ORGANIC CHEMISTRY

Alkyl Halides and Aryl Halides

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ALKYL HALIDES

INTRODUCTION

An alkyl halide, also known as haloalkane, halogenoalkane and alkylhalogenide, is an organic compound derived from an alkane by substituting one or more hydrogen atoms with halogen atoms. Substitution with fluorine, chlorine, bromine and iodine results in alkyl fluorides (or fluoroalkanes), alkyl chlorides (or chloroalkanes), alkyl bromides (or bromoalkanes) and alkyl iodides (or iodoalkanes) respectively. Substitution in general, is a term used to mean, the exchange of an atom or group of atoms by an equivalent atom or group of atoms. Mixed compounds are also possible such as chlorofluoroalkanes, more commonly known as chlorofluorocarbons.

Halogen - substituted organic compounds are widespread in nature and have a vast array of uses. Several thousand organic halides have been found in algae and various other marine organisms. Among their many uses, organohalides are valuable as industrial solvents, inhaled anaesthetics in medicine, refrigerants and pesticides. The modern electronics industry, for example, relies on halogenated organic solvent for cleaning semiconductor chips and other components. Some halo-substituted compounds are providing important leads to new pharmaceuticals.

\[
\begin{align*}
\text{F} & \quad \text{Br} \\
\text{F} - & \text{C} - \text{C} - \text{H} \\
\text{F} & \quad \text{Cl} \\
\text{F} & \quad \text{Cl}
\end{align*}
\]

Halothane (an inhaled anaesthetic)

\[
\begin{align*}
\text{F} & \quad \text{Cl} \\
\text{C} - & \text{C} - \text{F} \\
\text{Cl} & \quad \text{Cl}
\end{align*}
\]

Dichlorofluoromethane (a refrigerant)

\[
\begin{align*}
\text{H} & \quad \text{C} \equiv \text{C} - \text{Cl} \\
\text{Cl} & \quad \text{Cl}
\end{align*}
\]

Trichloroethylene (a solvent)

\[
\begin{align*}
\text{H} & \quad \text{C} - \text{Br} \\
\text{H} & \quad \text{I}
\end{align*}
\]

Bromomethane (a fumigant)

\[
\begin{align*}
\text{H} & \quad \text{N} \\
\text{Cl} & \quad \text{H}
\end{align*}
\]

Epibatidine (from the Ecuadorian frog and found to be 200 times as potent as morphine at blocking pain in animals)

STRUCTURE OF ALKYL HALIDES

Alkyl halides have the general formula \( \text{C}_n \text{H}_{2n+1} \text{X} \) and are represented as \( \text{R-X} \) where \( \text{R} \) is the alkyl group and \( \text{X} \) the halogen atom. The carbon-halogen bond in alkyl halide results from the overlap of a \( \text{sp}^3 \) hybrid orbital of carbon with \( \text{p} \) orbital of halogen. Thus, alkyl halide carbon atoms have a tetrahedral geometry with \( \text{H-C-X} \) bond angles near \( 109^\circ \).
From our past knowledge, we are aware that halogens are more electronegative than carbon.

The C-X bond is therefore polar, with the carbon atom bearing a slight positive charge (\(\delta^+\)) and the halogen a slight negative charge (\(\delta^-\)). This polarity of the C-X bond is the characteristic feature of the alkyl halide structure and the characteristic reactions of an alkyl halide are those that take place at the halogen atom. We know that an atom or group of atoms that define the structure of a particular family of organic compounds and determines their properties, is called the functional group. In alkyl halides, the functional group is the halogen atom.

**CLASSIFICATION AND NOMENCLATURE OF ALKYL HALIDES**

A carbon atom is classified as primary (1°) secondary (2°) or tertiary (3°) according to the number of other carbon atoms attached to it. A primary carbon is one that is bonded to only one other carbon. A secondary carbon and a tertiary carbon are the ones that are bonded to two and three other carbons respectively. Accordingly, alkyl halides are named as primary, secondary or tertiary alkyl halides depending on the nature of the carbon atom to which the halogen is directly attached.
Two systems are recognized by the IUPAC for the nomenclature of organic compounds.

**Radical Functional Nomenclature and Substitutive Nomenclature.**

Radical Functional Nomenclature is also called the common nomenclature for simplicity. Here, the common name of the alkyl halides is constructed from the name of the alkyl group followed by the name of the halide as a separate word.

