

UNIT – 1 Fundamentals of Organic reaction mechanism : - - - - [7]

1.1 Meaning of reaction mechanism.

1.2 Curved arrow notation; drawing electron movements with arrows. Half headed and double headed arrows.

1.3 Nature of fission – Homolytic and Heterolytic.

1.4 Types of reagents – Electrophiles and Nucleophiles.

1.5 Types and sub types of following organic reactions with definition and at least one example of each.

(a) Substitution (b) Addition (c) Elimination (d) Rearrangement. (Mechanism is not expected)

1.1 Reactive intermediates with examples – Carbocations, Carbanions, Free radicals, Carbenes, Arynes and Nitrenes.

Introduction:

Variety of organic compounds are in great demand and synthesized in large quantity in industry. Optimisation of product yield economically requires very detailed knowledge of the chemical reactions used. This helps in selection of reaction conditions, maximize-product yield and minimize by-product formation. Hence it is essential to know the mechanism of the reaction.

Reaction mechanism:

The reactant molecule which is attacked: substrate (S)

The reactant molecule which attacks: reagent (R)

The molecule formed by the interaction of S and R : product(P)

Representation of reaction: $S+R\rightarrow P$

It simply represents the reaction. i.e. transformation of substrate into product.

But it is essential to know how the reaction is taking place actually.

The description of the path followed by the reactants as they are transformed into products is called reaction mechanism.

It gives information about:

1. sequential account of the each step
2. redistribution of the electrons
3. bonds being broken and made.
4. Intermediates formed if any (structure, energies, destruction, life time) etc.



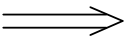
The study of reaction mechanism is important

1. to know the reactivity of the reactants
2. optimum reaction conditions
3. for classification of reactions into four classes.

1.2 Curved arrow notation; drawing electron movements with arrows. Half headed and double headed arrows.

Organic reactions involve breaking and making of some covalent bonds in the reactant molecule. This essentially involves the redistribution of one or more bond pair of electrons/lone pair of electrons. This movement of electron/ pairs within the substrate or in between the substrate and reagent during the reaction is shown by short hand notation of curved arrow. This notation simplifies the reaction mechanism, helps to visualize the process of bond breaking and making, helps to follow the structural changes occurring in the substrate while it is transformed into product.

Kinds of arrows used in the representation of the reaction mechanism:

1. Simple arrow: \longrightarrow represents the conversion of reactants to products.
2. Half headed double arrows: \rightleftharpoons represents the equilibrium i.e. forward and backward reactions occurring at same rate.
3. Double headed arrow: \longleftrightarrow represents the resonating structures of the same molecule.
4. Curved full headed arrow:  represents the movement of the pair of electrons from one bond/atom to another place between the atoms where the new bond is being made.
5. Curved half headed arrow:  represents the movement of a single electron from one atom/bond to new place between the atoms where the new bond is being made.
6. Zigzag arrow: represents movement of photon.
7. Double lines single arrow:  represents the retro synthesis (Possible way to produce the product).

References: 1. Glossary of arrows: Six fundamental arrow types denote different chemical processes.

Curly arrows: There are two types of curly arrows:

for pairs of electrons (more common)

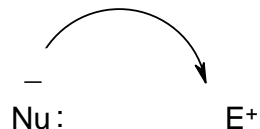


for single of electrons (i.e. radical reactions)



Drawing curly arrows:

Remember that a bond is due to a pair of electrons between atoms. Curly arrows flow from electron rich to electron poor (i.e. nucleophile to electrophile)



Curly arrows must start from either lone pairs or bonds (σ or π bonds)

Therefore, it's a good idea to draw in all the lone pairs as two dots e.g. or especially on oxygen or nitrogen atoms

If the curly arrow starts from a lone pair then the formal charge on that source atom will become more +ve (since electrons have been removed)

If the curly arrow starts from a bond then electrons are being taken out of that bond, so the bond is broken

Curly arrows must end either between a pair of atoms or on an atom

If the curly arrow ends between a pair of atoms, a new bond is formed

If the curly arrow ends on an atom then the formal charge on that destination atom will become more -ve (since electrons have been added)

Balance the charges : The overall charge in any particular step of a mechanism should always be balanced.

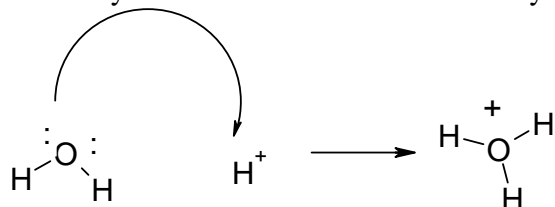
i.e. S (charges on reactants) = S (charges on products)

This is because the total number of electrons must be constant

Take the time to check this after every step of a mechanism.

This requires that you pay attention to the formal charges at each atom to do this.

The curly arrows themselves can also tell you this



Arrow begins at a lone pair on the O atom and goes to the H atom forming a new O-H bond.

Initial overall +ve charge. O atom in product is +ve, it gave away the electrons to form the O-H bond.

Remember to obey the rules of valence ! (i.e. no more than 8 valence electrons for C, N, O, F)

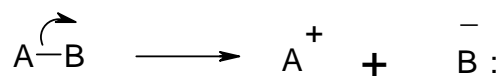
Significance of curly arrows:

Curly arrows are the notation used by organic chemists to indicate the movement of electrons when bonds are made, broken, or moved. You should have learned that a covalent bond between two atoms involves a pair of electrons shared between the two atoms that we say are bonded to one another. The bond is sometimes written as a pair of dots, as in A : B, instead of as the more common single line, as in A—B.

A curly arrow represents the movement of an electron pair from its original position to a new one. The tail of the arrow shows where the electron pair has come from, and the head of the arrow shows where the electron pair is going to. [In more depth, the curly arrow represents the actual movement of a pair of electrons from a filled orbital into an empty one.]

