to form β-hydroxyaldehyde or β-hydroxyketone respectively. This reaction is known as Aldol condensation. There are a large number of reactions related to aldol condensation, e.g., Perkin, Claisen, Knoevenagel, etc.
- When an aldehyde having no α-hydrogen is treated with concentrated alkali, self oxidation-reduction occurs to yield a mixture of an alcohol and the salt of the corresponding carboxylic acid. This reaction is known as Cannizzaro reaction.
- With compounds having a carbon-carbon double bond in conjugation with an electron withdrawing group addition of carbanions may occur at the β-position. This reaction is known as Michael addition reaction.

6.7 TERMINAL QUESTIONS

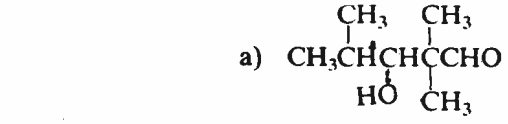
1) List the following aldehydes in terms of increasing reactivity.
CH_3CHO, Cl_3CCHO, $ClCH_2CHO$, Cl_2CHCHO

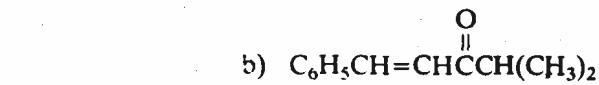
2) Write the structure of the carbinolamine intermediate and the imine/enamine product formed in the reaction of each of the following:

   a) Ethanal and benzylamine

   b) Propanal and dimethylamine

3) Show how would you prepare the following compounds by an aldol/cross aldol condensation?

   a) 

   b) 

4) Show in detail the mechanism of Knoevenagel reaction of diethyl malonate and benzaldehyde.

5) Suggest two synthetic routes to 2-butanol from an aldehyde and a Grignard reagent.

6.8 ANSWERS

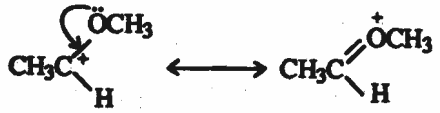
Self-assessment Questions

1) $CH_3\overset{O}{\overset{\|}{C}}CH_3 > CH_3\overset{O}{\overset{\|}{C}}C(CH_3)_3 > (CH_3)_3C\overset{O}{\overset{\|}{C}}C(CH_3)_3$

2) Compound (a) will form the most stable hydrate, because of electron-withdrawal by the Cl atoms.

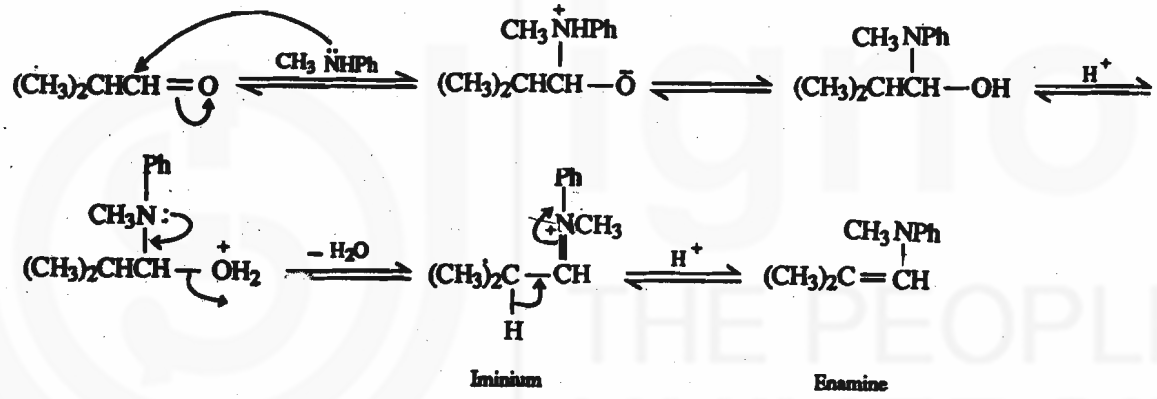
3) a) $CH_3CHO + CH_3OH \rightleftharpoons CH_3CH(OCH_3)OH$

b) $CH_3CH(OCH_3)OH \overset{H^+}{\rightleftharpoons} CH_3CH(OCH_3)-\overset{+}{O}H_2 \overset{H_2O}{\rightleftharpoons} CH_3\overset{+}{C}HOCH_3$



c) $CH_3\overset{+}{C}HOCH_3 + CH_3OH \rightleftharpoons CH_3CH(OCH_3)(\overset{+}{O}HCH_3) \xrightarrow{-H^+} CH_3CH(OCH_3)_2$

4)



5) a) $CH_3\overset{O}{\overset{\|}{C}}CH_2\overset{O}{\overset{\|}{C}}OCH_3 + H_2C{=}CH\overset{O}{\overset{\|}{C}}-C_6H_5$

b) $CH_3\overset{O}{\overset{\|}{C}}CH_3 + H_2C{=}CH\overset{O}{\overset{\|}{C}}CH_3$

c) $CH_2(CO_2CH_3)_2 + H_2C{=}CHCN$

d) $CH_3CH_2NO_2 + H_2C{=}CHCO_2CH_3$

Terminal Questions

1) $CH_3CHO < ClCH_2CHO < Cl_2CHCHO < Cl_3CCHO$

2) a) $CH_3\overset{O}{\overset{\|}{C}}H + C_6H_5CH_2NH_2 \rightarrow CH_3CH(OH)-NHCH_2C_6H_5 \xrightarrow{-H_2O} CH_3CH{=}NCH_2C_6H_5$

Carbinolamine intermediate — Imine

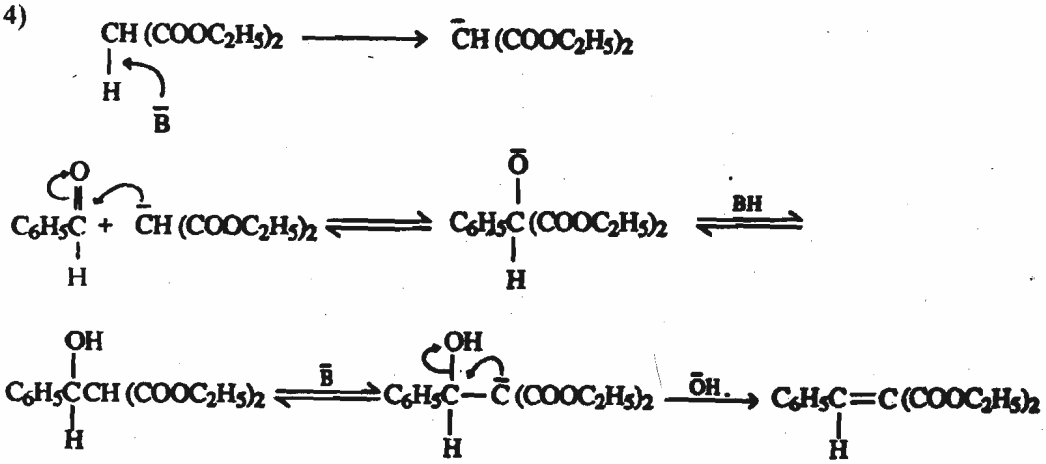
b) $CH_3CH_2\overset{O}{\overset{\|}{C}}H + CH_3NHCH_3 \rightarrow CH_3CH_2CH(OH)N(CH_3)_2 \xrightarrow{-H_2O} CH_3CH{=}CHN(CH_3)_2$

Carbinolamine intermediate — Enamine

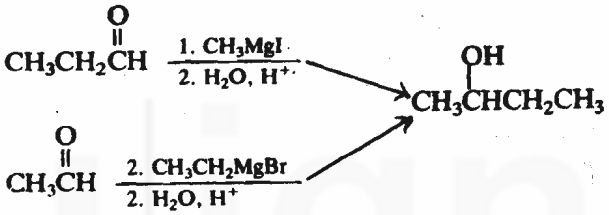
3) a) $2\,(CH_3)_2CHCH(=O) \rightleftharpoons CH_3CH(OH)CH(CH_3)CH(CH_3)CHO$

b) $C_6H_5CH(=O) + CH_3C(=O)CH(CH_3)_2 \rightleftharpoons C_6H_5CH{=}CHC(=O)CH(CH_3)_2$

4)



5)



UNIT 7 ELIMINATION REACTIONS

Structure

7.1 Introduction
Objectives

7.2 Types of Elimination Reactions

7.3 1,2-Elimination or β-Elimination

7.4 E2 Reactions
Evidence of E2 Reactions
Orientation in E2 Reactions
Stereochemistry of E2 Reactions

7.5 E1 Reactions
Evidence of E1 Reaction
Orientation in E1 Reactions
Stereochemistry of the E1 Reactions

7.6 Stereochemistry of E1 Reactions

7.7 Summary

7.8 Terminal Questions

7.9 Answers

7.1 INTRODUCTION

In Unit 3 you studied substitution reactions in aliphatic compounds and in Units 5 and 6 you studied nucleophilic addition to unsaturated hydrocarbons and carbonyl compounds. Now in this unit we will discuss elimination reactions. The term elimination normally refers to the loss of two atoms or groups from a molecule. Thus, an elimination reaction is the reverse of an addition reaction. In this unit we will discuss the types of mechanism (E_1, E_2), the stereochemistry and the orientation pattern of the elimination reaction. Finally we will compare elimination and substitution reactions.

Objectives

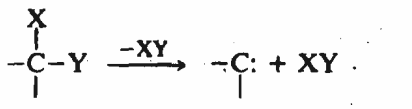
After studying this unit, you should be able to:

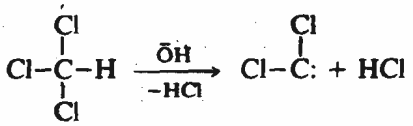
- classify different types of elimination reactions,
- explain the unimolecular (E1) and bimolecular (E2) elimination mechanisms,
- explain the stereochemistry of E1 and E2 reactions,
- discuss the orientation pattern of E1 and E2 reactions, and
- compare elimination and substitution reactions.

7.2 TYPES OF ELIMINATION REACTIONS

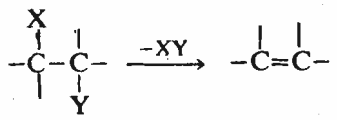
When an alkyl halide is treated with a *base,* an elimination reaction can occur. In organic chemistry elimination normally refers to the loss of two atoms or groups from a molecule. There are many types of elimination reactions i.e. 1,1-elimination, 1,2-elimination, 1,3-elimination etc.

When both the atoms or groups are lost from the same carbon atom to give a carbene, the reaction is called an 1,1-elimination or α-elimination. The most common example of 1,1-elimination is generation of dichlorocarbene from chloroform.

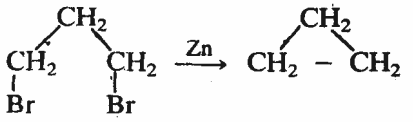




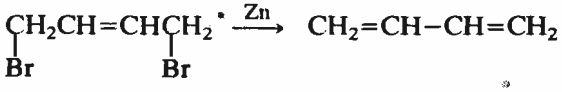
When both the two atoms or groups are lost from two adjacent carbon atoms, resulting in the formation of a double or a triple bond, the reaction is called 1,2-elimination or β-elimination.



Similarly, 1,3-elimination and 1,4-elimination are also known. In 1,3-elimination 3-membered ring is formed and in 1,4-elimination a conjugated diene or a four membered ring is formed.



1,3-elimination



1,4-elimination

Very few examples of 1,1-elimination, 1,3-elimination or 1,4-elimination are known. However, 1,2-elimination is quite common. Therefore, in this unit our discussion will be confined to 1,2-elimination only.

SAQ 1

Fill in the blanks in the following statements.

a) ..... refers to the loss of two atoms or groups from a molecule.

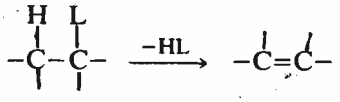
b) When the two atoms are lost from the same carbon atom, the reaction is called ..... .

c) When both the atoms are lost from the adjacent carbon atoms, the reaction is called .....

d) In 1,3-elimination a ..... ring is formed.

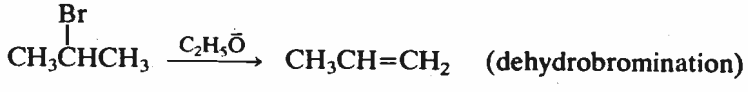
7.3 1, 2-ELIMINATION OR β-ELIMINATION

Alkenes are generally synthesised by elimination reactions from saturated compounds. Elimination of two substituents from adjacent carbon atoms is the usual method for the preparation of an alkene. Most 1,2-eliminations involve the removal of a proton from a carbon atom and another leaving group, L, attached to the adjacent carbon atom.

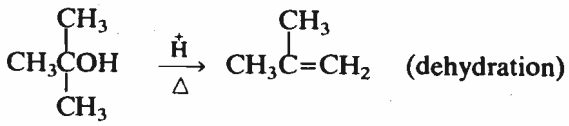


(L = halogen, NR_3, OH, SR_2, OSO_2, OCOR)

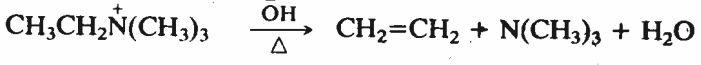
Following are some common examples of such eliminations;



(dehydrobromination)



(dehydration)



In the above instances, the leaving group, L, is respectively $\bar{B}r$, $\bar{O}H$ and $N(CH_3)_3$ and hydrogen atom on the β-carbon atom is lost alongside. Though a hydrogen atom is generally lost in nearly all elimination reactions, there are some reactions where this is not so. An example is removal of halogen atoms from dihalides by metals.