**Common Name**

\[
\begin{align*}
\text{CH}_3\text{CH}_2\text{CH}_2\text{Br} & \quad \text{propyl bromide} \\
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{Cl} & \quad \text{butyl chloride}
\end{align*}
\]

These examples refer to unbranched alkyl group in the alkyl halides. The straight chain alkyl group is sometimes called n-alkyl to emphasise that all carbon atoms are in an unbranched chain. If the alkyl groups are branched then they carry prefixes of iso, sec, tert, neo. The prefix ‘iso’ is used when the branched alkyl group has an ‘iso’ structural unit (a carbon bonded to two methyl groups and a hydrogen) at one end of the molecule i.e. an iso group has a methyl group on the next-to-the-last carbon in the chain.

\[
\begin{align*}
\text{CH}_3\text{CHCH}_2\text{CH}_2\text{Cl} & \quad \text{isopentyl chloride} \\
\text{CH}_3\text{CHCH}_2\text{CH}_2\text{CH}_2\text{Br} & \quad \text{isoheptyl bromide} \\
\text{CH}_3\text{CHCH}_2\text{CH}_2\text{CH}_3\text{Cl} & \quad \text{isoheptyl chloride}
\end{align*}
\]

All isoalkyl compounds have the functional group joined to the primary carbon except for isopropyl halide which has the halide atom joined to the secondary carbon. The prefix ‘sec’ is used when halogen atom is attached to secondary carbon and so can be used only for sec-butyl. The name sec-pentyl cannot be used because pentane has two different secondary carbon atoms. Therefore, two different alkyl groups can result from the removal of a hydrogen from a secondary carbon of pentane giving two alkyl halides both of which would be sec-pentyl chloride.

\[
\begin{align*}
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{Cl} & \quad \text{CH}_3\text{CH}_2\text{CHCH}_2\text{CH}_2\text{Cl} \\
\text{both alkyl chlorides would be sec-pentyl chlorides}
\end{align*}
\]

Prefix ‘tert’ is used when halogen atom is joined to tertiary carbon and is found in tert - butyl and tert - penty1 groups because each of these substituents names describes only one alkyl group. The name ‘tert hexyl’ cannot be used because it describes two different alkyl groups.
In the IUPAC system, alkyl halides are named as substituted alkanes (Substitutive Nomenclature) i.e. halogen is always treated as substituent. The names of the halogens are prefixed to the name of the parent hydrocarbon by replacing the 'ine' ending in the name of the element with 'o' (i.e. fluoro, chloro, bromo, iodo). The name is written as a single word. Therefore alkyl halides (common name) are often called haloalkanes. The following rules are followed for the IUPAC Nomenclature:

1. Find the longest carbon chain and name it as the parent hydrocarbon. If a double or triple bond is present, the parent chain must contain it.

2. Number the carbon atoms of the parent chain beginning from the end nearer the first substituent, regardless of whether it is alkyl or halo. Assign each substituent a number according to its position on the chain and list them alphabetically in writing the name. Use hyphen between number (locant) and name of substituent and commas between numbers to keep the entire name as one word.

\[
\begin{align*}
\text{CH}_3 & \quad \text{Br} \\
\text{CH}_3\text{CHCHCHCHCHCH}_3 & \\
& \text{CH}_3 \\
& \text{2-bromo-4,5-dimethylheptane}
\end{align*}
\]

\[
\begin{align*}
\text{CH}_3 & \quad \text{Br} \\
\text{CH}_3\text{CHCHCHCHCHCH}_3 & \\
& \text{CH}_3 \\
\text{CH}_3\text{CH}=&\text{CHCHCHCH}_2 & \text{Cl} \\
& \text{5-chloropent-2-ene} \\
& \text{(numbering begins at the end nearer to the double bond)}
\end{align*}
\]

If more than one of the same kind of halogen is present, number each and use one of the prefixes di, tri, tetra and so on. These prefixes are ignored in alphabetizing substituent groups.

\[
\begin{align*}
\text{Br} & \quad \text{CH}_3 \\
\text{CH}_3\text{CHCHCHCHCHCHCH}_3 & \\
& \text{Br} \\
& \text{2,3-dibromo-4-methylheptane}
\end{align*}
\]

\[
\begin{align*}
\text{Br} & \quad \text{Br} \\
\text{Br} & \quad \text{Br} \\
\text{Br} & \quad \text{Br} \\
\text{1,4-dibromocyclobutane}
\end{align*}
\]
If different halogens are present, number all of them and list them in alphabetical order on writing the name.