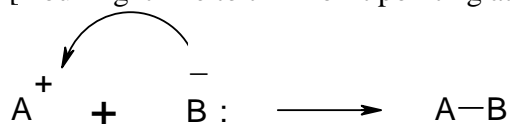
Bond Breaking

The arrow in this diagram indicates that the pair of electrons that form the A-B bond are leaving A and becoming the exclusive property of B. Fragment A becomes positively charged because it is losing an electron, and B becomes negatively charged because it gains an electron. This arrow starts in the centre of the bond and the head should lie on the bromine atom itself, because both the electrons will end up in an orbital on the bromide ion.



Bond Making

In this second diagram, the arrow indicates that an electron pair that was the exclusive property of B is now shared in the bond formed between A and B. Again, the arrow starts at the source of the moving electrons, and the head is drawn in the place where the new bond will be formed. [You might like to think of it pointing at an empty orbital on A.]



Thus, the bond has been formed between a nucleophile and an electrophile. In such a reaction, the nucleophile, which is electron-rich, will always be the source of the electron pair.

Note the following general points

The base of the arrow begins at the original location of the pair of electrons

The head of the arrow points to the destination of the electrons

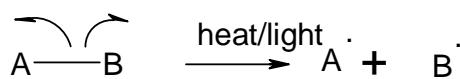
The arrow always starts at a region of relatively high electron density and ends at a region of lower electron density, or on an atom with a strong affinity for electrons.

1.3 Nature of fission – Homolytic and Heterolytic.

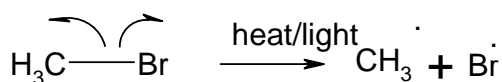
The breaking of the covalent bond of a molecule to form two or more fragment species is called bond fission.

Depending upon the nature of attacking group, leaving group, reacting group and experimental conditions, it occurs in two ways:

1. **homolytic fission** : In homolytic fission, one electron of the shared pair in the covalent bond goes with each of the bonded atoms forming free radicals
The movement of single electron is shown by fishhook arrow as:



Eg.

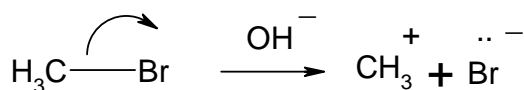
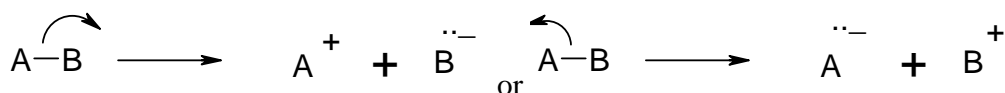


Methyl bromide

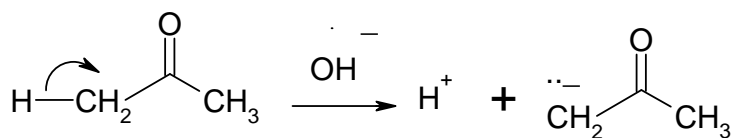
Homolytic fission normally occurs in gaseous phase, in presence of heat, uv light and peroxide catalyst. Organic reactions which proceed by homolytic fission are called free radical reactions/nonpolar reactions.

and

2. **heterolytic fission**: In heterolytic fission, the bonding electron pair is shifted to the more electronegative atom. The movement of the pair of electrons is shown by the full headed curved arrow as:



Eg. Methyl bromide



acetone

Heterolytic fission normally occurs in solution phase, in presence of polar solvents.

The organic reactions which proceed by heterolytic fission are called ionic /polar reactions.

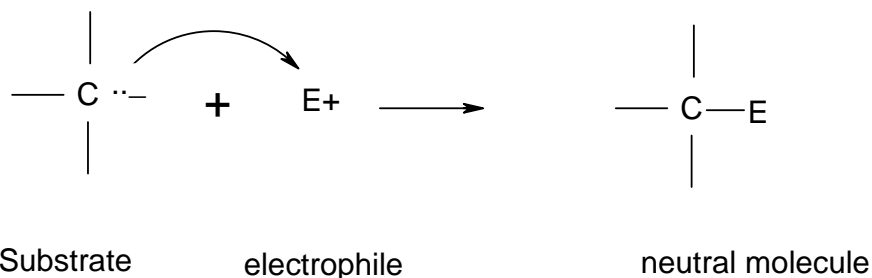
1.4 Types of reagents – Electrophiles and Nucleophiles.:

A reagent is a chemical species that attacks the substrate to form the product in a chemical reaction. Depending on the nature, the reagents are grouped into two types:

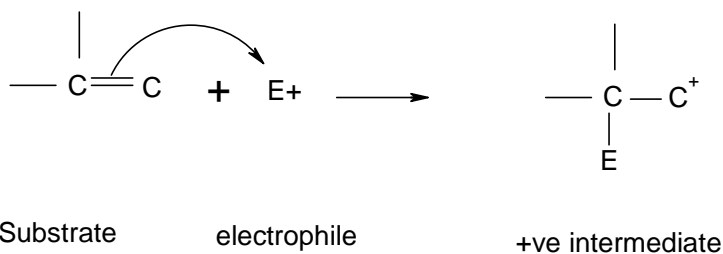
1. Electrophilic reagents:[E]: It is an electron deficient species which attacks an area of high electron density. An electrophile attracts and accepts the pair of electrons from the electron rich centre in a substrate and forms a covalent bond with it. So it acts as a Lewis acid. An electrophile therefore can be a positively charged ion or a neutral molecule having incomplete octet in it.

Eg.