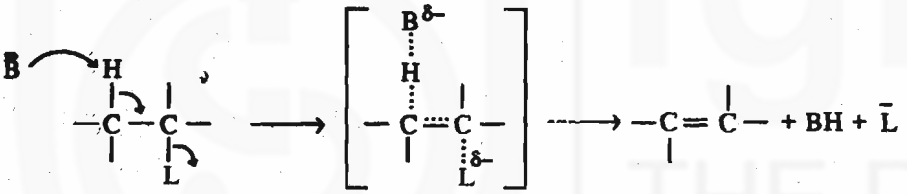
$$BrCH_2CH_2Br \xrightarrow{Zn} CH_2=CH_2 + ZnBr_2 \quad \text{(debromination)}$$

While most of 1,2-eliminations are ionic, there are a few examples of non-ionic 1,2-eliminations that occur on pyrolysis. These are actually uncatalysed intramolecular 1,2-elimination. We are not going to discuss them at this level.

Elimination reactions often accompany nucleophilic substitutions. It is therefore logical to expect a similarity of the kinetics and even mechanistic features in these reactions. Thus, like substitution reactions, elimination reactions also take place through one of the two mechanisms, i.e. unimolecular elimination (E1) or bimolecular elimination (E2). E1 and E2 mechanisms are closely related to S_N1 and S_N2 mechanisms respectively. E1 and E2 mechanisms are different from each other in the timing of the breaking of C–H and C–L bonds and consequently in their kinetics. Now, let us discuss each mechanism separately.

7.4 E2 REACTIONS

E2 mechanism involves breaking of C–L and C–H bonds simultaneously. The base pulls away hydrogen, as a proton, from carbon atom; simultaneously the leaving group departs and a double bond is formed. The leaving group takes its electrons pair with it and hydrogen leaves its electrons pair behind to form the double bond. The mechanism thus a one step mechanism involving a transition state with a partial double bond character,



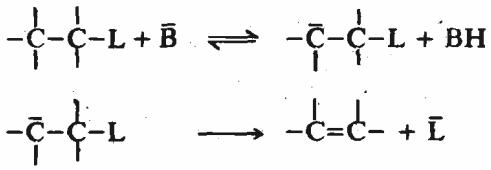
Transition state

Since it is a one step reaction, both reactants are involved in the transition state and the rate of overall reaction depends on the concentration of the substrate as well as concentration of the base, i.e.

Rate α [substrate] [base]

This reaction is known as bimolecular elimination or E2 reaction. Reaction kinetics is typically second order: first order in base and first order in the substrate.

Another mechanism that is consistent with the above kinetic requirements is called the carbanion or ElcB mechanism in which hydrogen leaves first. This is a two steps mechanism. The base removes the hydrogen in the first step to form an intermediate carbanion, which then can react rapidly, in the second step, either to reform the reactants or lose L^- to form the alkene.



ElcB mechanism is the least common of the elimination pathways. The carbanion mechanism has been shown to be a special case and occurs only where the carbanion from the substrate is strongly stabilised and where the leaving group is a poor leaving group and would not be lost from the developing anion. An example of a reaction, which follows

ElcB mechanims, is the formation of 1,1-dichloro-2,2-difluoroethene from 1,1-dichloro-2,2,2-trifluoroethane in the presence of $C_2H_5\bar{O}\overset{+}{N}a$. You may note that the carbanion is strongly stabilised due to -I effect of halogens, further $\bar{F}$ is a poor leaving group.

$$CHCl_2-CF_3 \overset{C_2H_5\bar{O}\overset{+}{N}a}{\rightleftharpoons} Cl_2\bar{C}-CF_3 \xrightarrow{-\bar{F}} Cl_2C=CF_2$$

The name ElcB comes from the fact that it is the conjugate base of the substrate that is giving up the leaving group. The process usually, shows second order kinetic but is designated as ElcB (elimination, unimolecular, of a conjugated base) to indicate that departure of the leaving group from the initially formed carbanion leads to the product.

SAQ 2

Fill in the blanks in the following statements.

a) E2 elimination is a ....step reaction.

b) Rate of E2 elimination depends on concentration of ..... and ..... .

c) Reaction kinetics of ElcB elimination is ..... order.

d) Reaction kinetics of E2 elimination is ..... order.

7.4.1 Evidence of E2 Reaction

The most important evidence supporting this mechanism is the reaction kinetics, which you have just studied. Now, let us see at the other evidence that support E2 mechanism.

i) Absence of Rearrangement

You have studied in Unit 5, that rearrangement is characteristic of carbocations. Since E2 is a single step mechanism, it does not involve intermediate carbocation and therefore, it does not give rearranged product (compare with E1 reaction given later in this unit).

ii) Isotope Effect

A second and more compelling piece of evidence that supports our understanding of E2 mechanism is isotope effect. Isotope effect for been discussed in Unit 2.

Let us consider dehydrohalogenation of labelled (deuterated) and unlabelled 1-bromopropanes.

$$CH_3CH_2CH_2Br \xrightarrow{E2} CH_3CH=CH_2$$

$$CH_3CD_2CH_2Br \xrightarrow{E2} CH_3CD=CH_2$$

The labelled 1-bromopropane contains two deuterium atoms at β-carbon, from which one deuterium atom must be lost in the elimination reaction. We have seen that breaking of the C–H bond is an integral part of the rate determining step of an E2 reaction. The stronger C–D bond requires more energy to be broken. Therefore, rate of elimination in deuterated 1-bromopropane should be slower. In fact, it has been observed that the unlabelled alkyl halide reacts seven time faster than the labelled alkyl halide, $K_H/K_D = 7$.

What is significant about the existence of isotope effect here? This shows the breaking of C-H bond taks place in rate-determing step. Let us compare the rate of this reaction if it was procceding according to E1 mechanism. In E1 elimination, too, C–D and C–H bonds would be broken but from the carbocation, in the second step, which is not the rate determining step. Thus it has no effect on the overall rate of reaction.

iii) Absence of Hydrogen Exchange

E2 eliminations are not accompanied by hydrogen exchange. A distinction between the E2 and ElcB mechanisms can be made by means of tracer experiments to test for hydrogen exchange. The reaction of 1-bromo-2-phenylethane with sodium ethoxide, was run in deuterated ethanol, C_2H_5OD. C_2H_5OD and the unchanged

1-bromo-2-phenylethane was recovered. If the carbanion mechanism had operated, deuterium would have been found in the recovered 1-bromo-2-phenylethane i.e.

$$C_6H_5CH_2CH_2Br + C_2H_5\bar{O} \rightleftharpoons C_6H_5\bar{C}HCH_2Br + C_2H_5OH$$

$$C_6H_5\bar{C}HCH_2Br + C_2H_5OD \rightleftharpoons C_6H_5\overset{D}{\underset{|}{C}}HCH_2Br + C_2H_5\bar{O}$$

The recovered 1-bromo-2-phenylethane did not contain any deuterium, so the carbanion mechanism does not operate in this case.

7.4.2 Orientation in E2 Reactions

An unsymmetrical substrate with at least two hydrogen-bearing β-carbons can afford a mixture of alkenes. For example, 2-bromobutane on 1,2-elimination can give either 1-butene or 2-butene.

$$\underset{\text{2-Bromobutane}}{CH_3\overset{Br}{\underset{|}{C}}HCH_2CH_3} \longrightarrow \underset{\text{1-Butene}}{CH_2=CHCH_2CH_3} + \underset{\text{2-Butene}}{CH_3CH=CHCH_3}$$

Similarly, decomposition of *sec.* butyl tri-methyl ammonium hydroxide also gives a mixture of 1-butene and 2-butene.

$$\underset{\substack{\text{sec. Butyl tri-methyl}\\ \text{ammonium hydroxide}}}{CH_3CH_2\overset{+N(CH_3)}{\underset{|}{C}}HCH_3} \longrightarrow \underset{\text{1-Butene}}{CH_3CH_2CH=CH_2} + \underset{\text{2-Butene}}{CH_3CH=CHCH_3}$$

Now the question arises, which isomer will predominate? The direction of orientation is governed by Hofmann rule or Saytzeff rule. Therefore, let us fist discuss these rules.

Hofmann Rule

Hofmann rule governs the direction of orientation in elimination reactions in which the α-carbon atom is attached to a positively charged atom (Onium Compounds). It states that elimination reactions of positively charged species, the least substituted alkene will be the major product. Although originally applied to quarternary ammonium compounds, this rule has since been applied to other substrates also, in which the α-carbon is attached to a positively charged atom, e.g.

$$CH_3CH_2\overset{S(CH_3)_2}{\underset{|}{C}}H-CH_3 \xrightarrow[-S(CH_3)_2]{C_2H_5O^-} \underset{\text{Major}}{CH_3CH_2CH=CH_2} + \underset{\text{Minor}}{CH_3CH=CHCH_3}$$

$$CH_3CH_2CH_2\overset{+N(CH_3)_3}{\underset{|}{C}}H-CH_3 \xrightarrow[\Delta]{OH^-\Delta} \underset{\text{Major}}{CH_3CH_2CH_2CH=CH_2} + \underset{\text{Minor}}{CH_3CH_2CH=CHCH_3} \quad (-N(CH_3)_3)$$

Saytzeff Rule

Saytzeff rule governs the direction of orientation in elimination reactions involving neutral substrates. It states that a neutral substrate, such as an alkyl halide, is converted preferably to the more substituted alkene. Thus in the above reaction (elimination of 2-bromobropane), 2-butene will be the major product i.e.

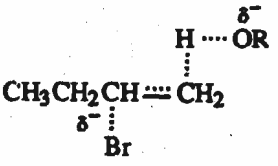
$$CH_3\overset{Br}{\underset{|}{C}}HCH_2CH_3 \xrightarrow{C_2H_5\bar{O}} \underset{81\%}{CH_3CH=CHCH_3} + \underset{19\%}{CH_3CH_2CH=CH_2}$$

or

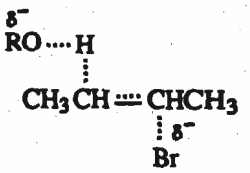
$$CH_3CH_2\overset{CH_3}{\overset{Br}{\underset{|}{C}}}CH_3 \xrightarrow{C_2H_5\bar{O}} \underset{71\%}{CH_3CH=\overset{CH_3}{\underset{|}{C}}CH_3} + \underset{29\%}{CH_3CH_2\overset{CH_3}{\underset{|}{C}}=CH_2}$$

The elimination reactions covered by these orientation rules are base-induced, a property characteristic of E2 reactions. But why is there such a variation in the nature of products obtained from quarternary ammonium compounds on the one hand and alkyl halides on the other? There is no complete agreement on the cause of this entirely different orientation in reactions which apparently follow the same E2 mechanisms. The following reasoning may best explain these differences.

Let us first consider the transition states (T.S.) for the formation of the two alkenes i.e. less substituted and more substituted alkene from an alkyl halide. Both the transition states for the E2 elimination reaction have partial double bond character as shown below:



T.S. of less substituted alkene



T.S. of more substituted alkene

Since both the transition states have double bond character, the transition state leading to more stable alkene is itself more stabilised and is of lower energy (Fig. 7.1)

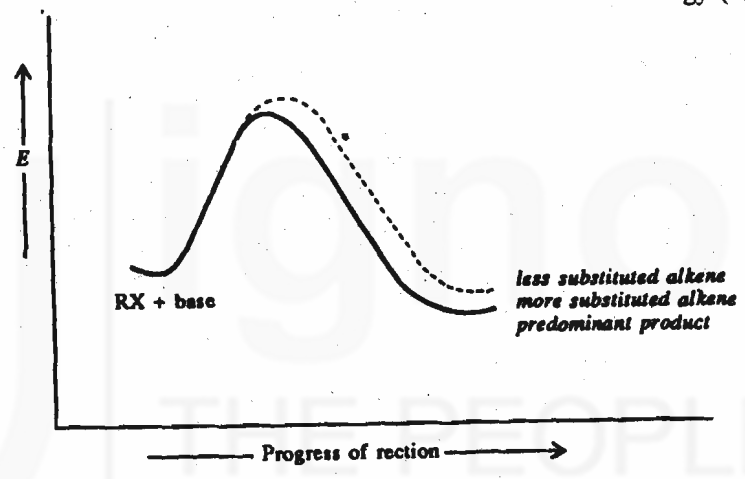
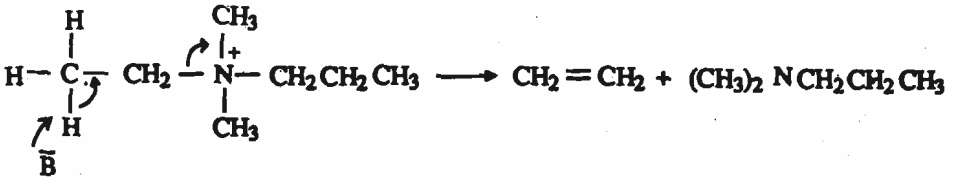


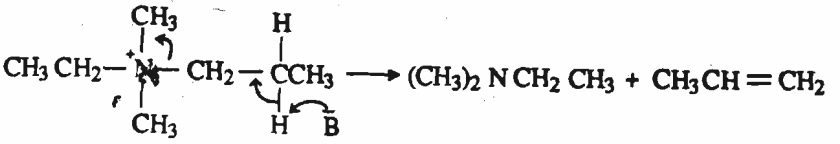
Fig. 7.1 : Energy diagram for a typical E2 reaction, showing why the more substituted alkene predominates.