\[
\begin{align*}
&\text{Br} \\
&\text{CH}_3\text{C}H\text{CH}_2\text{CH}_2\text{Cl} \\
&\text{CH}_3
\end{align*}
\]

3-bromo-1-chloro-4-methylpentane

\[
\begin{align*}
&\text{Br} \\
&\text{Cl} \\
&\text{C}H_3\text{C}H\text{CH}_2\text{CH}_2\text{Cl}
\end{align*}
\]

3-bromo-1,1-dichloro-2-fluorobutane

3. If the parent chain can be numbered from either end by rule 2, begin at the end nearer the substituent(either alkyl or halo) that has alphabetical precedence.

\[
\begin{align*}
&\text{Cl} \\
&\text{CH}_3 \\
&\text{CH}_3\text{C}H\text{CH}_2\text{CH}_2\text{C}H\text{CH}_3
\end{align*}
\]

2-chloro-5-methylhexane

(Not 5-chloro-2-methylheptane)

On the basis of these rules the halides of cycloalkanes can be named as well.

\[
\begin{align*}
&\text{Br} \\
&\text{bromocyclohexane}
\end{align*}
\]

\[
\begin{align*}
&\text{Br} \\
&\text{Cl} \\
&\text{CH}_3 \\
&\text{4-bromo-2-chloro-1-methylcyclohexane}
\end{align*}
\]

Certain compounds are more popularly used by their common names

\[
\begin{align*}
&\text{CH}_2=\text{CH}-\text{CH}_2-\text{Cl} \\
&\text{CH}_2=\text{CH}-\text{Br} \\
&\text{CH}_2=\text{CH}-\text{Cl} \\
&\text{CCl}_4
\end{align*}
\]

allyl chloride benzyl bromide vinyl chloride carbon tetrachloride

As such, vinyl chloride and related compounds are not alkyl halides since they have halogen attached to alkene carbon. Nevertheless, it is convenient to discuss their nomenclature here.

Methyl trihalides are another class of alkyl halides which are commonly known as haloforms.

\[
\begin{align*}
&\text{HCCl}_3 \\
&\text{HCl}_3 \\
&\text{HBr}_3
\end{align*}
\]

methyl trichloride or chloroform methyl tribromide or bromoform methyl triiodide or iodoform
PREPARATION OF ALKYL HALIDES

PREPARATION METHOD I: HALOGENATION OF ALKANES

Alkanes react with chlorine and bromine to give alkyl chlorides and alkyl bromides respectively. Reaction with fluorine is strongly exothermic; reaction is violent and is accompanied by the fragmentation of alkyl groups. On the other hand, with iodine the reaction is so strongly endothermic that it is ineffective.

The reaction of an alkane with a halogen is called halogenation. The general reaction to produce a monohaloalkane can be written as follows.

\[ R-H + X_2 \rightarrow R-X + HX \]

Effectively, one hydrogen has been replaced by a halogen atom and therefore it is a Substitution Reaction.

Reaction Conditions: Take a test-tube half filled with hexane and add 10 drops of 1% solution of bromine (in CCl₄). Divide this solution between two test-tubes. Keep one tube shaded from strong light by wrapping black paper around the tube. Hold the other tube about 30 cm from a 100 watt lamp, shaking the tube at intervals.

Observation: The test tube kept in dark does not undergo any change in colour whereas the colour of the solution in the other test tube fades within a short time.

The following information is gathered from this experiment.

(i) The reaction is promoted by heat or light: The reaction does not occur in the dark at room temperature, but it takes place rapidly if the mixture is either exposed to sunlight (U.V.) or heated to above 300°C even in the dark.

(ii) The light promoted reaction is highly efficient: A relatively small number of photons permit the formation of relatively large amounts of brominated product.

Thus, the halogenation reaction should actually be written as:

\[ R - H + X_2 \xrightarrow{\Delta \text{or}\ hv} R - X + HX \]

\[ X = \text{Br, Cl} \]

**Mechanism : Free Radical Substitution**

The conditions of the above reaction (heat or light initiation) suggest the involvement of free-radical intermediates with the end result of substitution of a halogen atom for one of the hydrogen atoms of the alkane.

\[ \text{CH}_4 + \text{Cl}_2 \xrightarrow{\Delta \text{or}\ hv} \text{CH}_3\text{Cl} + \text{HCl} \]

The mechanism of this reaction, in fact, follows the typical pattern of a free radical chain reaction: it has initiation, propagation and termination steps. Halogenation by free radical mechanism is an example of Free-Radical Substitution Reaction.