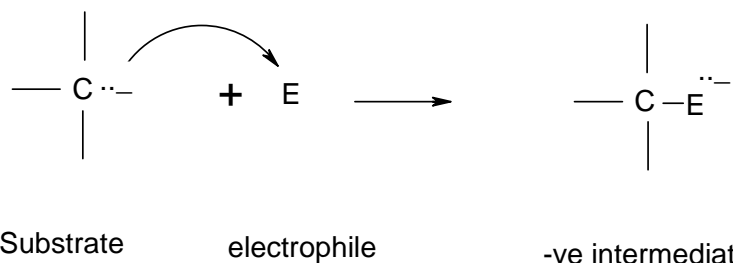
- Positively charged ions as H^+ , Br^+ , Cl^+ , NO_2^+ , NO^+ , NH_4^+ , H_3O^+ , R_3C^+ , $Ar-N^+ \equiv N$ etc. A cationic electrophile when attacks electron rich negatively charged substrate, forms neutral molecule



and when attacks a neutral molecule, forms a positively charged intermediate.



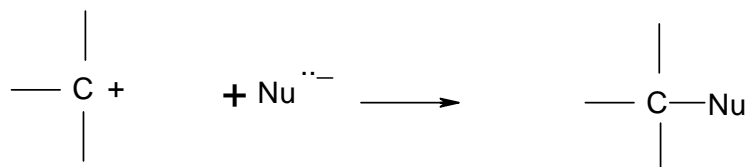
- Neutral electrophiles as BF_3 , $AlCl_3$, $ZnCl_2$, $FeCl_3$ etc. A neutral electrophile when attacks the electron rich molecule forms a negatively charged intermediate



The reactions initiated by attack of electrophile are called electrophilic reactions

2. Nucleophilic reagents: [Nu:] It is an electron rich species which attacks electron deficient centre of the substrate and forms covalent bond with it..

- A nucleophile may be a negatively charged ion: [Nu:⁻] as OH⁻, CN⁻, Cl⁻, Br⁻, I⁻, NH₂⁻, RCOO⁻ etc. Anionic nucleophile when attacks positively charged substrate forms neutral molecule

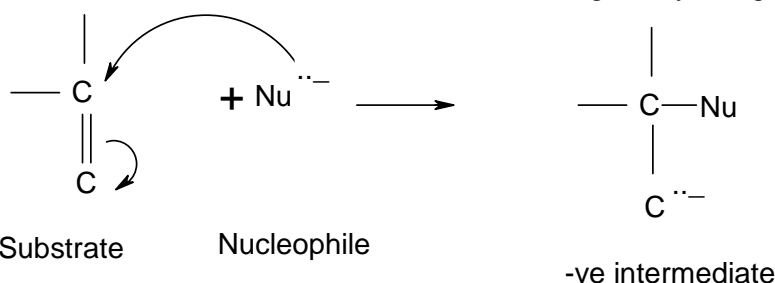


Substrate

Nucleophile

molecule

and when attacks the neutral molecule forms negatively charged intermediate.

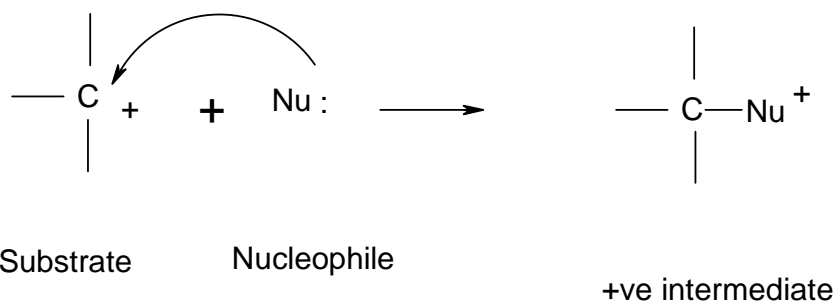


Substrate

Nucleophile

-ve intermediate

- A neutral species with atleast one lone pair of electrons on the central atom. As H₂O, ROH, RNH₂, NH₃, RSH etc where N, O and S carry 1,2 and 2 lone pairs of electrons respectively. When the neutral nucleophile attacks the positively charged substrate, forms positively charged intermediate.



Substrate

Nucleophile

+ve intermediate

1.5 Types and sub types of following organic reactions :

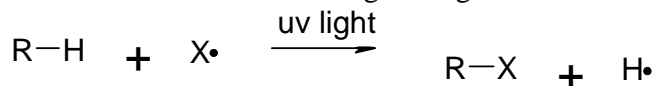
Organic reactions are broadly classified into four classes as:

- (a) Substitution (b) Addition (c) Elimination and (d) Rearrangement.

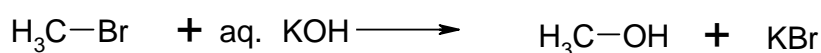
Depending upon the mode of reaction, they are further subclassified accordingly.

[a] Substitution: An organic reaction in which one atom or group is replaced by another atom or group is called substitution. There can be a substitution of free radical by free radical or electrophile by electrophile or nucleophile by nucleophile.

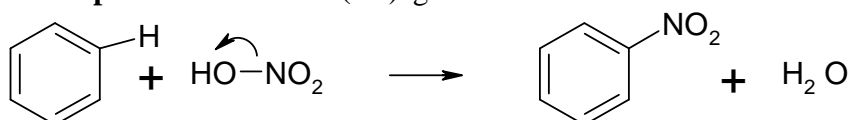
- **Free radical substitution:** eg. Halogenations of alkane



- **Nucleophilic substitution (SN)** eg. hydrolysis of methyl bromide with aq. KOH