Therefore, the more stable alkene formed as a major product. The more the number of alkyl substituents on either side of the double bond, the greater the stability of the resulting alkene. Thus, another way of stating Saytzeff rule is to say that the more stable of the possible alkenes is formed preferentially. This is also an instance of "*thermodynamic control*" as the product composition reflects the relative rates of formation of the products. However, Hofmann rule predicts the preferential formation of the less-substituted (i.e. the less stable) alkene. How does one account for this?

The rule can be understood by considering the mechanism of elimination reaction of quarternary ammonium hydroxide. In this reaction, base abstracts a proton from the β-carbon atom with simultaneous expulsion of a tertiary base from the α-carbon atom giving rise to the formation of a double bond, i.e.,



There is one more possibility,



In the presence of strong electron withdrawing group, positive charge is induced on all the surrounding atoms causing the loosening of a β-hydrogen which gets easily abstracted by the base. But if an electron releasing group, say an alkyl group, is attached to this carbon, it tends to neutralise the induced positive charge and thus abstraction of β-hydrogen becomes difficult. It is understandable that if the ammonium salt has an ethyl as well as a propyl group attached to the positively charged nitrogen, ethyl group would be lost more readily to form ethene.

Dehydrohalogenation of alkyl halide using a bulky base leads to the formation of terminal alkene as a major product (steric effect). An example of this type of elimination is:

$$CH_3CH_2\underset{\underset{Br}{|}}{C}HCH_3 + t\text{BuO}^- \rightarrow \underset{73\%}{CH_3CH_2CH{=}CH_2} + \underset{27\%}{CH_3CH{=}CHCH_3} + t\text{BuOH} + Br^-$$

Another type of "orientation" effect may be mentioned here briefly. When a 1,2-disubstituted or a more highly substituted alkene is formed, *cis-trans* isomerism is possible. Thus, 2-bromobutane actually yields three products rather than the two indicated previously. Two of these are geometrical isomers, the third a structural isomer,

$$CH_3CH_2\underset{\underset{Br}{|}}{C}HCH_3 \rightarrow \underset{\underset{cis}{}}{\overset{CH_3}{\underset{H}{>C=C<}}\overset{CH_3}{\underset{H}{}}} + \underset{\underset{trans}{}}{\overset{H}{\underset{CH_3}{>C=C<}}\overset{CH_3}{\underset{H}{}}} + CH_3CH_2CH{=}CH_2$$

As you would expect, the more stable of the isomeric 2-butenes is the *trans* isomer, since the two methyl groups are as far from each other as possible. In general, the geometric isomer of an alkene, which has the two largest groups *trans* to each other is the more stable isomer.

SAQ 3

Give the major products of the following reactions.

a) $CH_3CH_2\underset{\underset{Br}{|}}{C}HCH_3 \xrightarrow{KOH} .....$

b) $CH_3CH_2\overset{+}{S}(CH_3)_2 \xrightarrow{C_2H_5OH} .....$

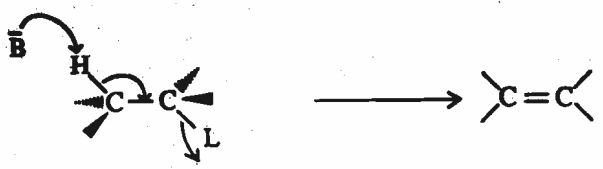
c) $CH_3CH_2CH_2\underset{\underset{{}^+N(CH_3)_3}{|}}{C}HCH_3 \longrightarrow .....$

7.4.3 Stereochemistry of E2 Reactions

A knowledge of the stereochemistry of E2 eliminations is important for a complete understanding of their mechanism and for proper planning of a synthesis. This knowledge is also essential for predicting the product when the substrates are diastereoisomers that can form stereoisomeric alkenes.

An elimination reaction can occur in two stereochemically different ways, *viz.*, *syn* elimination and *anti* elimination. In *syn* elimination H and L leave the alkyl halide from the same side, while in *anti* elimination H and L leave from the opposite sides, i.e.

Syn-elimination

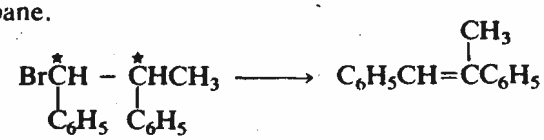


Anti-elimination

Experimentally, it is found that E2 elimination is an *anti*-elimination. The interesting feature of an *anti*-elimination is that the groups that are lost in the formation of the product determine the stereochemistry of that product.

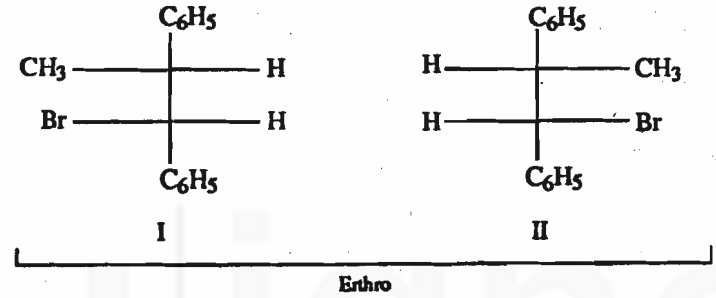
The, E2 reaction seems to be easier when hydrogen and the leaving group are *trans* and the four atoms involved (H, C_β, C_α, L) are in the same plane (*trans* coplanar).

Let us consider another example, dehydrohalogenation of 1-bromo-1,2-diphenyl-propane.

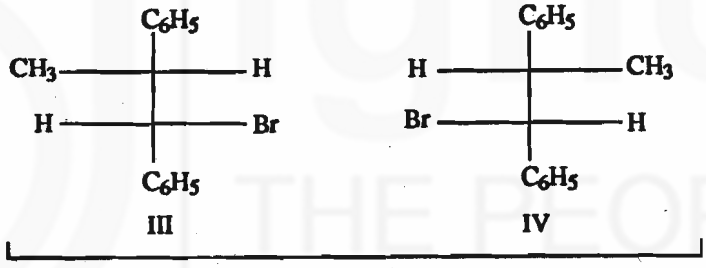


1-Bromo-1,2-diphenyl propane — 1,2-Diphenylpropene

This compound contains two chiral centres and hence it has four stereoisomers. (Two pairs of enantiomers i.e. *erythro* and *threo*.)



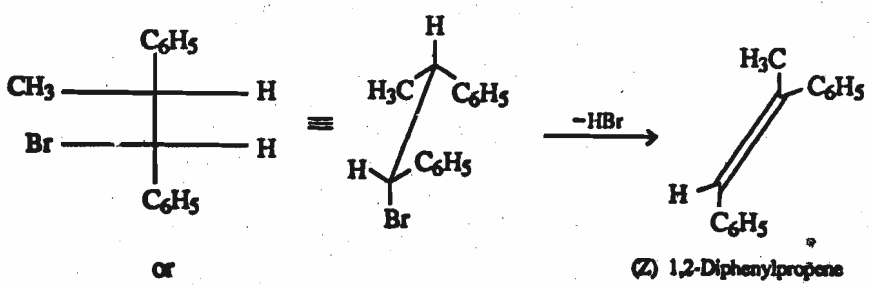
Erthro



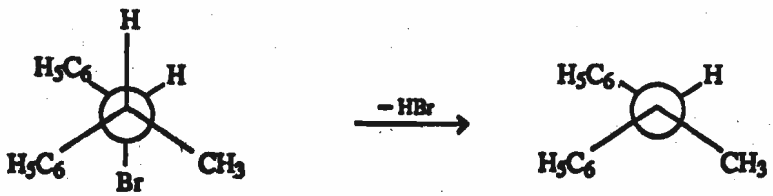
Erythro

Since there is only one β-hydrogen present in the molecule, all the four isomers yield the same product, i.e. 1,2-diphenyl-1-propene. But this product too, exists as a pair of stereoisomer: the *Z* and *E* geometrical isomers.

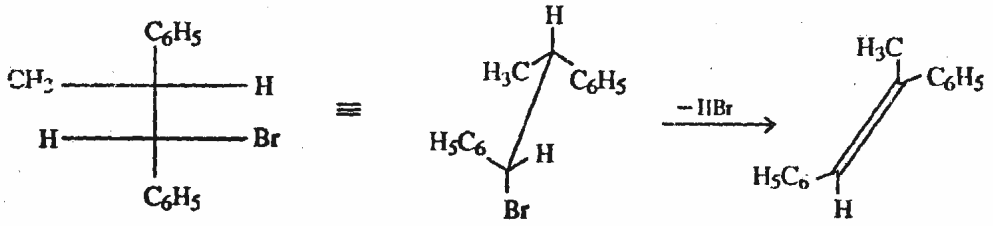
The elimination of HBr from *erythro* halide (I or II), which follows *anti* elimination gives only z-alkene. Since the reaction yields only one diastereomer, *Z*, of a possible pair, it is stereoselective.



(Z) 1,2-Diphenylpropene

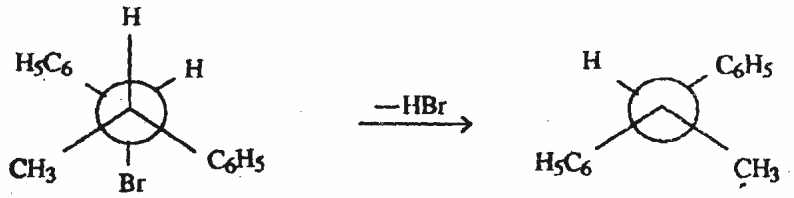


Similarly, elimination of HBr from *threo* halide (III or IV) gives only the *E*-alkene, which also follows *anti*-elimination.



(E) 1,2-Diphenylpropene

or



A reaction in which different stereoisomers of the reactant yield stereochemically different products is said to be stereospecific reaction. Our studies have shown that E2 elimination is both stereoselective and stereospecific.

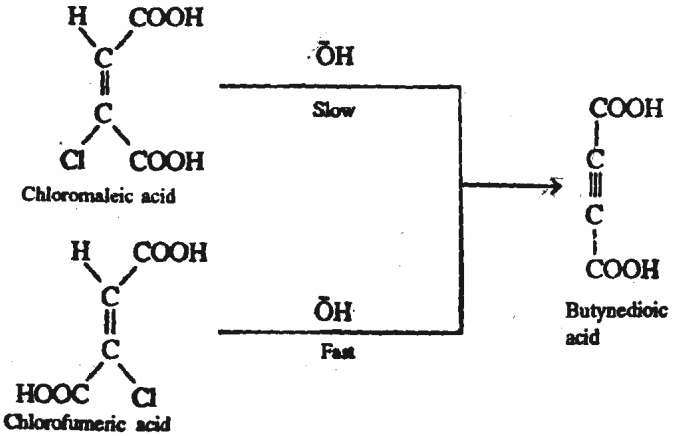
These discussions show that E2 is an *anti*-elimination. Now, the question arises why is *anti*-elimination preferred? This is because *anti*-elimination occurs through a transition state in which the molecule assumes a staggered conformation and *syn*-elimination occurs through a transition state that has an eclipsed conformation. Since staggered conformation is more stable, the transition state of *anti*-elimination is also more stable. Hence *anti*-elimination is faster and preferred over *syn*-elimination. This can also be explained on the basis of steric factor. In *anti*-elimination the attacking species, a base and the leaving group are on opposite side of the molecule and cannot interfere with each other. However, in syn-elimination both, base and leaving group are on the same side and therefore, they can interfere sterically with each other. Therefore, anti-elimination is preferred over syn-elimination. over *syn*-elimination.

The foregoing example shows that the stereochemistry of E2 elimination requires a *trans*-coplanar disposition of the leaving groups in the transition state.

To accommodate the transition state, the eliminated substituents should not only be *trans* but also be coplanar with the α and β carbons. In cyclic compounds such an arrangement can be achieved only when the eliminated substituents are axial.

The requirement of *stereospecificity* in E2 eliminations is dramatically demonstrated in the following example. Benzene hexachloride $C_6H_6Cl_6$ can exist in eight isomeric forms one of which loses HCl 10,000 times more slowly than the others. This isomer has no adjacent chlorine and hydrogen atoms *trans* to each other.

The rate of the following reactions support an *anti*-elimination E2 reactions. The isomeric chloromaleic acid (H and Cl *cis*) and chlorofumaric acid (H and Cl *trans*) both give butynedioic (acetylene dicarboxylic) acid on treatment with a base; but chlorofumaric acid reacts about 50 times faster.



SAQ 4

Predict the dehydrohalogenation products, including their stereochemistry, of the following:

a) mesodibromostilbene
b) ± dibromostilbene.