Let us understand the mechanism by examining a simple example: Reaction of methane with chlorine that takes place in the gas phase.
**Initiation:** Homolytic bond cleavage: The reaction is initiated when a small number of halogen molecules absorb the energy provided by high temperature (or light) to break the halogen-halogen bond homolytically. Homolytic cleavage is shown by an arrowhead with one barb signifying the movement of one electron.

\[
\begin{align*}
\text{(A)} & \quad :\text{Cl} + :\text{Cl}^\cdot & \xrightarrow{\Delta \text{or} \text{hv}} & 2 \cdot \text{Cl}^\cdot \\
\end{align*}
\]

This step, therefore, results in the formation of halogen radicals (chlorine radicals in this case). A radical, often called free radical, is a species containing an atom with an unpaired electron. Due to its incomplete octet, it is an extremely reactive species.

**Propagation:** Chlorine radical, being very reactive, abstracts a hydrogen atom from the methane molecules forming HCl and a reactive methyl radical (step B). In the next step, methyl radical reacts with chlorine molecule by abstracting a chlorine atom forming chloromethane and another chlorine radical which can, in turn, abstract a hydrogen atom from another molecule of methane. These two steps are called propagation steps because the radical created in the first propagation step reacts in the second propagation step to produce a radical that can repeat the first propagation step and so on. Thus, the two propagation steps (B) and (C) are repeated over and over.

\[
\begin{align*}
\text{(B)} & \quad :\text{Cl}^\cdot & + & \text{H-CH}_4 & \longrightarrow & \text{H-Cl} + \text{CH}_3 \\
\text{(C)} & \quad \text{CH}_3 & + & :\text{Cl}^\cdot & \longrightarrow & \text{CH}_3 - \text{Cl} + :\text{Cl}^\cdot \\
\end{align*}
\]

Step (B) is found to be more difficult than step (C) and controls the rate of overall reaction. i.e. formation of methyl radicals is difficult, but once formed it readily converts to methyl chloride. This type of sequential, stepwise mechanism, in which each step generates the reactive intermediate that causes the next step to occur, is called a CHAIN REACTION.

**Termination:** In order that propagation continues, intermediates need to be continuously produced by a continuous supply of energy (heat or light). As a result, the propagation steps cannot go on forever. The chain sequence is interrupted whenever two odd-electron species combine to give an even-electron product. These reactions, therefore, constitute the chain terminating steps. As a result of these reactions, the reactive intermediates get used up.

The possible chain terminating steps are:
(D)  \(\cdot \text{Cl}^\cdot + \cdot \text{Cl}^\cdot \rightarrow \text{Cl} - \text{Cl} \quad \text{chlorine} \)  
(combination of two chlorine radicals)

(E)  \(\cdot \text{Cl}^\cdot + \cdot \text{CH}_3 \rightarrow \text{Cl} - \text{CH}_3 \quad \text{chloromethane} \)  
(combination of one chlorine radical and one methyl radical)

(F)  \(\text{H}_2\text{C}^\cdot + \cdot \text{CH}_3 \rightarrow \text{H}_2\text{C} - \text{CH}_3 \quad \text{ethane} \)  
(combination of two methyl radicals)

While some chloromethane is coming from termination reaction (E), most of it is contributed by propagation reaction.

**Characteristics of Free Radical Substitution Reactions**

A few points must be noted for a clearer and deeper understanding:

(I)  The chlorine radical formed in the first propagation step could have collided with a molecule of chlorine but would result in no net change - only an exchange of one chlorine atom for another.

\[ \cdot \text{Cl}^\cdot + \cdot \text{Cl}^\cdot \rightarrow \cdot \text{Cl}^\cdot + \cdot \text{Cl}^\cdot \]

The other possible collision is with another chlorine radical which is quite unlikely simply because very few of these reactive species are there at any point of time.

(II)  The same logic holds for the methyl radical reaction. With methane molecule, the reaction will be simply an exchange of one methyl radical with another.

\[ \text{CH}_3\text{H} + \cdot \text{CH}_3 \rightarrow \cdot \text{CH}_3 + \text{CH}_4 \]

(III)  The fact that propagation comprises of the steps described earlier, is very clear. Let us look into some other possibilities that might come in our mind.