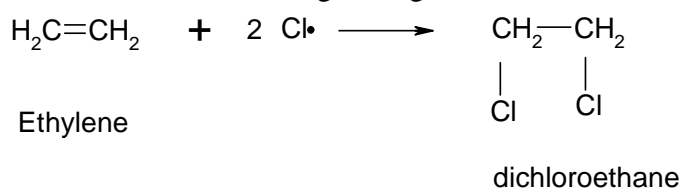


- **Electrophilic substitution (SE)** eg. Nitration of benzene

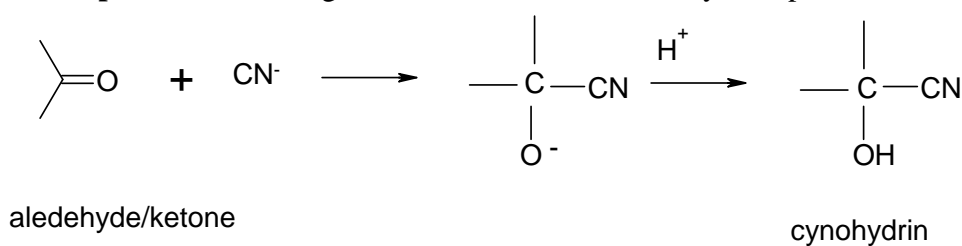


[B] Addition reaction: An organic reaction in which the molecule adds to a multiple bond to form a single product is called addition reaction. Depending upon the attacking group in initial step, it is subclassified into free radical, nucleophilic or electrophilic addition reaction.

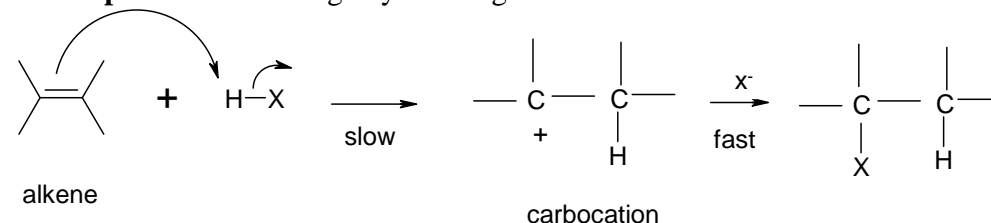
- **Free radical addition:** eg. Halogenation of alkene



- **Nucleophilic addition:** eg. Addition of HCN to Carbonyl compound

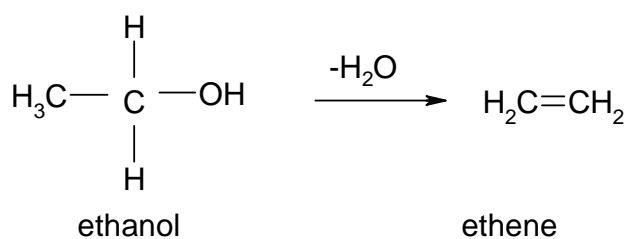


- **Electrophilic addition:** eg. Hydrohalogenation of alkene

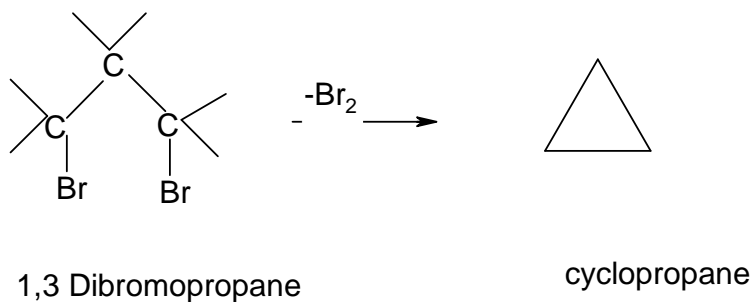


[C] Elimination reactions: Organic reactions in which two atoms or groups are removed from a molecule to form a multiple bond are called elimination reactions. Depending upon the position of the two groups removed, it can be sub classified into subtypes as (1,2-) or 1,3-) eliminations.

- **(1,2-) or (α - β) elimination:** eg. dehydration of ethanol



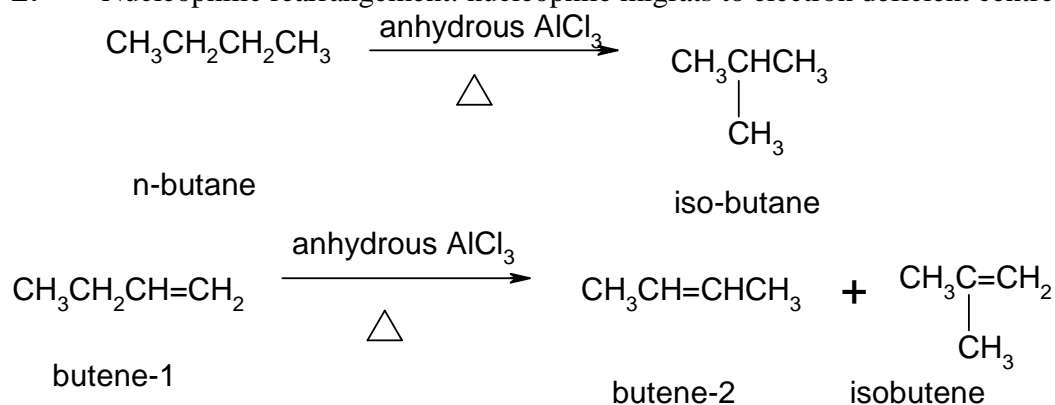
- **(1,3-)or (α - γ) elimination:** eg. dehalogenation of 1,3 dibromopropane



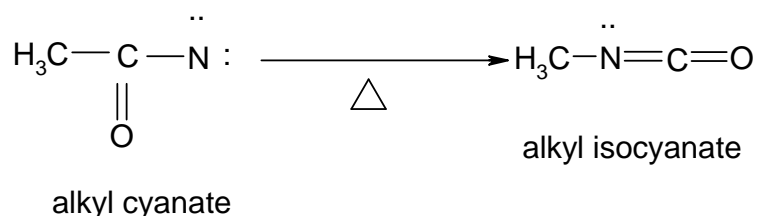
4. Rearrangement reactions:

The reactions in which an atom or group from one position migrates from one position to another within the molecule to form its isomer is called rearrangement reaction. Depending upon the nature of the migrating group they can be grouped into subclasses as

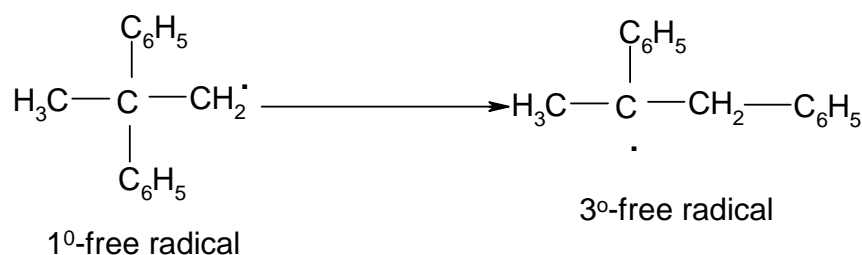
1. Nucleophilic rearrangement: nucleophile migrates to electron deficient centre.