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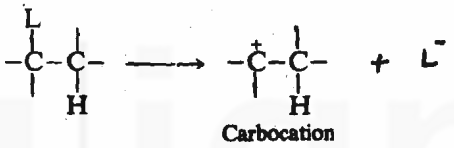
7.5 E1 REACTIONS

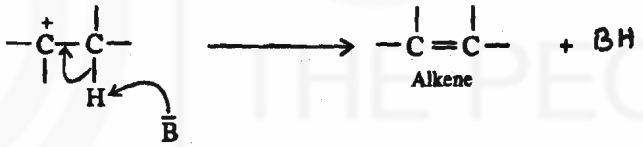
E1 mechanism involves first the breaking of C–L bond which is then followed by breaking of C–H bond and formation of a new π bond between the two carbon atoms. In this mechanism, the bond broken and bond-made are the same as in E2 mechanism; however, bond breaking and bond making here are taking place not simultaneously, but one after the other. Sq, whereas E2 is a one step process, E1 is a two step process.

The first step in an E1 mechanism is identical to the first step of the S_N1 mechanism i.e., the substrate undergoes heterolysis to form a carbocation.



Carbocation

In the second step, the carbocation rapidly loses a β-proton to the base, which is generally the solvent itself, and forms the alkene.



Alkene

The first step of E1 mechanism is slow and therefore, is the rate determining step.

As shown above, only the substrate is involved in the rate determining step that means the rate of reaction is dependent only on the concentration of the substrate and is independent of the concentration of base.

Rate α [substrate]

Therefore, it is known as unimolecular elimination or E1 elimination and the reaction kinetic is of first order.

7.5.1 Evidence of E1 Reaction

Like in E2 reactions, here too, the reaction kinetics is the most important evidence supporting E1 mechanism. The other evidences are given below:

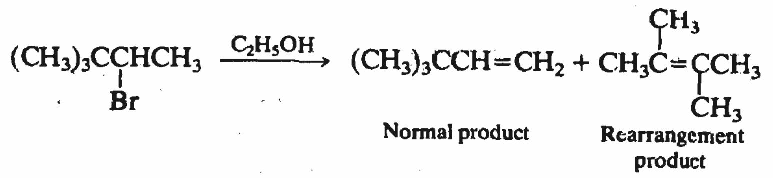
i) Absence of Isotope Effect

E1 mechanism does not show isotope effect. We have seen that isotope effect occur in elimination only if the β-carbon-hydrogen bond is broken in the rate determining step. In E1 mechanism rupture of the C–H (or C–D) bond occurs in the second step which is not the rate determining step, so there is no difference in the rate of reaction in an unlabelled and isotopically (D) labelled compound.

ii) Rearrangement

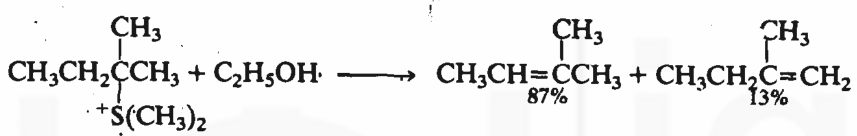
We know that reactivity of E1 reaction is determined by the rate of formation of carbocation and this depends upon the stability of carbocation.

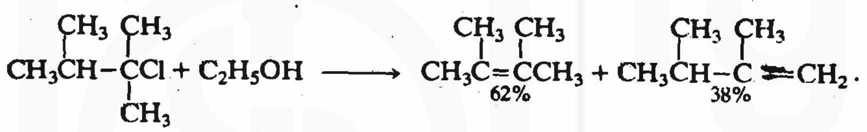
The first step of an E1 reaction gives a carbocation. Since rearrangement is characteristic of carbocations, E1 reaction should be susceptible to rearrangements. This, too, is confirmed by experiment. For example,



7.5.2 Orientation in E1 Reactions

We have studied in section 7.4.2 that the orientation of E2 reactions is governed by the Hofmann and Saytzeff rules. Do E1 eliminations follow these rules? In the E1 reaction, hydrogen is not lost until the carbocation is formed and therefore, the loss should not depend on the nature of the departing group. So, the distinction of a positively charged leaving group and a neutral one cannot be invoked here. Since the same carbocation would arise from ionization of halide or a quarternary ammonium group the same orientation should be observed. This hypothesis has been validated by showing that E1 reactions of both halides and quarternary ammonium salts give the same product — the Saytzeff product i.e., the more substituted alkene. Since the most stable alkene arises from the most stable transition state, one should expect the Saytzeff product to predominate regardless of the substrate or mechanism.





SAQ 5

Does the nature of leaving group effect the E1 reaction?

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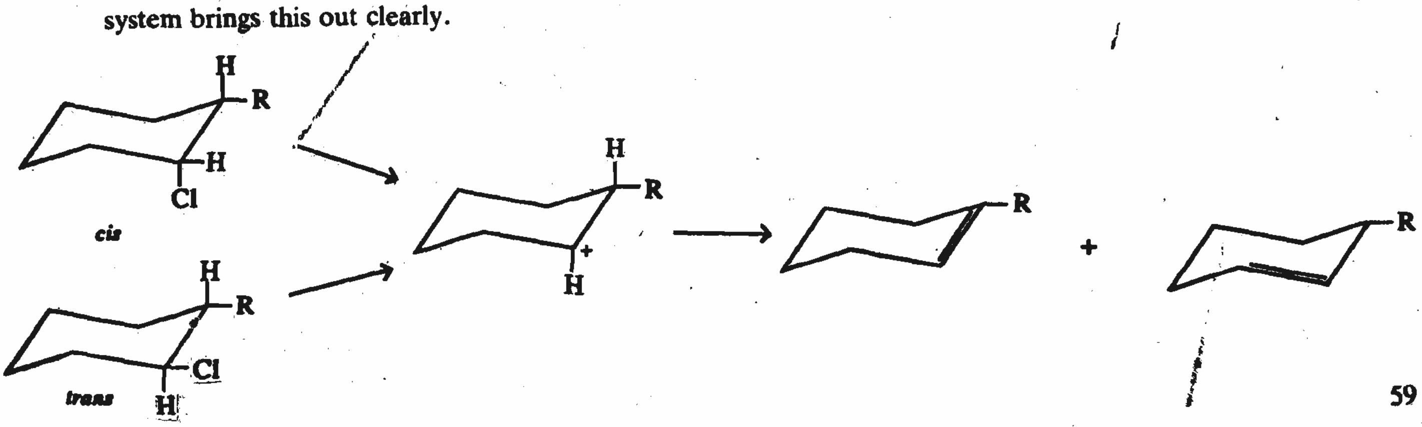
7.5.3 Stereochemistry of the E1 Reactions

You may recall, at this point, the uncertainty in the stereochemistry of S_N1 displacement reactions. The same uncertainty could be expected to exist in the E1 reaction too. The crux of the problem is the half-life of the intermediate carbocation. If the carbocation is sufficiently long-lived, it will become planar and the course of elimination will be independent of the original configuration. In this case, there is no stereospecificity and the more stable alkene is formed. If, however, elimination is completed before the group L has departed far enough to leave a planar carbocation, a *trans*-elimination is favoured. A simple picture of elimination in a cyclohexane system brings this out clearly.



The groups attached to the intermediate carbocation are in a plane and the distinction between *cis* and *trans* disappears because the two sides of the plane are equivalent. Thus *cis* and *trans* isomers of a 2-alkyl cyclohexyl chloride would be expected to yield the same carbocation and hence the same mixture of alkenes, under E1 conditions. In fact, the 1-alkylcyclohexene is favoured. But more of it is formed form the *cis* isomer where H and Cl are *trans* coplanar. The explanation is similar to that for preferred inversion in S_N1 reactions. Apparently the carbocation is still shielded by the leaving group, or is unsymmetrically solvated. It, has thus, some "memory" of the isomer from which it was formed and by analogy with the E2 reactions prefers *trans* elimination. You will also note that the 1-alkylcyclohexene is more stable than 3-alkyl isomer.

7.6 SUBSTITUTION VERSUS ELIMINATION

Substitution and elimination reactions may occur simultaneously. Since the success or failure of a synthetic method will hinge upon the ability of the desired reaction to proceed in the right direction, some understanding of the facts influencing this competition is necessary. We shall now discuss some of these facts that would help us in designing synthesis so as to get the desired products by either substitution or elimination.

Bimolecular substitution as well as elimination are affected by:

- structure of the substrate
- structure of the attacking reagent
- nature of the solvent
- temperature

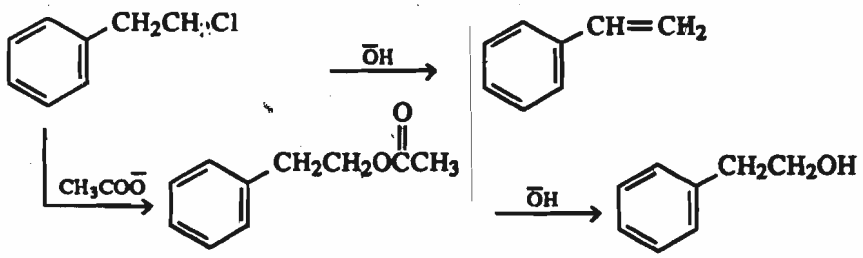
What would be the effect of the structure of the substrate in a competition between the two bimolecular reactions i.e. S_N2 and E2? The rate of the S_N2 reaction decreases and the rate of the E2 reaction increases with increased chain branching in the substrate. The alkene yield should therefore, increase sharply in the series.

$$CH_3CH_2-L < (CH_3)_2CH-L < (CH_3)_3C-L$$

In fact, when bromo alkane are reacted with sodium ethoxide in ethanol, bromo ethane gives mostly ether and only 1% of ethene, while 2-bromo-2-methylpropane (t-butylbromide) gives almost quantitative yield of 1,1-dimethylethene. 2-bromopropane (Isopropyl bromide) gives both propene and 1-ethoxy propane (ethyl propyl ether) in about 3:1 ratio. Thus the E2/S_N2 ratio increases with increasing in α-branching.

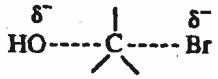
Let us now consider the effect of structure of the attacking reagent on the E2/S_N2 ratio. In E2 reactions, the *basicity* of the attacking reagent is critical since a proton is removed in the first step. In S_N2 reactions, *nucleophilicity* is important. Hence to effect elimination, strong bases such as $\bar{O}H$, $\bar{O}Et$ and $\bar{N}H_2$ should be used rather than merely strong nucleophiles.

An awareness of the role of the base in E2 and S_N2 reactions is essential for designing syntheses properly. Frequently, for example, an alcohol has to be prepared from an alkyl halide that easily dehydrohalogenates. To repress formation of the alkene, the alkyl halide is treated with potassium acetate, a weak base and the resulting ester is saponified. This two-step synthesis affords a better yield of alcohol than the direct one-step treatment of the alkyl halide with KOH, a strong base that gives a preponderance of the alkene.

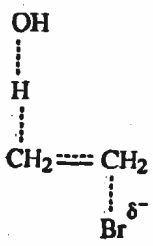


On the other hand, hindered tertiary bases such as NN-diethylaniline and triethylamine are often used to promote dehydrohalogenation when it is desired to avoid displacement.

Effect of the solvent on the E2/S_N2 ratio depends on how well it solvates the two transition states, for the reactants are the same for both the reactions. Let us consider the attack by hydroxide ion on bromoethane. The charge is concentrated on the oxygen atom of the reactant. In the S_N2 transition state, it is spread over three atoms:



In the E2 transition state, it is spread over five atoms.



Charge is dispersed in both reactions, so both will be favoured by less polar solvents. This effect will be more pronounced in an E2 reaction where the extent of charge dispersal is greater. A less polar solvent, then favours an E2 more than an S_N2 reaction. By analogous reasoning, attack of an anionic base on a sulphonium or ammonium salt should give higher elimination/substitution ratios in less polar solvents.

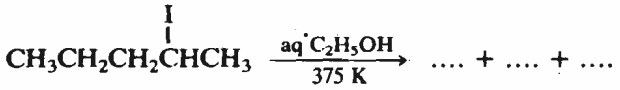
Experimentally it is seen that the alkene yields are usually better in ethanol-ethoxide than in water-hydroxide mixtures. A combination of 2-methylpropoxide ion-2-methyl-2-propanol is stil better than ethoxide ion in ethanol and gives a better yield of alkene. This is as expected, for 2-methyl-2-propanol is a less polar solvent than ethanol, and 2-methylpropoxide is a stronger base than ethoxide.

In unimolecular substitution as well as elimination, the E1/S_N1 ratio is determined almost exclusively by the nature of the alkyl group in the substrate. In general E1 is favoured over S_N1 by branching at the β-carbon. Thus in 80% alcohol at 300 K, 2-Chloro-2-methylpropane affords 16% alkene while 3-Chloro-3-ethyl-4,4-dimithpentane gives 90% alkene.

Careful investigation has shown that where substitution and elimination compete in a given system, elimination normally has the higher activation energy and is thus the more favoured of the two by rise in temperature.

SAQ 6

Predict the products and probable mechanistic path of the following reaction. Justify your answer.



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7.7 SUMMARY

- There are many types of elimination reactions but 1,2-elimination is the most common.

- In 1,2-elimination the two atoms or groups are lost from the adjacent carbon atoms and a double bond is formed.
- Elimination reactions take place either by E2 or E1 mechanisms.
- In E1 reaction the leaving group departs first to produce an intermediate carbocation in rate determining step. In E2 reaction both groups depart simultaneously.
- In E2 reaction both reactants are involved in the rate determining step and therefore, its reaction kinetic is of second order.
- In E1 reaction only the substrate is involved in the rate determining step and therefore, it follows a first order kinetics.
- E2 reactions a) are not accompanied by rearrangement, b) show isotope effect and c) are not accompanied by hydrogen exchange.
- E1 reactions a) are accompanied by rearrangement and b) do not show isotope effect.
- When the more substituted alkene is the product it is said to follow Saytzeff orientation. Formation of the less substituted alkene is the result of Hofmann orientation.
- E2 elimination is normally referred to as *anti*-elimination.