Abstraction of methyl radical and release of hydrogen atom

\[(B') \quad \text{Cl}^\cdot + \text{CH}_4 \rightarrow \text{CH}_3\text{Cl} + \text{H}^\cdot \]

Abstraction of chlorine radical by hydrogen atom

\[(C') \quad \text{H}^\cdot + \text{Cl}_2 \rightarrow \text{HCl} + \text{Cl}^\cdot \]

However these two steps do not occur. This is because, although chlorine radical attacks methane molecule here as well, it does so to expel a hydrogen atom. There is thus a competition between the two reactions - one in which hydrogen atom is expelled and the other in which methyl radical is expelled. The \(E_{\text{act}}\) (4 Kcal) for the latter is much lower than the former (at least 20 Kcal), hence this path of chlorine radical attack on methane, is not favoured. This high \(E_{\text{act}}\) of one reaction pathway \((B')\) arises from the fact that here a C-Cl bond is formed that is weaker than H - Cl bond formed in the alternate pathway \((B)\). Hence lesser heat is evolved in C - Cl bond formation that cannot be sufficient enough to help break the C - H bond of methane substrate. H - Cl bond formation, on the other hand, releases enough
heat to help break the C-H bond of methane. On the same basis, C1-C1 bond cleavage requires much more energy than that supplied by the release from the formation of H-C1 bond (reaction \((\text{C}^1)\)).

(IV) The rates of halogenation are slowed down by the presence of \(\text{O}_2\) molecules. These oxygen molecules are said to act as inhibitors in the chain reaction. With methyl radical, oxygen molecule reacts to form a new radical, the methyl peroxy radical.

\[ \text{CH}_3 + \text{O}_2 \rightarrow \text{CH}_3-\text{O}-\text{O} \]

Inhibitors are also called free radical scavengers. The formation of methyl peroxy radical breaks the propagation of the chain reaction and prevents formation of several molecules of methyl chloride. Several such peroxy radicals are formed that consume methyl radicals. Hence, the rate of substitution reaction slows down. Once all oxygen molecules are used up, the reaction regains the original rates.

(V) Free radical chain reactions involve free radical intermediates that carry unpaired electrons but no positive or negative charge. Hence, such reactions are not affected by solvent polarity.

(VI) Free radical reactions do not involve any rearrangement of intermediate free radicals. This was shown by H.C. Brown and G. Russell based on Isotopic labelling studies.

**Disadvantage of Halogenation Reaction**

Alkane halogenation is, however, a poor method of haloalkane synthesis. This is because a mixture of products is invariably formed. e.g. chlorination of methane does not stop at the mono-chlorination stage. Reaction continues to go on to give a mixture of dichloro, trichloro and even tetrachloro products.

\[
\text{CH}_4 + \text{Cl}_2 \xrightarrow{\Delta/\text{hv}} \text{CH}_3\text{Cl} + \text{HCl} \\
\text{CH}_3\text{Cl} \xrightarrow{\Delta/\text{hv}} \text{CH}_2\text{Cl}_2 + \text{HCl} \\
\text{CH}_2\text{Cl}_2 \xrightarrow{\Delta/\text{hv}} \text{CHCl}_3 + \text{HCl} \\
\text{CHCl}_3 \xrightarrow{\Delta/\text{hv}} \text{CCl}_4 + \text{HCl}
\]

This mixture of halogenated methanes is sometimes used usefully as solvent in industries. The monochlorinated product can be increased by taking an excess of methane (methane should be 6 times chlorine) which increases the probability of collision of chlorine radicals with methane rather than with methyl chloride.