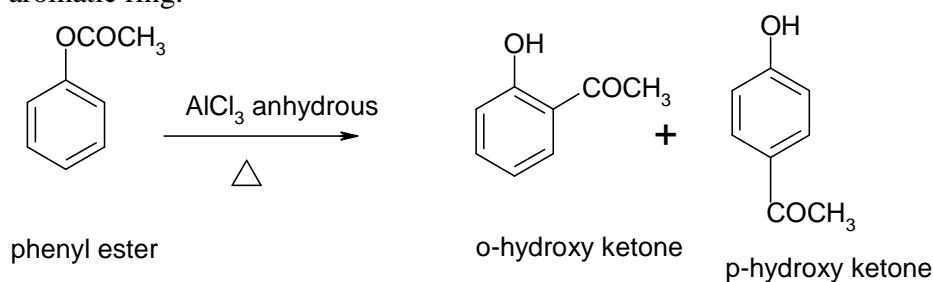
2. Electrophilic rearrangement: electrophile migrates to electron rich centre.



3. Free radical rearrangement: less stable free radical gets rearranged to more stable free radical.



4. Aromatic rearrangement: Migrating group moves to a different position in aromatic ring.



3.6 Reactive intermediates:

These are highly reactive, short lived intermediates formed transiently due to bond fission during a chemical reaction called reactive intermediates.

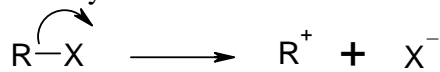
They vary in their stability, have different half life time ranging from few milliseconds to several minutes. They are formed during the reaction and cannot be separated their existence is proved by spectroscopic studies.

Examples: Carbocation, Carbanion, Carbon free radical, Carbene, Nitrene etc.

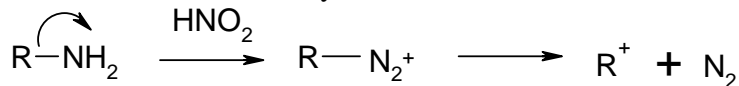
1. **Carbocation:** An organic species in which the positive charge is carried by trivalent carbon having electron sextet in its valence shell is called carbocation.

Formation: Carbocation is formed due to heterolytic fission of a bond between carbon and more electronegative atom like O,N,X or due to protonation. Eg.

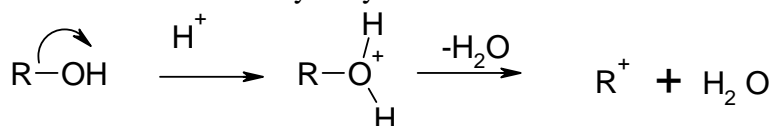
- A. Solvolysis of C-X bond



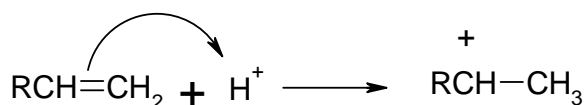
- B. Deamination of amines by nitrous acid



- C. Protonation followed by dehydration of alcohols



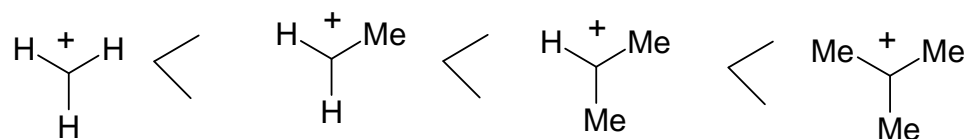
- D. Protonation of alkenes



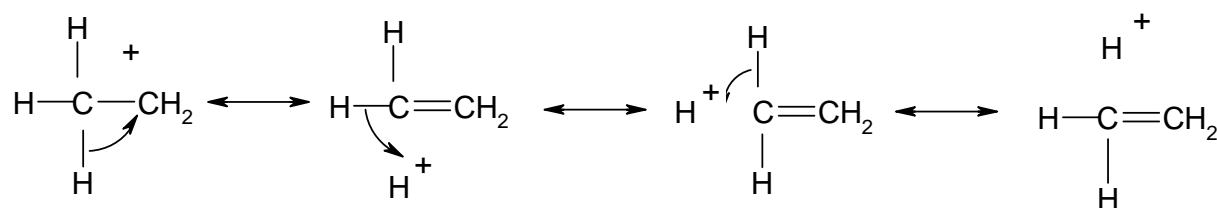
Structure: A **carbocation** is an [ion](#) with a positively-charged [carbon atom](#). The charged carbon atom in a carbocation is a "sextet", i.e. it has only six [electrons](#) in its outer [valence shell](#) instead of the eight valence electrons that ensures maximum stability ([octet rule](#)). Therefore carbocations are often reactive, seeking to fill the octet of valence electrons as well as regain a neutral [charge](#). The reactivity of a carbocation more closely resembles [sp² hybridization](#) with a [trigonal planar](#) molecular geometry



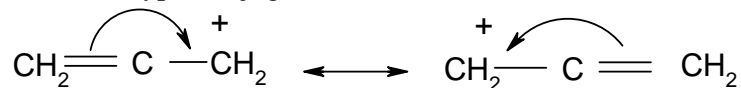
Stability: The relative stability of carbocation is increased by factors which help to disperse the positive charge on carbon. Eg. electron releasing effects like +I effect (inductive effect of electron donating groups) and hyperconjugation, resonance in unsaturated compounds stabilizes the carbocation.