7.8 TERMINAL QUESTIONS

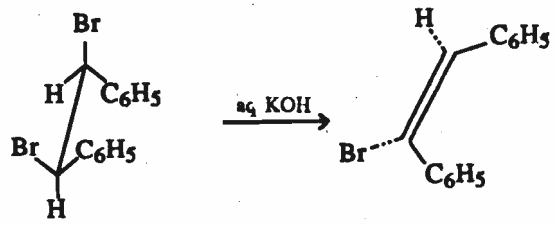
1) Why is isotope effect not observed in E1 reactions?
2) Would you expect a strong stereochemical basis in E1 elimination, that is a perference for *anti* or *syn* elimination? Explain taking specific examples.
3) Define each of the following:
   a) Saytzeff rule b) Hofmann rule
4) Outline the evidence for an E2 reaction.
5) For each of the following pair which compound will react most readily by E2 elimination with sodium hydroxide in ethyl alcohol.
   a) $CH_3CH_2CH_2Cl$ and $(CH_3)_3CCH_2Cl$
   b) $CH_3CH_2CH_2CH_2Cl$ and $CH_3CH_2CH_2Cl$
   c) $CH_3CH_2CH_2OCH_3$ and $CH_3CH_2CH_2OSO_2C_6H_5$
   d) $\begin{matrix} H & & H \\ & >C=C< & \\ CH_3 & & Cl \end{matrix}$ and $\begin{matrix} H_3C & & H \\ & >C=C< & \\ H & & Cl \end{matrix}$

7.9 ANSWERS

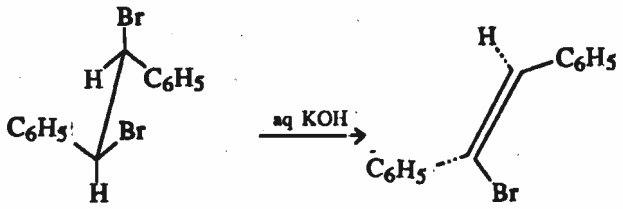
Self-assessment Questions

1) a) Elimination b) 1,1-elimination
   c) 1,2-elimination d) 3-membered
2) a) one b) substrate, base
   c) second d) second
3) a) $CH_3CH{=}CHCH_3$ (Major) + $CH_3CH_2CH{=}CH_2$
   b) $CH_2{=}CH_2$
   c) $CH_3CH_2CH_2CH{=}CH_2$ + $CH_3CH_2CH{=}CHCH_3$ (major)

4) a)



b)



5) No. In the E1 reaction the leaving group is expelled in the first step before the double bond is formed.

6)

$$CH_3CH_2CH_2\underset{\displaystyle OH}{\underset{|}{C}}HCH_3 + CH_3CH_2CH_2\underset{\displaystyle OCH_2CH_3}{\underset{|}{C}}HCH_3 + \underset{(trans)}{CH_3CH_2CH{=}CHCH_3}$$

The two substitution products are formed by an S_N1 mechanism and the one elimination product by E1 mechanism. The alkyl halide is secondary. A weak nucleophile, but polar solvent, is used. These conditions favour substitution reactions, while the high temperature favours elimination.

Terminal Questions

1) The cleavage of C–H bond is not observed in rate determining step of an E1 reaction.

2) No. The carbocation intermediate in an E1 reaction is approximately planar, so proton loss from either side is equally possible.

3) **Hofmann Rule:** It states that the elimination from the charged substrates yield the least substituted alkenes as a major product.

Saytzeff Rule: It states the elimination from neutral substrates generally gives more substituted alkenes as a major product.

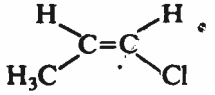
4) Reaction kinetic
Absence of rearrangements
Isotope effect
Absence of hydrogen exchange

5) a) $(CH_3)_3CCH_2Cl$

b) $CH_3CH_2CH_2CH_2Cl$

c) $CH_3CH_2CH_2OCH_3$

d)



UNIT 8 OXIDATION AND REDUCTION

Structure

8.1 Introduction
Objectives

8.2 What is Oxidation and Reduction
Oxidation State

8.3 Oxidation Reactions
Oxidation of Alkenes and Alkynes
Oxidation of Alcohols
Oxidation of Aldehydes and Ketones
Selectivity in Oxidation
Biological Oxidation

8.4 Reduction Reactions
Reduction of Alkenes and Alkynes
Reduction of Aldehydes and Ketones
Reduction of Some Nitrogen Functional Groups

8.5 Summary

8.6 Terminal Questions

8.7 Answers

8.1 INTRODUCTION

You are familiar with reactions involving loss or gain of electrons which are known as oxidation or reduction reactions respectively. Such oxidation and reduction reactions play an important role in organic syntheses and biochemical transformations. It is, therefore, very useful to know the methods and reagents used for oxidising and reducing various types of organic compounds. In this unit you will learn some of these methods.

Objectives

After studying this unit, you should be able to:

- define the terms oxidation and reduction,
- calculate the oxidation number of an element in a molecule,
- describe various methods for the oxidation of alkenes, alkyne, alcohols, aldehydes and ketones,
- explain selective oxidation,
- describe various methods for the reduction of the alkenes, alkynes, aldehydes ketones, and some nitrogen functional groups.

8.2 WHAT IS OXIDATION AND REDUCTION

First we must know what oxidation and reduction mean. Oxidation and reduction can be defined in two ways: loss of electrons or increase in the oxidation state, is defined as oxidation and gain of electron or decrease in the oxidation state as reduction. In organic reactions it is not easy to determine whether a carbon atom loses or gains electrons. However, it is easy to calculate the change in oxidations state. of the carbon atoms and hence, classify a particular reaction as oxidation or reduction. Thus, conversion of a functional group in a molecule, from a lower oxidation state to a higher one will be termed as oxidation, while the opposite of it would be reduction. It is obvious that to fully comprehend oxidation and reduction, one must know what oxidation state stands for.

Oxidation State

A comparison of the oxidation states of atoms in reactants and products enables us to keep an account of the transfer of electrons in a chemical reaction. Oxidation state is equal to the charge an atom would have if all the electrons in a covalent bond were

assigned to the more electronegative atom. You will understand the significance of this definition as you go through the examples given in this section.

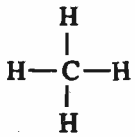
If you know how to calculate the oxidation states of different atoms present in the reactants and the products, you can find out what is oxidised and what is reduced. The importance of oxidation state for the oxidation-reduction reactions is similar to the importance of currency in a business transaction.

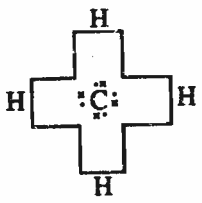
To calculate oxidation states one must know how to write the Lewis structure of molecules and ions. The method of writing Lewis structure has been discussed in detail in Unit 3 of "Atoms and Molecules" course.

You can calculate the oxidation state of a particular atom in a compound or ion using the following formula:

$$\text{Oxidation state} = \text{No. of valence electron(s)} - \text{No. of electrons assigned to the atom after adjustment as per electronegativety}$$

Suppose we want to calculate the oxidation state of carbon and hydrogen atoms in methane molecule. Let us first write the Lewis structure of methane:





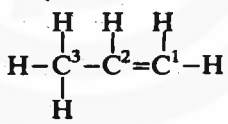
Methane

Note that the bonding electrons which are assigned to carbon atom are shown by means of enclosing lines. Since carbon is more electronegative than hydrogen, all the eight electrons have been assigned to the carbon atom. Hence as per relative electronegativity values, electrons assigned to carbon atom = 8 and electrons assigned to each hydrogen atom = 0.

We know that carbon atom has four valence electrons and hydrogen atom has one. Since carbon is more electronegative than hydrogen, eight bonding electrons of the four C−H bonds have to be assigned to the carbon atom while calculating the oxidation state of this carbon atom. Using the equation stated above:

Oxidation state of carbon = 4−8 = −4
Oxidation state of hydrogen atom = 1−0 = +1

Similarly you can calculate the oxidation states of various carbon atoms in a propene molecule. Since in propene all the three carbon atoms have different electron environment, all the three carbon atoms will have different oxidation state. We will first write the Lewis structure of propene.



No. of valence electrons of all the three carbon = 4
No. of electrons assigned to C_1 = 6
No. of electrons assigned to C_2 = 5
No. of electrons assigned to C_3 = 7

Thus,

Oxidation state of C_1 = 4−6 = −2
Oxidation state of C_2 = 4−5 = −1
Oxidation state of C_3 = 4−7 = −3

Note that the oxidation state of an element in a compound is the average value for the element, if more than one atom of the same element is present in one molecule of the compound. Thus the average oxidation state of carbon in propene is:

$$\frac{(-2) + (-1) + (-3)}{3} = \frac{-6}{3} = -2$$

While assigning the bonding electrons, care must be taken in case of bonds linking atoms of the same element, (e.g., C−C, C=C and N=N). In such cases, the bonding electrons must be distributed equally to each of the two atoms linked.

For example, the four electrons constituting the double bond between two carbon atoms must be distributed equally to each of these two carbon atoms.

We can list a series of compounds according to the increasing oxidation state of carbon:

CH_3CH_3	$CH_2=CH_2$	$CH\equiv CH$	CH_3COOH	CO_2
	CH_3CH_2OH	CH_3CHO	and its	CCl_4
	CH_3CH_2Cl	$CH_3CH_2Cl_2$	derivatives	

increasing oxidation state of carbon

SAQ 1

Calculate the oxidation state of the carbon atom(s) in the following molecules.

a) $CH_2=CH_2$

b) CH_3CHO

.....

.....

.....

.....

8.3 OXIDATION REACTIONS

Some important oxidation reactions are discussed below:

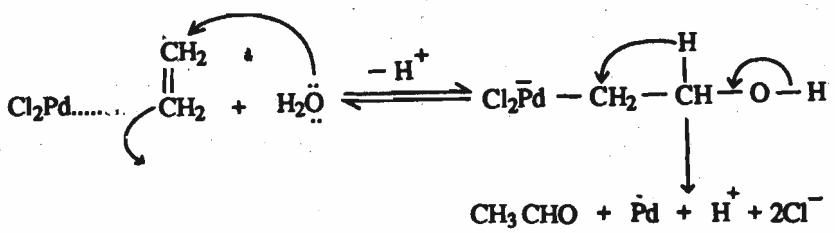
8.3.1 Oxidation of Alkenes and Alkynes

Some oxidation reactions of alkenes and alkynes have been discussed in Unit 5 of this course. In this unit we shall study the oxidation of alkenes using transition metal complexes.

Many organic reactions can be brought about by transition metal complexes. This is a rapidly growing area of organic chemistry with extensive applications in industries. Transition metals possess unfilled orbitals capable of accepting electrons. Simple alkenes can provides a pair of electrons by coordination through the π bond. Such complexes can rearrange to form intermediates, with a carbon metal bond, which undergo further transformation. An example is palladium catalysed oxidation of ethene, known as **Wacker process**, which is used for commercial preparation of ethanal.

$$CH_2=CH_2 + {}^1/_2O_2 \xrightarrow[CuCl_2]{PdCl_2/H_2O} CH_3CHO$$

The reaction is believed to proceed through a palladium complex with the alkene. Water adds to this complex with the formation of a metal carbon σ bond and loss of a proton. In the final step, hydride ion migration occurs as shown.



Cupric chloride reoxidises the palladium formed, regenerating $PdCl_2$ for the continuation of the catalytic cycle.

$$Pd + 2CuCl_2 \rightleftharpoons PdCl_2 + 2CuCl$$

The resultant cuprous chloride can be again oxidized to cupric chloride as shown below:

$${}^1/_2O_2 + 2CuCl + 2HCl \longrightarrow 2CuCl_2 + H_2O$$

Later in this unit, we will see how transition metal complexes can also bring about reduction of alkenes and alkynes.

Terminal alkynes undergo oxidative coupling. For example

$$C_6H_5C{\equiv}CH \xrightarrow{Cu(OH)_2} C_6H_5C{\equiv}CCu \xrightarrow[C_2H_5OH]{O_2,\ NH_3} C_6H_5C{\equiv}CC{\equiv}CC_6H_5$$

This reaction has been used to prepare monocyclic, unsaturated large ring compounds (annulenes)

8.3.2 Oxidation of Alcohols

An important reaction of alcohols is their oxidation to yield carbonyl compounds. Alcohols with α-hydrogen atom(s) undergo oxidation readily. Oxidation of an alcohol involves the loss of one or more α-hydrogens. The nature of the product formed depends upon the number of α-hydrogens present in the alcohol, that is, whether the alcohol is primary, secondary or tertiary. Primary alcohols first give aldehydes by losing two hydrogens. The aldehyde formed tends to undergo further oxidation to give a carboxylic acid. In aqueous solution, aldehydes are more easily oxidised than alcohols. Therefore, oxidation usually continues until the carboxylic acid is formed.

$$\underset{\text{Alcohol}}{RCH_2OH} \xrightarrow{[O]} \underset{\text{aldehyde}}{RCHO} \xrightarrow{[O]} \underset{\text{carboxylic acid}}{RCOOH}$$

Oxidising agents commonly used for the oxidation of primary alcohols to carboxylic acids are, chromium trioxide (CrO_3) in aqueous sulphuric acid (Jone's reagent), potassium permanganate or potassium dichromate. For example,

$$\underset{\text{1-Decanol}}{CH_3(CH_2)_8CH_2OH} \xrightarrow{\text{Jone's reagent}} \underset{\text{Decanoic acid}}{CH_3(CH_2)_8COOH}$$

If the reaction mixture is kept in between the boiling points of the aldehyde and the alcohol, the aldehyde distils off as soon as it is formed and further oxidation is avoided. Yield of aldehydes by this method is usually low. Therefore, this technique is of limited synthetic value.