Bromination of alkanes follows the same mechanism as chlorination.
Halogenation of Higher Alkanes: Chlorination

Let us discuss halogenation of higher alkanes which is essentially the same as the halogenation of methane. However, the situation gets complicated due to the presence of more than one type of hydrogen. Mono-halogenation of ethane gives only one haloethane; however, propane, n-butane and iso-butane can yield two isomers each; n-pentane can yield three and isopentane four isomers. Thus, we get mixture of monohaloproducts apart from di, and tri substituted products.

\[
\begin{align*}
\text{CH}_3\text{CH}_3 & \xrightarrow{\text{Cl}_2, \text{hv}} \text{CH}_3\text{CH}_2\text{Cl} \\
\text{ethane} & \quad \text{chloroethane} \\
\text{CH}_3\text{CH}_2\text{CH}_3 & \xrightarrow{\text{Cl}_2, \text{hv}} \text{CH}_3\text{CH}_2\text{CH}_2\text{Cl} + \text{CH}_3\text{CHCH}_3 \\
\text{propane} & \quad \text{1 - chloropropane} \quad \text{2 - chloropropane} \\
& \quad 45\% \quad 55\% \\
& \quad (\text{substitution of 1' H}) \quad (\text{substitution of 2' H}) \\
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_3 & \xrightarrow{\text{Cl}_2, \text{hv}} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{Cl} + \text{CH}_3\text{CHCH}_2\text{CH}_3 \\
\text{n-butane} & \quad \text{1 - chlorobutane} \quad \text{2 - chlorobutane} \\
& \quad 28\% \quad 72\% \\
& \quad (\text{substitution of 1' H}) \quad (\text{substitution of 2' H}) \\
\text{CH}_3\text{CHCH}_3 & \xrightarrow{\text{Cl}_2, \text{hv}} \text{CH}_3\text{CHCHCl} + \text{CH}_3\text{CH}_2\text{C} - \text{Cl} \\
\text{Isobutane or} & \quad \text{2 - methyl - 1} \quad \text{2 - methyl - 2} \\
\text{2 - methylpropane} & \quad \text{- chloropropane} \quad \text{- chloropropane} \\
& \quad 65\% \quad 35\% \\
& \quad (\text{substitution of 1' H}) \quad (\text{substitution of 3' H})
\end{align*}
\]

The percentage of monochloroproducts formed clearly shows that the isomers are not formed in equal amounts. Chlorination gives mixtures wherein no isomer greatly predominates. It is obvious that 1-chloropropane is obtained from propane by the abstraction of terminal H (1'H) and 2-chloropropane by the abstraction of secondary H. The same is true for the isomeric products obtained by chlorination of n-butane. Isobutane has primary H and tertiary H which on replacement give 1- and 2-substituted product respectively.

The fact that the isomers are formed in different amounts, clearly indicates that the rate of abstraction of the different types of hydrogen is different and compete with each other. The rates of the competing reactions depend on (a) the number of one type of hydrogen that can be abstracted (probability factor) (b) reactivity of the reacting molecules.
Based on these factors one can calculate the order of rate of abstraction of Hs. i.e. reactivity order towards chlorination for different types of hydrogen atoms in a molecule. Take the chlorination of n-butane. Butane has six equivalent primary hydrogens (-CH₃) or the probability factor of 1°H is 6 in n-butane. Also, it has four equivalent secondary hydrogens (-CH₂H) or the probability factor of 2°H is 4 in n-butane. The fact that butane gives 28% of 1 - chlorobutane product means that each one of the six primary hydrogens is responsible for 28% ÷ 6 = 4.66% of the product. Similarly, formation of 72% of 2 - chloro product shows that each one of the four secondary hydrogens is responsible for 72% ÷ 4 = 18% of the product. Thus, reaction of a secondary hydrogen happens 18% ÷ 4.66% = 3.8 times as often as reaction of a primary hydrogen. In other words, on the basis of probability factor, we get the ratio of abstraction of primary to secondary Hs as 6 : 4. From the amounts actually obtained we see that the ratio is 28 : 72 or 6 : 15.45. The amount of secondary H abstraction is 15.45 ÷ 4 = 3.8 times more than predicted. This means that it must be easier to abstract secondary H or E₁ for abstraction of secondary H is less than that for primary H. A similar calculation for the chlorination of 2 - methyl propane indicates that each of the nine primary hydrogens accounts for 65% ÷ 9 = 7.2% of the product while the single tertiary hydrogen accounts for 35% of the product. Thus, a tertiary H is 35% ÷ 7.2% = 5 times as reactive as a primary hydrogen towards chlorination. Again, E₁ for abstraction of tertiary H is less than that for secondary and primary H. Thus, irrespective of the alkane, the order of reactivity of H depends solely on its class and is as follows:

```
<table>
<thead>
<tr>
<th>R</th>
<th>R-C-H</th>
<th>H-C-H</th>
<th>H-C-H</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td></td>
<td>R-C-H</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td></td>
<td>R</td>
<td>H</td>
</tr>
</tbody>
</table>
```

5 : 3.8 : 1

(order of decreasing reactivity)

This order of reactivity can be understood if we look into their bond dissociation energies (The amount of energy that must be supplied to convert a mole of alkane into radicals and hydrogen atom).