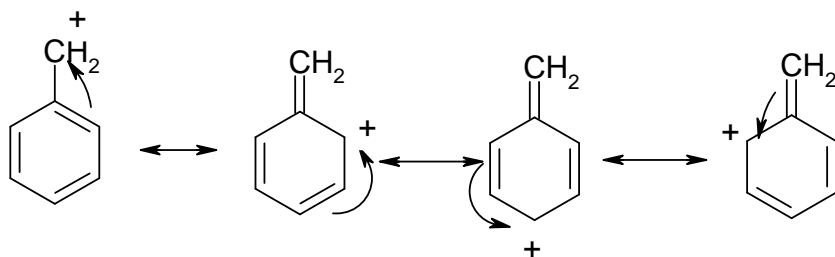
+I effect of electron donating methyl groups



Effect of hyperconjugation

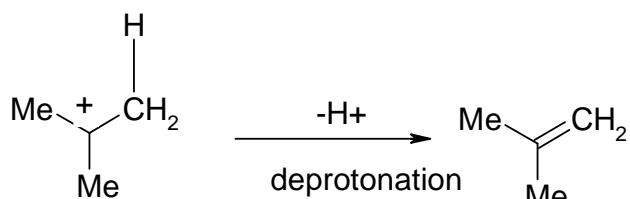
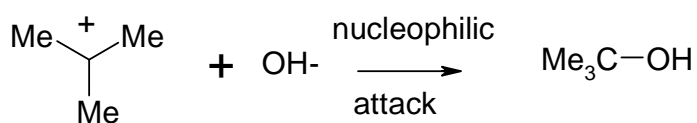


Effect of resonance in allylic carbocation



Effect of resonance in aromatic rings

Reactions of carbocation: carbocation reacts with a negatively charged nucleophile or deprotonates to give a neutral compound.

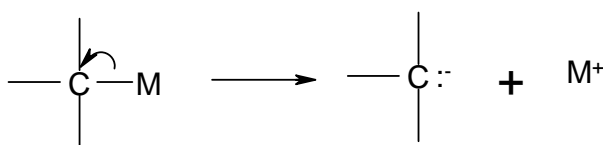
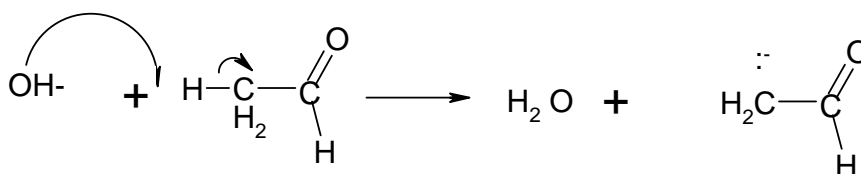


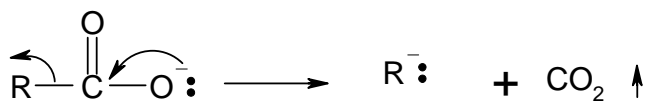
1^o-carbocation

3^o-carbocation

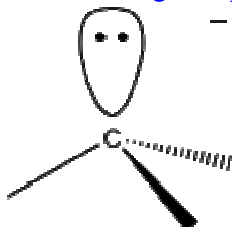
2. Carbanion: An organic species in which trivalent carbon having eight electrons in its octet carries negative charge is called carbanion.

Formation: It is formed due to heterolytic fission of bond between carbon and less electronegative atom like H or any metal, it is also formed by decarboxylation reaction.



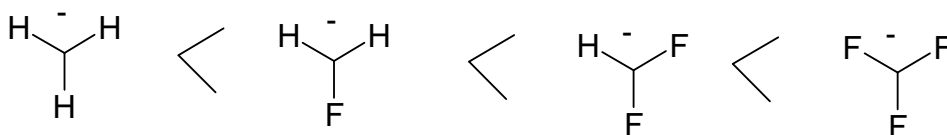


Structure: A carbanion is an [anion](#) in which [carbon](#) has an unshared pair of [electrons](#) and bears a negative charge usually with three substituents for a total of eight [valence electrons](#) ^[1]. The carbanion exists in a [trigonal pyramidal](#) geometry.

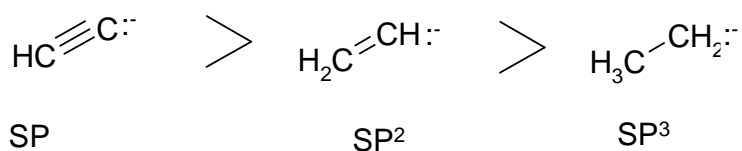


Stability: A carbanion is a [nucleophile](#). The stability and reactivity of a carbanion is determined by several factors. These include

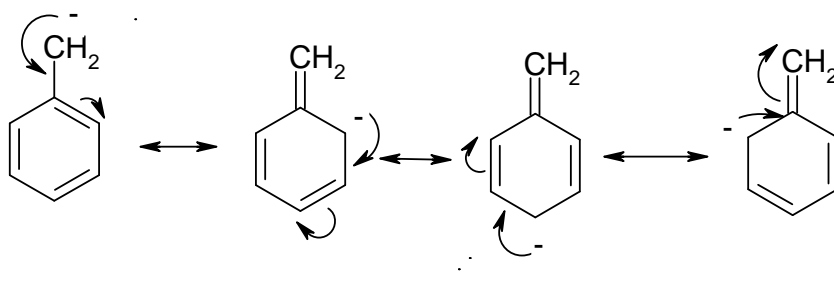
1. The electron withdrawing i.e. -I ([inductive effect](#)): Electronegative atoms adjacent to the charge will stabilize the charge as the electron density is withdrawn to such electronegative atoms.