You will recollect that due to hydrogen bonding alcohols are higher boiling than the corresponding aldehydes.

Pyridinium chlorochromate or chromium-pyridine complex is a more selective reagent. These reagent are soluble in non-aqueous solvents, such as CH_2Cl_2 and oxidation stops at the aldehyde stage.

$$\underset{\text{1-Decanol}}{CH_3(CH_2)_8CH_2OH} \xrightarrow[CH_2Cl_2]{C_5H_5\overset{+}{N}H\ CrO_3\bar{C}l} \underset{\text{Decanal}}{CH_3(CH_2)_8CHO}$$

Secondary alcohols on oxidation give excellent yields of ketones which are stable. Acidic conditions are usually maintained because, ketones get oxidised further in alkaline solution.

$$-\underset{|}{\overset{|}{C}}HOH \xrightarrow{[O]} -\underset{|}{\overset{|}{C}}{=}O \xrightarrow{[O]} \text{Oxidation products}$$

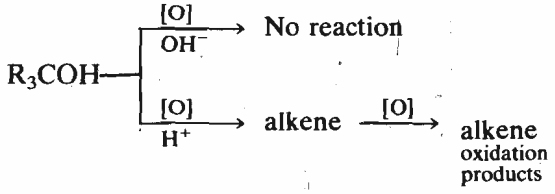
For large-scale oxidations, an inexpensive reagent, sodium dichromate in aqueous acetic acid is used.

$$\underset{\text{2-Octanol}}{CH_3(CH_2)_5CH(OH)CH_3} \xrightarrow[H^+]{Na_2Cr_2O_7} \underset{\text{2-Octanone (96\%)}}{CH_3(CH_2)_5COCH_3}$$

Oxidation of primary and secondary alcohols follows E2 reaction pathway which you have studied in Unit 7. The first step involves the reaction between alcohol and the chromium (VI) reagent to form the chromate intermediate. In the next step, bimolecular elimination takes place to give carbonyl compound.

$$-\underset{|}{\overset{|}{C}}-OH \xrightarrow{CrO_3^-} -\underset{|}{\overset{|}{C}}(H)-O-CrO_3^- \xrightarrow[\text{elimination}]{B_2} -\underset{|}{\overset{|}{C}}{=}O + HCrO_3^-$$

Tertiary alcohols do not get oxidised under alkaline conditions. Under acidic conditions, tertiary alcohols undergo dehydration and the resultant alkene may get oxidised.



SAQ 2

Predict the product(s) of the following reactions

a) $CH_3CH_2OH \xrightarrow{\text{Jone's reagent}}$

b) $CH_3CH(CH_3)OH \xrightarrow{\text{Jone's reagent}}$

c) $(CH_3)_3COH \xrightarrow{\text{Jone's reagent}}$

8.3.3 Oxidation of Aldehydes and Ketones

As mentioned above, aldehydes are very readily oxidised to acid. Aldehydes can be oxidised by the same reagents that oxidise alcohols. Permanganate or dichromate salts are the most common oxidising agents.

$$RCHO \xrightarrow[H_2O]{KMnO_4,\ H^+} RCOOH$$

Aldehydes are so easy to oxidise that even a mild reagent like silver-diammonia complex (Tollens, reagent) can be used for oxidation. For example:

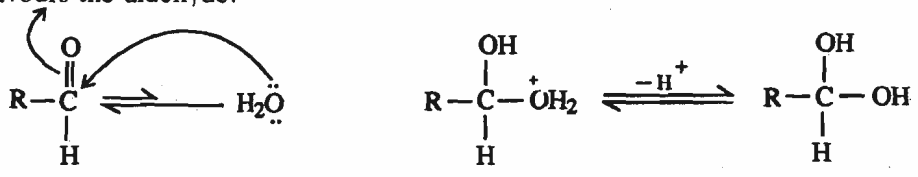
$$RCHO + 2Ag(\overset{+}{N}H_3)_2 + H_2O \longrightarrow RCO\bar{O} + 2Ag + NH_3 + 3\overset{+}{N}H_4$$

Tollens' reagent oxidises aldehydes in high yield without attacking carbon-carbon double bond or other functional groups.

$$\underset{\alpha,\beta\text{-unsaturated aldehyde}}{RCH=CHCHO} \xrightarrow[\text{reagent}]{\text{Tollen's}} \underset{\alpha,\beta\text{-unsaturated acid}}{RCH=CHCOOH}$$

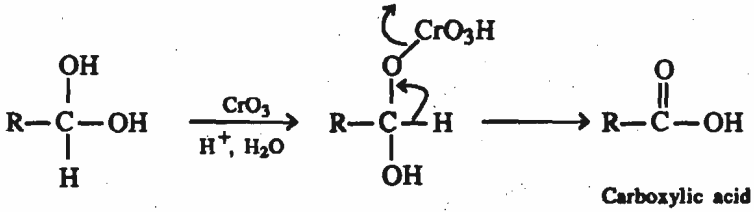
In this reaction, a shining coat of silver metal gets deposited on the glass surface of the reaction vessel. So it can be used as a test to detect the presence of aldehydes. Mirrors are also prepared commercially in this way.

Mechanism: In the first step, H_2O as nucleophile adds to the carbonyl carbon to give a 1,1-diol or a hydrate. Diol formation is a reversible step and the equilibrium usually favours the aldehyde.



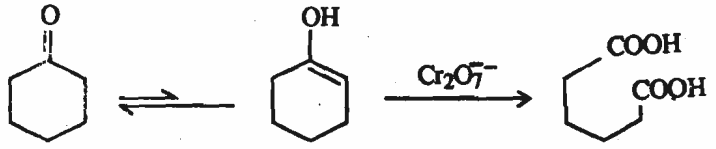
Diol

In the second step the diol reacts like any normal primary or secondary alcohol and is oxidised to a carboxylic acid as discussed in the case of oxidation of alcohol.



Carboxylic acid

Ketones are not easily oxidised. Oxidation of ketones occurs only when forced by the use of strong oxidising agents and perhaps involves the cleavage of the molecule through the corresponding enol to produce an acid.

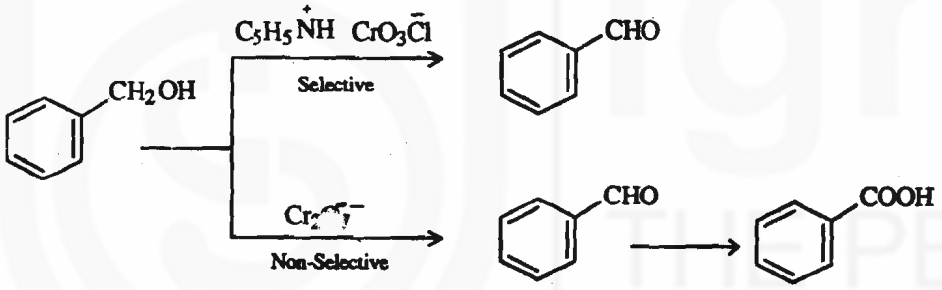


The arrows of unequal length indicate that the equilibrium lies in favour of the ketone. However, as the enol is oxidised more of it gets formed and the reaction can go to completion. The reaction is only useful for symmetrical ketones such as cyclohexanone, as a mixture of products is formed from unsymmetrical ketones.

Oxidation is the reaction in which aldehydes differ from ketones. It is because an aldehydic group contain one hydrogen atom at carbonyl carbon. While a ketonic group has no such hydrogen atom. This hydrogen is abstracted in oxidation. The analogous reaction for a ketone requires abstraction of alkyl or aryl group which does not take place.

8.3.4 Selectivity in Oxidation

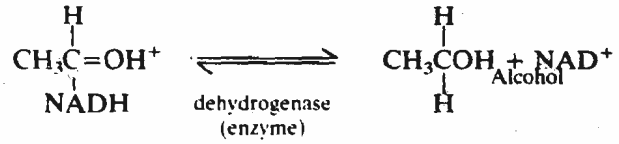
A molecule may contain a functional group which can be oxidised to a product which is susceptible to further oxidation. To stop at the intermediate stage we must use a selective oxidising agent.



In the above example, the dichromate is non-selective between primary alcohol and aldehyde groups while pyridinium chlorochromate oxidises only the alcohol but no the aldehyde. Similarly, for oxidation of a molecule containing more than one oxidisable group, a selective reagent will be needed if oxidation at only one centre is desired.

8.3.5 Biological Oxidation

Oxidation and reduction are very important reactions in living organisms. These reactions are usually very complex. We may, at this stage talk about the technical reduction of ethanal to ethyl alcohol in a simplified manner because it also proceeds through a hydride transfer reaction. The hydride source is the reduced form of the coenzyme nicotinamide adenine dinucleotide. It is a complex molecule but for our purpose we can look at it as NADH which can transfer a hydride ion (like lithium aluminium hydride) and get converted into its oxidised form NAD^+. In biological systems an enzyme catalyst brings together the molecule to be reduced i.e., acetaldehyde and the reducing agent, i.e. NADH. The situation may be considered somewhat similar to a metal bringing together hydrogen and an alkene in catalytic hydrogenation.



Ethanal gains a hydride ion from NADH and a proton from the solvent.

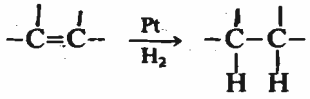
The reaction is reversible and the same enzyme can catalyse the oxidation of alcohol to ethanal.

8.4 REDUCTION REACTIONS

In this section we shall study the reduction of different classes of compounds, like alkenes, alkynes, aldehydes ketones and some nitrogen functional groups.

8.4.1 Reduction of Alkenes and Alkynes

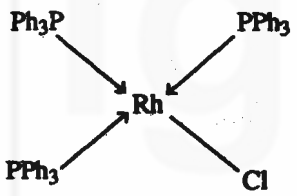
Addition of hydrogen to carbon-carbon multiple bonds (hydrogenation) can be carried out with the help of transition metal catalysts such as platinum, palladium or nickel. The finally divided catalyst is shaken as a suspension with a solution of the alkene in an organic solvent in the presence of hydrogen gas (heterogeneous hydrogenation). You may remember that the manufacture of vegetable fats involves hydrogenation of double bonds present in vegetable oils.



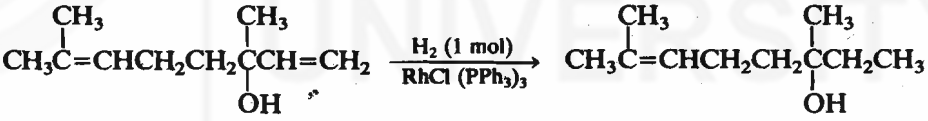
Hydrogen and the alkene first become associated with the metal surface. Hydrogen is then transferred to the unsaturated carbons of the organic molecule. The two hydrogens are added on the same side (*syn*-addition) of the alkene.

Wilkinson and Fischer were given Nobel Prize in 1973 for their work in transition metal chemistry

Some transition metals can be rendered soluble in organic solvents by complexation with ligands, like triphenylphosphine. These complexes can be used for homogeneous hydrogenation e.g. tris(triphenylphosphine) chlororhodium called **Wilkinson** catalyst is soluble in benzene. These complexes can be used for homogeneous hydrogenation.

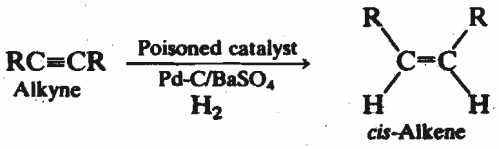


Rhodium catalyst is more selective and can be used to reduce less substituted double bonds in the presence of more substituted double bonds.



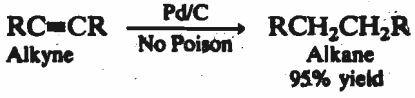
A catalyst mixed with a selective inhibiting agent is called a poisoned catalyst.

Like alkenes, alkynes also undergo catalytic hydrogenation. Addition of hydrogen to an alkyne takes place in two steps. The first addition results in the formation of an alkene; since an alkene can also undergo catalytic hydrogenation, the second addition gives an alkane. By using a calculated amount of hydrogen and a poisoned catalyst, hydrogenation can be stopped at the alkene stage. The catalytic poisons selectively block hydrogenation of alkenes.



Stereoselective reaction is a reaction which yield predominantly one isomer.

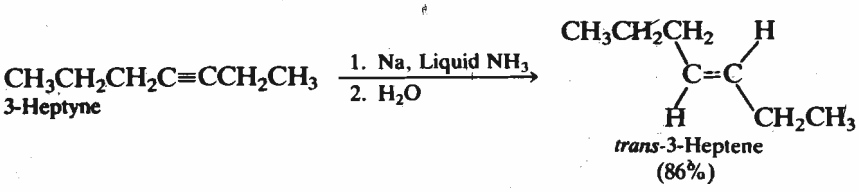
This is a stereoselective addition reaction giving predominantly *cis* alkenes. In the absence of a poison, catalytic hydrogenation of an alkyne gives the alkane.