<table>
<thead>
<tr>
<th>Bond dissociation energy (Kcal/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R₁C - H</td>
</tr>
<tr>
<td>R₂CH - H</td>
</tr>
<tr>
<td>RCH₃ - H</td>
</tr>
<tr>
<td>CH₄ - H</td>
</tr>
</tbody>
</table>

Bond dissociation energy is lowest for tertiary C-H followed by secondary C-H and primary C-H bond. Thus, it is easiest to break tertiary C-H bond. Ease of formation of radicals is directly related to ease of abstraction of hydrogen atom i.e. this is also the order of stability of the radicals. Tertiary alkyl radical is
most stable followed by secondary, primary and methyl radical. Hyperconjugation explains this order, with tertiary radical having the maximum number of no-bond resonance structures (10 structures) contributing to delocalisation of unpaired electron followed by secondary (7 structures), primary (4 structures) and methyl radical (1 structure).

The more stable the radical, the more easily it is formed i.e. $E_{act}$ leading to the formation of the radical is lower. This, in turn, means that the more stable the radical intermediate the more stable is the T.S. leading to its formation (fig.1.). T.S. bears a developing radical character and gets more and more stable with increasing alkyl substitutions (because they help in delocalising the unpaired electron).

$$\begin{align*}
\text{C} - \text{H} + \cdot \text{X} & \longrightarrow \left[ \begin{array}{c}
\text{C} - \text{H} - \text{X} \\
\text{C} - \text{H} - \text{X}
\end{array} \right] \\
& \longrightarrow \text{C}^\cdot + \text{H-X}
\end{align*}$$

_T.S. with radical character_

Hence, knowing the probability factor and reactivity, the isomeric product of monochlorination of any alkane can be predicted. e.g. 2,2,5-trimethylhexane on monochlorination gives five products.

$$\begin{align*}
\text{CH}_3, \text{CH}_3, \text{CH}_2, \text{CH}_2, \text{CH}_3 + \text{Cl}_2 & \xrightarrow{\Delta} \text{CH}_3, \text{CH}_3, \text{CH}, \text{CHCHCH}_3, + \\
\text{CH}_3, \text{CH}_3, \text{CH}_2, \text{CH}_2, \text{CH}_3, \text{CH}_3 & (A) \\
\text{CH}_3, \text{CH}_3, \text{CH}, \text{CHCHCH}_3, \text{CH}_3 & (B) \\
\text{CH}_3, \text{CH}_3, \text{CH}, \text{CHCHCH}_3, \text{CH}_3 & (C) \\
\text{CH}_3, \text{CH}_3, \text{CH}, \text{CHCHCH}_3, \text{CH}_3 & (D) \\
\text{CH}_3, \text{CH}_3, \text{CH}, \text{CHCHCH}_3, \text{CH}_3 & (E)
\end{align*}$$
Relative amounts of = Probability factor x reactivity

(A)  (t - H abstraction)  = 1 x 5.0 = 5.0
(B)  (sec - H abstraction) = 2 x 3.8 = 7.6
(C)  (sec - H abstraction) = 2 x 3.8 = 7.6
(D)  (pri - H abstraction) = 9 x 1.0 = 9.0
(E)  (pri - H abstraction) = 6 x 1.0 = 6.0

% yield of t-H substituted product (A) = \frac{5.0}{35} = 14\%
% yield of sec-H substituted product (B) = \frac{7.6}{35} = 22\%
% yield of sec-H substituted product (C) = \frac{7.6}{35} = 22\%
% yield of pri-H substituted product (D) = \frac{9.0}{35} = 26\%
% yield of pri-H substituted product (E) = \frac{6.0}{35} = 17\%

The % yield of each product is calculated by dividing the relative amount of the particular product by the sum of the relative amount of all products (9.0 + 7.6 + 7.6 + 5.0 + 6.0 = 35)

**Bromination**

In contrast to chlorination, the attack of bromine radical on alkanes gives relative rate factors of 1600 : 82 : 1 for the abstraction of t - H : sec - H : pri - H. This clearly shows that bromine is much more choosy or selective in abstracting Hs as compared to chlorine (order is 5 : 3.8 : 1). In other words, it is much less reactive than chlorine. In fact, the less reactive the attacking radical the more selective it is.