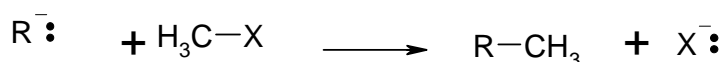
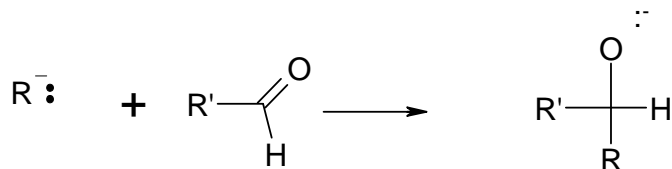
2. [Hybridization](#) of the charge-bearing atom. The greater the s-character of the charge-bearing atom, the more stable the anion;



3. The extent of [conjugation](#) of the anion. [Resonance effects](#) can stabilize the anion. This is especially true when the anion is stabilized as a result of [aromaticity](#).

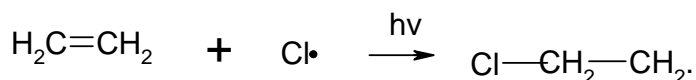
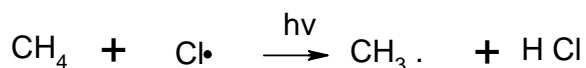


Reactions of carbanion: Carbanion being electron rich behaves as nucleophile and takes part in nucleophilic addition or substitution reactions.



3. **Carbon free radical:** An electrically neutral organic species in which carbon carries odd or unpaired electron is called carbon free radical.

Formation: it is formed due to homolytic fission of carbon with any other atom. When organic reactions are carried out at high temperature or in presence of light, peroxide or nonpolar solvents, the carbon free radical is formed.



Structure: The geometry of carbon free radical is either planar or pyramidal



or

Stability: The stability is influenced by resonance and hyperconjugation. The stability order is as follows:

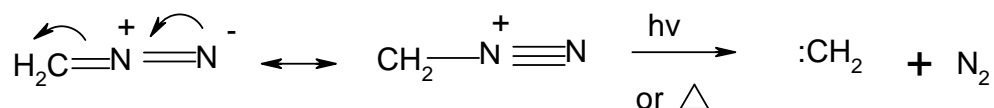
Benzyl > allyl > tertiary > secondary > primary > methyl free radical

Reactions: The carbon free radicals react with other free radicals or themselves to form neutral compounds. They usually set up chain reactions.

4. **Carbene:** an electrically neutral carbon species in which divalent carbon carries two non-bonded orbitals containing two electrons in them is called carbene, It is denoted by two dots on divalent carbon.

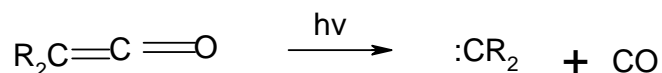
Formation: carbenes are formed by

1. Photolysis or thermolysis of diazoalkanes



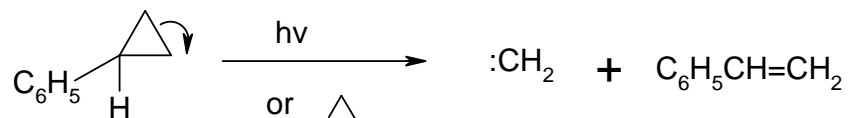
diazomethane

2. From ketenes on exposure to uv light.

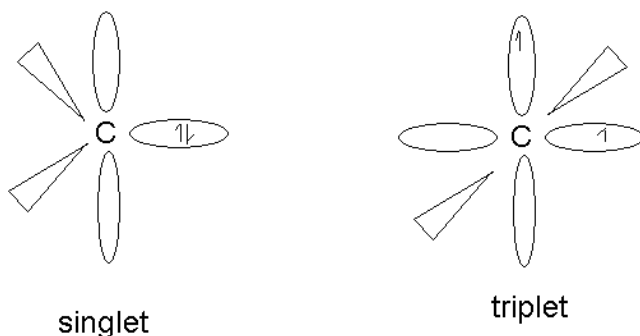


KETENE

3. Cycloelimination of cyclic compounds by light or heat.



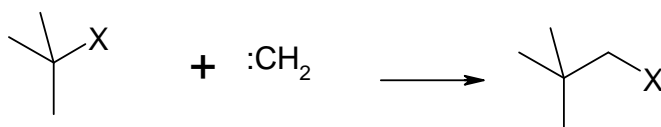
Structure: It exists in two states as singlet and triplet. When the two nonbonded electrons are in same sp^2 hybridised orbital and paired the state is called singlet state. Whereas when the electrons lie in the two different unhybridised p orbitals of sp hybridized carbon, the state is called triplet state.



Stability: The carbenes are very short lived, highly reactive intermediates. They accept a pair of electrons to complete their octet so act as strong electrophiles.

Reactions: Carbenes undergo reactions such as insertion, cycloaddition, addition, dimerization etc.

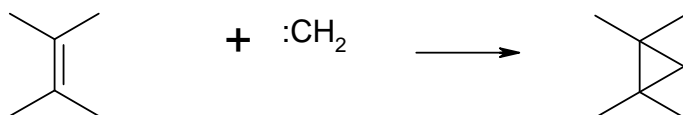
1. Insertion:



alkyl halide C_n

alkyl halide C_{n+1}

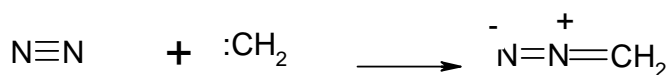
2. Cycloaddition



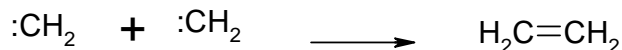
alkene

cycloalkane

3. Addition



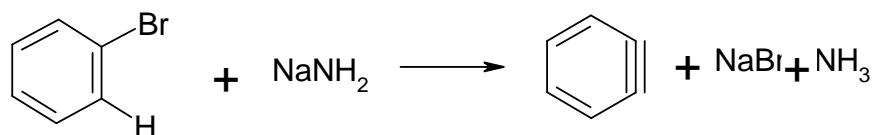
4. Dimerisation



Arynes: The aromatic compounds containing a formal carbon carbon triple bond are called arynes.