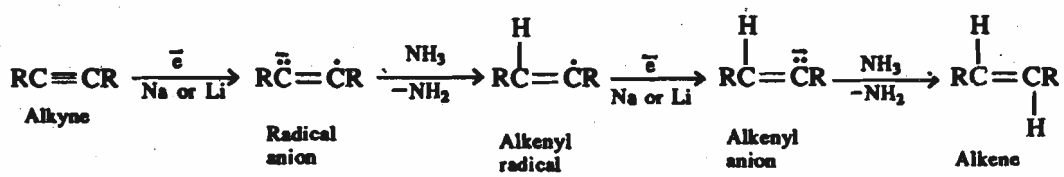
Can we modify the reduction of alkynes so as to get only *trans* alkenes? The answer is yes; we can get only *trans* products, but with a different reducing agent and throgh a different mechanism.

A radical anion has one centre with a negative charge and another, with an unpaired electron.

If we carry out the reduction of an alkyne with sodium metal or lithium metal in liquid ammonia, *trans* alkene is almost the exclusive product. For example, 3-heptyne is reduced to *trans*-3-heptene in this way:

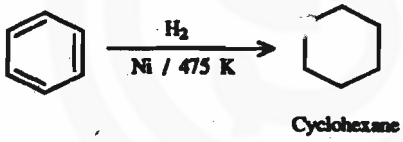


In the first step of this mechanism, the alkyne accepts one electron to give a radical anion. The radical anion is protonated by the ammonia solvent to give an alkenyl radical; which gets further reduced by accepting another electron to give an alkenyl anion. This species is again protonated to give the alkene.

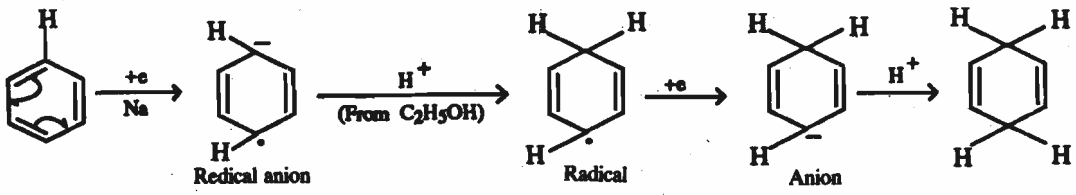


Formation of the *trans* alkene is due to the rapid equilibration of the intermediate alkenyl radical between the *cis*- and *trans*-forms. The equilibrium lies on the side of the more stable *trans* species.

Aromatic rings are resistant to catalytic hydrogenation and hence forcing conditions of high temperature and pressure are required for their hydrogenation.



When aromatic rings are reduced by sodium, potassium or lithium in liquid ammonia, usually in the presence of an alcohol, they yield 1,4-dihydrobenzene (cyclohexa-1, 4-diene). This reaction is called **Birch reduction.** This reaction proceed through a radical anion intermediate.



The function of sodium is to supply electrons while the function of alcohol is to supply protons.

Groups attached to the aromatic ring effect the rate of Birch reduction. Electron donating groups decrease the rate of the reaction and are generally found on the nonreduced position of the product. On the other hand, electron withdrawing groups increase the rate of the reaction and are found on the reduced positions of the product.

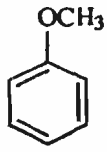
Ordinary alkenes do not undergo Birch reduction. However, phenylated alkenes, internal alkynes and conjugated alkenes do undergo Birch reduction.

Alkenes and alkynes can also be reduced by hydroboration which you have studied in Unit-5.

SAQ 3

Give the products in the following Birch reduction.

a) $CH_3CH=CH_2$ $\xrightarrow{\text{Birch reduction}}$ .....

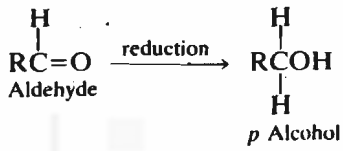
b) 

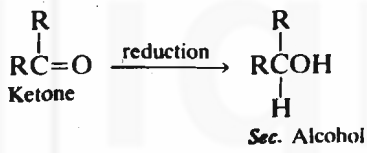
$\xrightarrow{\text{Birch reduction}}$ .....

c) $CH_3CH_2C\equiv CCH_2$ $\xrightarrow{\text{Birch reduction}}$ .....

8.4.2 Reduction of Aldehydes and Ketones

Both aldehydes and ketones undergo reduction, the nature of the product depending on the reagent used for the purpose. Catalytic hydrogenation or reduction with dissolving metals (e.g., sodium and alcohol) or metallic hydrides (lithium aluminium hydride or sodium borohydride) give alcohols. Reduction of aldehydes gives primary alcohols and that of ketones gives secondary alcohols.

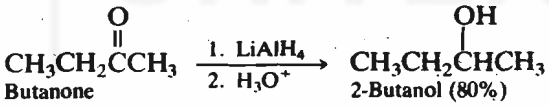




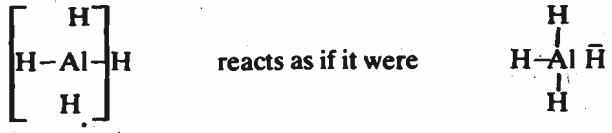
Reduction of aldehydes or ketones can be carried out by a number of reagents. Let us discuss them separately.

Reduction with Metal Hydrides

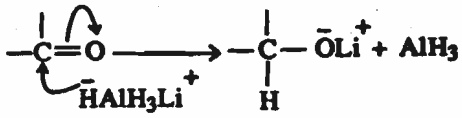
Complex metal hydrides (lithium aluminium hydride or sodium borohydride) are versatile reducing agents. Lithium aluminium hydride ($LiAlH_4$) readily reduces aldehydes, ketones, carboxylic acids, amides and esters. It can be used in solvents like ether or tetrahydrofuran (THF), for example,



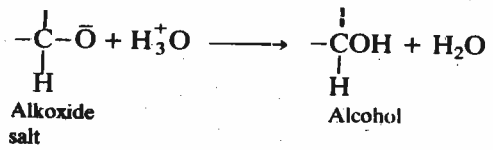
Mechanism: To understand the mechanism of reduction with $LiAlH_4$, let us first study some important characteristics of $LiAlH_4$. This reagent is a good source of H^-, the hydride ion. This is because hydrogen is more electronegative than aluminium. Thus, the Al–H bonds of the $\bar{A}lH_4$ ion carry a substantial fraction of the negative charge. In other words,



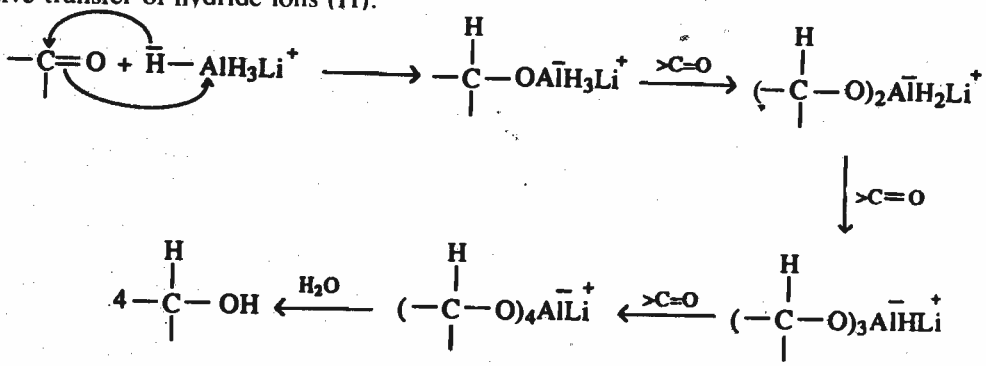
In the reaction of $LiAlH_4$ with an aldehyde or a ketone, the hydride ion (obtained from $A\bar{l}H_4$) attacks the carbonyl carbon and the lithium ion, coordinated to the carbonyl oxygen, acts as a Lewis-acid catalyst.



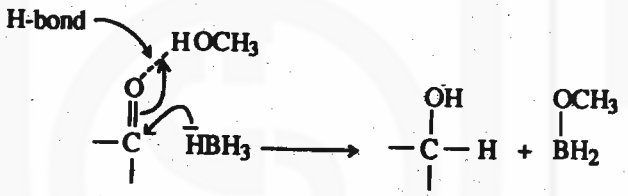
In the second step, proton from hydronium ion is added to the alkoxide salt to give the alcohol.



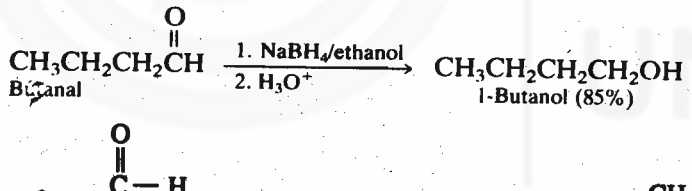
All the four hydrogen atoms in $LiAlH_4$ may be used in reduction which involves successive transfer of hydride ions ($\bar{H}$).

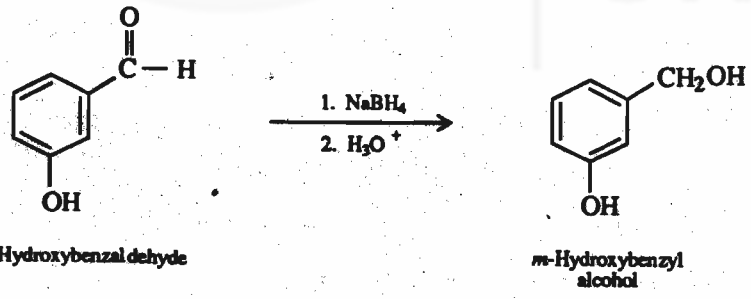


Sodium borohydride ($NaBH_4$) is another important reducing agent. It also reduces aldehydes and ketones to alcohols. The reduction of aldehydes and ketones with $NaBH_4$ is conceptually similar to that of $LiAlH_4$. But unlike lithium ion, sodium ion does not coordinate to the carbonyl oxygen. For this reason $NaBH_4$ reduction can be carried out in protic solvents, like water or alcohol. Hydrogen bonding between the solvent (alcohol) and the carbonyl group serves as a weak acid catalyst that activates the carbonyl group.



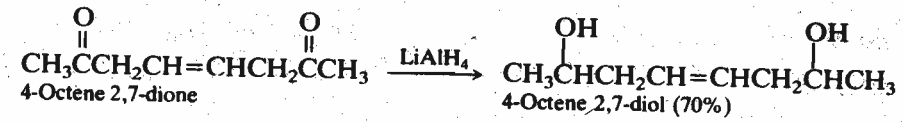
High yields are usually obtained by such reduction, as the following examples indicate.



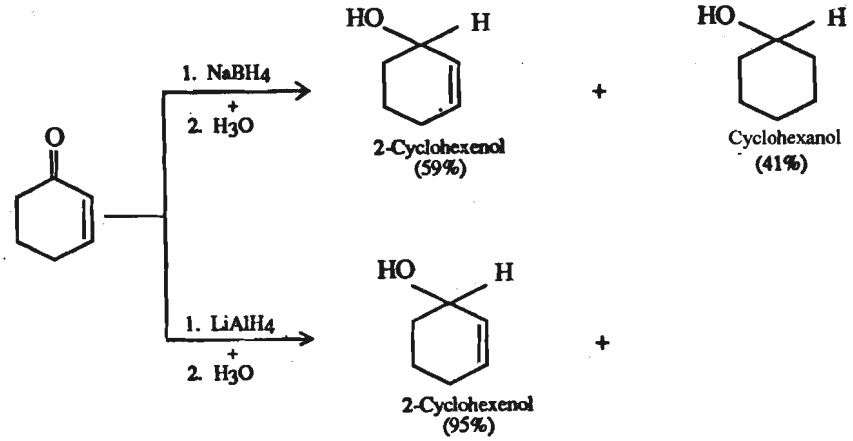


Both $LiAlH_4$ and $NaBH_4$ are highly useful reducing agents. However, $LiAlH_4$ is much more reactive than $NaBH_4$. There are a number of functional groups that react with $LiAlH_4$ but not with $NaBH_4$.

Neither $NaBH_4$ nor $LiAlH_4$ reduces isolated double bonds, consequently, a molecule that contains both a double bond and a carbonyl group can often be reduced selectively at the carbonyl position, e.g.

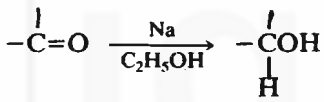


However, a carbon-carbon double bond in conjugation with a carbonyl group is some times attacked.$LiAlH_4$ is particularly useful for reducing α, β-unsaturated ketones which often undergo overreduction with $NaBH_4$ to give a mixture of both unsaturated and saturated alcohols. With $LiAlH_4$, however, a clean reduction to the allylic alcohol occurs. For example, 2-cyclohexenone on reduction with $NaBH_4$ gives 59%, 2-cyclohexenol and 41% cyclohexanol, whereas 95% 2-cyclohexenol is obtained when $LiAlH_4$ is used as a reducing agent.