Formation: Arynes are formed by

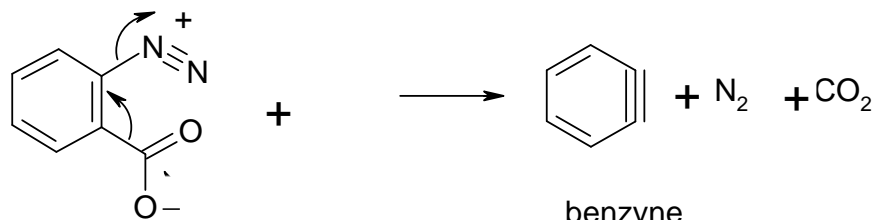
1. base catalysed dehydrohalogenation of aryl halide



bromobenzene

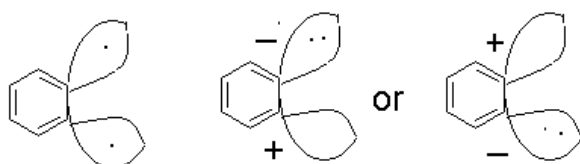
benzyne

2. thermal decomposition of disubstituted aromatics.



benzyne

Structure: In arynes, the aromatic pi orbital system remains intact and the two electrons are accommodated in the sp² hybrid orbitals. They can exist in singlet or triplet state.



Triplet

singlet

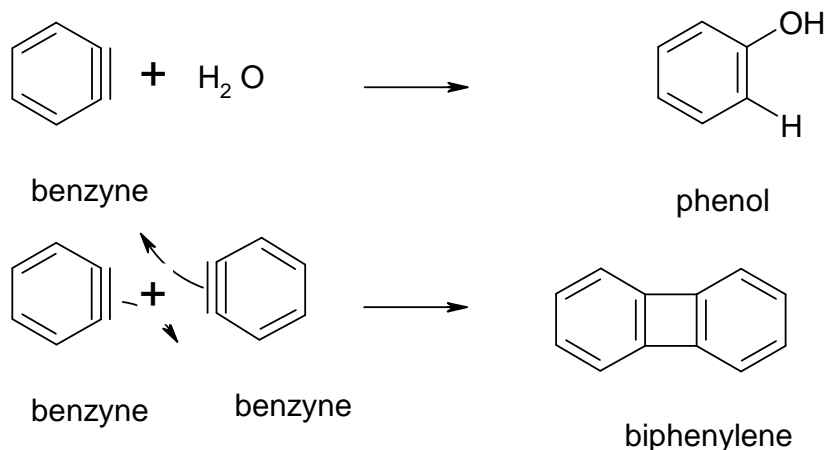
Stability: They are highly reactive neutral electron deficient species. The half life time is about 10⁻⁵ to 10⁻⁴ seconds.

Reactions: Arynes undergo reactions like addition and dimerisation



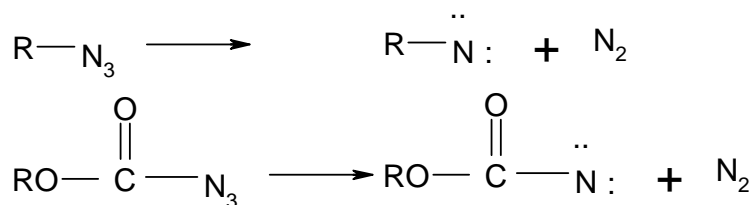
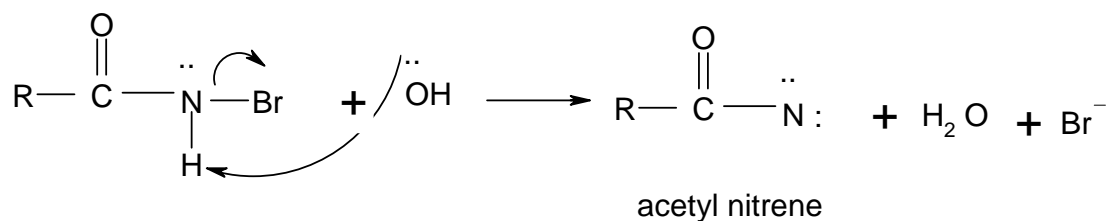
benzyne

aniline



6. Nitrenes: The high energy, neutral, organic species carrying univalent nitrogen with electron sextet similar to carbenes is called nitrene.

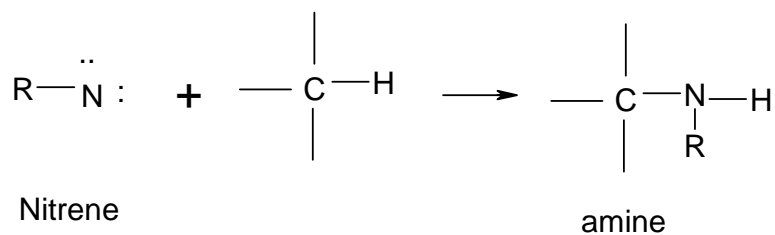
Formation: Nitrenes are formed by elimination of N compounds

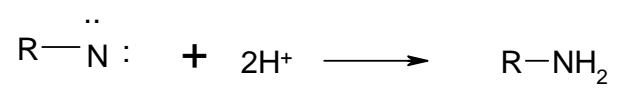


Structure: Nitrenes also exist in singlet or triplet state.

Stability: since the nitrogen atom of nitrene has a sextet of electrons it is highly reactive.

Reactions: nitrenes undergo addition reactions similar to carbenes.





Nitrene

amine