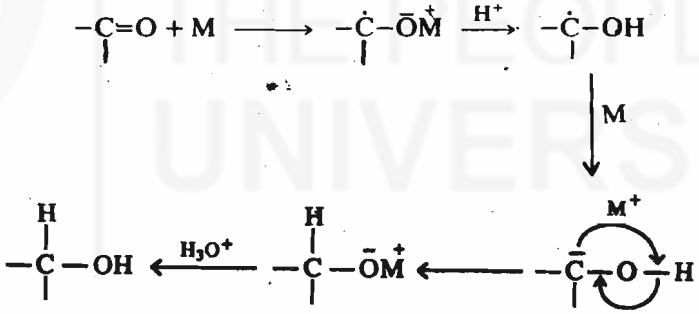


Reduction with Metals

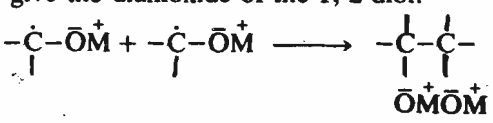
Aldehydes and ketones can also be reduced by treatment with metals e.g., sodium in ethanol.



In connection with the reduction of aromatic compounds, you have learnt that a metal transfers an electorn to the aromatic ring and the radical anion formed takes up a proton to give a neutral radical which is then reduced further. A similar mechanism operates here.



If a proton source is not available, dimerisation of the first formed radical anion may occur to give the dialkoxide of the 1, 2-diol.



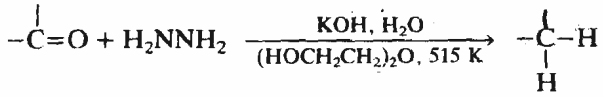
Reduction of Aldehydes or Ketones to Hydrocarbons

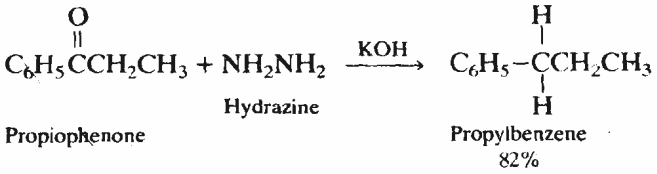
Aldehydes and ketones can be reduced to hydrocarbons by the action of (i) hydrazine and a strong base like potassium hydroxide (wolff-Kishner reduction) or (ii) amalgamated zinc and concentrated hydrochloric acid (Clemmensen reduction) or (iii) aldehydes or ketone and phosphonium ylides (Wittig reaction). Wittig reaction you have studied in Unit 6. Here we shall discuss only wolff-kishner reduction and Clemmensen reduction.

In 1911 Ludwing Wolff in Germany and N.M. Kishner in Russia discovered this reaction independently.

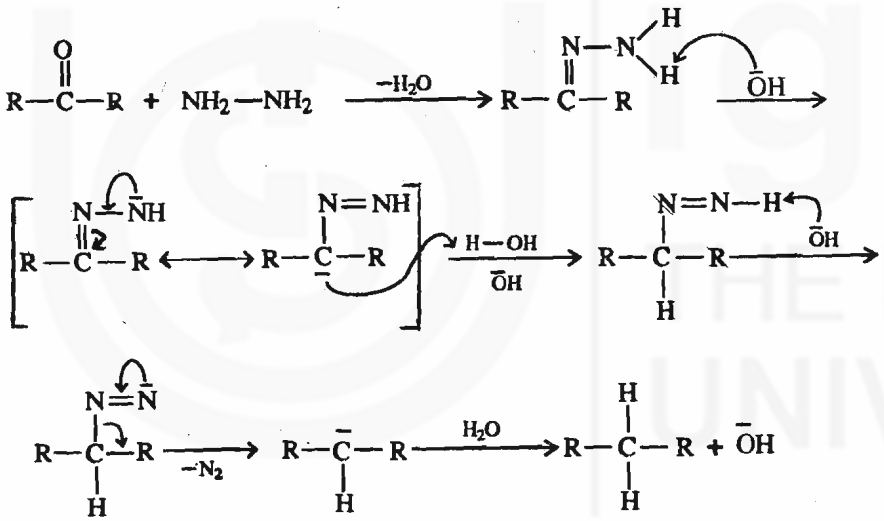
i) Wolff-Kishner Reduction

Aldehydes and ketones can be reduced to alkanes by treating them with hydrazine, H_2N-NH_2, at a high temperature, in alkaline medium. This reaction is known as Wolff-Kishner reduction. It is a useful synthetic method for converting an aldehyde or a ketone to an alkane. For example,





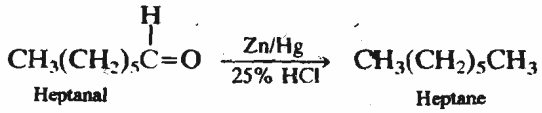
This reaction is an extension of imine formation, discussed in Unit 6. The aldehyde or ketone is first converted to a hydrazone, the imine of hydrazine, by reaction with hydrazine. The hydrazone is then treated with a base, which leads to the expulsion of nitrogen and formation of a carbanion which is instantaneously protonated by water to give an alkane.



Wolff-Kishner reduction can be carried out at room temperature if a strong base like potassium 2-methyl-2-propoxide is used in a polar solvent like dimethyl sulphoxide.

ii) Clemmensen Reduction

Aldehydes and ketones can be converted into the corresponding alkanes under acidic conditions by **Clemmensen reduction**. In this reaction, zinc amalgam (an alloy of zinc and mercury) and concentrated HCl are used to reduce an aldehyde or ketone.



There is considerable uncertainty about the mechanism of this reaction.

Wolff-Kishner or Clemmensen reduction are particularly useful for the introduction of alkyl groups into benzene ring. You may recall that **Friedel-Crafts alkylation can** also be used for this purpose. But the problem with Friedel-Crafts alkylation is that rearrangement of the alkyl groups is usually observed.

SAQ 4

Give the products of the following reactions

a) $CH_3CH_2\overset{O}{\overset{\|}{C}}H \xrightarrow{LiAlH_4}$ .....

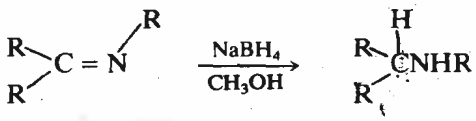
b) $CH_3CH_2\overset{O}{\overset{\|}{C}}CH_3 \xrightarrow{LiAlH_4}$ .....

c) $CH_3CH=CH\overset{O}{\overset{\|}{C}}CH_3 \xrightarrow{LiAlH_4}$ .....

d) $CH_3CH=CH\overset{O}{\overset{\|}{C}}CH_3 \xrightarrow{NaBH_4}$ .....

8.4.2 Reduction of Some Nitrogen Functional Groups

Carbon-nitrogen double bond can be easily reduced by reagents used for carbon oxygen double bond.



Nitriles containing a carbon nitrogen triple bond can be reduced to primary amines with $LiAlH_4$

$$RC{\equiv}N \xrightarrow[Ether]{LiAlH_4} RCH_2NH_2$$

Primary amines can also be obtained by reduction of nitro compounds

$$RNO_2 \xrightarrow[Ether]{LiAlH_4} RNH_2$$

Aromatic nitro compounds are often reduced using a metal, tin or iron, with hydrochloric acid. The amine is obtained as salt from which it can be liberated with aqueous sodium hydroxide. Tin(0) is oxidised to Tin(IV) in the process.

$$2C_6H_5NO_2 + 3Sn + 14HCl \longrightarrow 2\,C_6H_5NH_2 + 3\,SnCl_4 + 4H_2O$$

The reduction is believed to proceed through the following stages:

$$C_6H_5NO_2 \longrightarrow C_6H_5NO \longrightarrow C_6H_5NHOH \longrightarrow C_6H_5NH_2$$

By varying the reaction conditions, specially the pH of the solution, some of these intermediates can be isolated. For example, with Zn dust and ammonium chloride solution, the main product is C_6H_5NOH (phenyl hydroxylamine).

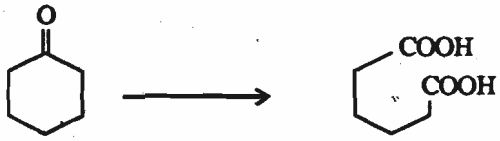
8.5 SUMMARY

- Conversion of a functional group in a molecule from a lower oxidation state to a higher oxidation state is known as oxidation, reduction is just the reverse of oxidation.
- Alkenes can be oxidised to aldehydes using transition metal complexes.
- Alcohols with α hydrogen undergo oxidation with a number of oxidising agents. Primary alcohols first give aldehydes which tend to get oxidised further to give carboxylic acids. Secondary alcohols on oxidation give ketones and tertiary alcohols do not get oxidised easily.
- Unsaturated aliphatic hydrocarbons can be reduced with the help of transition metal catalyst. Aromatic ring can be reduced by sodium or potassium in liquid ammonia to give 1,4-dihydrobenzene.
- Aldehydes are easily oxidised to acids while ketones are fairly resistant to oxidation.

- Both aldehydes and ketones undergo reduction with metals or metallic hydrides ($LiAlH_4$ or $NaBH_4$) to give alcohols.
- Aldehydes and ketones can be reduced to hydrocarbons by (a) Clemmensen reduction (b) Wolff Kishner reduction and (c) Wittig reaction.

8.6 TERMINAL QUESTIONS

1) What reagents can be used to bring about the following transformation.

a) 

b) $CH_3CH_2\overset{O}{\overset{\|}{C}}CH_3 \longrightarrow CH_3CH_2\overset{OH}{\overset{|}{C}}HCH_3$

c) $CH_3CH_2CH_2OH \longrightarrow CH_3CH_2\overset{O}{\overset{\|}{C}}OH$

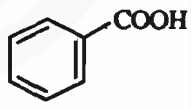
2) Complete the following equations

a) $CH_3CH_2CH{=}CHCH_3 \xrightarrow[Ni]{H_2}$ .....

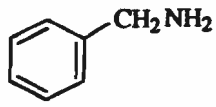
b) $CH_3CH_2C{\equiv}CCH_3 \xrightarrow[2.\ H_2O]{1.\ NaNH_3\ (liq)}$ .....

c) $CH_3CH_2C{\equiv}CH \xrightarrow[H_2\ (excess)]{Pt}$ .....

3) Give starting compounds for the following

a) (?) $\xrightarrow{LiAlH_4}$ 

b) (?) $\xrightarrow[or\ NaBH_4]{LiAlH_4} CH_3CH{=}CHCH_2CH_2OH$

c) (?) $\xrightarrow{LiAlH_4}$ 

4) Write one example for the following reactions

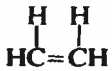
a) Wolff-Kishner reaction

b) Clemmensen reaction

8.7 ANSWERS

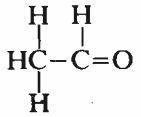
Self Assessment Questions

1) a) Lewis structure of ethene:

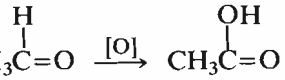


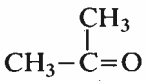
No. of valence electrons of carbon = 4
No. of electron assigned to carbon = 6
Oxidation state = 4−6 = −2

b) Lewis structure of ethanal



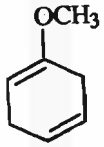
No. of valence electrons of carbon = 4
No. of electrons assigned to alkyl carbon = 7
No. of electrons assigned to carbonyl = 3
Therefore,
Oxidation state of alkyl carbon = 4−7 = −3
Oxidation state of carbonyl carbon = 4−3 = +1
Average oxidation state = (−3) + (+1)/2 = −1

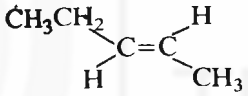
2) a) 

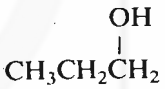
b) 

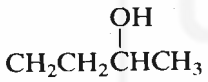
c) No reaction

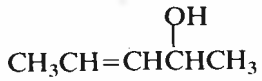
3) a) No reaction

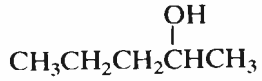
b) 

c) 

4) a) 

b) 

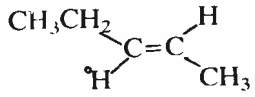
c) 

d) 

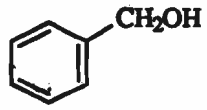
Terminal Questions

1) a) $KMnO_4$, OH
b) $LiAlH_4$ or $NaBH_4$
c) Jone's reagent

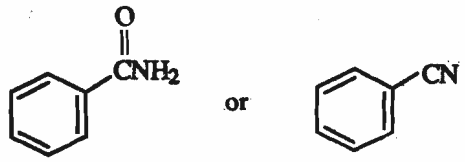
2) a) $CH_3(CH_2)_3CH_3$

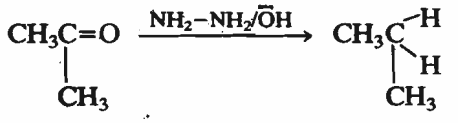
b) 

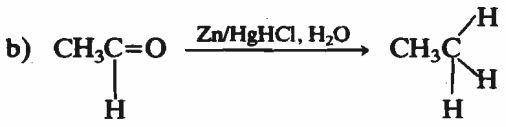
c) $CH_3CH_2CH_2CH_3$

3) a) 

b) $CH_3CH=CHCH_2CHO$

c) 

4) a) 

b) 

Further Reading

1) Organic Chemistry, 5th edition; by R.T. Morrison and R.N. Boyd; Prentice-Hall of India Pvt. Ltd.
2) A Text Book of Organic Chemistry; by B.S. Bhal and Arun bahal; R. Chand & Company Ltd.
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; Himalava Publishing House.