\[
\begin{align*}
\text{(A) 82\%} & \quad \text{(B) 8.6\%} \\
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 + \text{Br}_2 & \xrightarrow{\Delta} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 + \text{Br} \\
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 + \text{Br}_2 & \xrightarrow{\Delta} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 + \text{Br} \\
\text{(C) 8.6\%} & \\
\text{(D) 0.5\%} & \\
\text{(E) 0.3\%}
\end{align*}
\]
This high selectivity (or low reactivity) of bromine radical as against chlorine radical can be understood if we compare $\Delta H^\circ$ of the hydrogen abstraction step from both halogen radical species.

The $\Delta H^\circ$ values can be calculated from the bond dissociation energies ($\Delta H^\circ$ is the energy of the bond being broken minus the energy of the bond being formed)

$$\begin{align*}
\text{Cl}^* + \text{CH}_3\text{CH}_2\text{CH}_3 &\longrightarrow \text{CH}_3\text{CH}_2\text{CH}_2^* + \text{HCl} & \Delta H^\circ (\text{kcal/mol}) \\
101 - 103 &= -2 \\
\text{Cl}^* + \text{CH}_3\text{CH}_2\text{CH}_3 &\longrightarrow \text{CH}_3\text{CH}^* + \text{HCl} & 99 - 103 = -4 \\
\text{Cl}^* + \text{CH}_3\text{CHCH}_3 &\longrightarrow \text{CH}_3\text{CCH}_3 + \text{HCl} & 97 - 103 = -6 \\
\text{Br}^* + \text{CH}_3\text{CH}_2\text{CH}_3 &\longrightarrow \text{CH}_3\text{CH}_2\text{CH}_2^* + \text{HBr} & 101 - 87 = 14 \\
\text{Br}^* + \text{CH}_3\text{CH}_2\text{CH}_3 &\longrightarrow \text{CH}_3\text{CH}^* + \text{HBr} & 99 - 87 = 12 \\
\text{Br}^* + \text{CH}_3\text{CHCH}_3 &\longrightarrow \text{CH}_3\text{CCH}_3 + \text{HBr} & 97 - 87 = 10
\end{align*}$$

As we can see, alkyl radical formation by chlorine radical is exothermic in nature whereas by bromine radical is endothermic in nature. Also, bromine radical attacks alkane (or abstracts H) much more slowly than chlorine radical as is seen from the $E_{ss}$ values. $E_{ss}$ value for hydrogen abstraction by bromine radical is 4.5 times higher than that by chlorine radical, thereby indicating the lower reactivity of bromine radical. Taking $\Delta H^\circ$ and $E_{ss}$ values, we can draw the reaction coordinate diagram for the formation of alkyl radical using bromine radical (fig. 2) and chlorine radical (fig. 3).

Since bromine atom is much more unreactive (endothermic reaction), the transition state in the formation of alkyl radical is reached late in the reaction process, after the alkyl group has gained considerable radical character. Thus, transition state resembles the product (alkyl radical) more. Factors stabilizing the product will stabilize the transition state. More the number of alkyl groups, as in tertiary alkyl radical, more will be the delocalisation, hence more stable the product radical and consequently more stable the corresponding transition state. Whereas chlorine radical being very reactive (exothermic reaction), enables the transition state to be attained much earlier in the reaction process, when the alkyl group has gained very little radical character. The T.S. (transition state) resembles reactants (alkane) more. This is in accordance with
Hammond Postulate which states that T. S. for exothermic reaction is achieved quickly, hence resembles reactants whereas T.S in endothermic reaction is achieved late, hence resembles products.

Bromination

\[
\text{R} \text{H} + \text{Br}^* \xrightarrow{\text{transition state}} \text{R}^* \text{H} - \text{Br}^* \xrightarrow{\text{transition state}} \text{R}^* + \text{H} - \text{Br}
\]

Chlorination

\[
\text{R} \text{H} + \text{Cl}^* \xrightarrow{\text{transition state}} \text{R}^* \text{H} - \text{Cl}^* \xrightarrow{\text{transition state}} \text{R}^* + \text{H} - \text{Cl}
\]

If the T.S. resembles the reactants, the energies of T.S. and reactants will be approximately the same, hence \( E_{\text{act}} \) for H abstraction will be narrowly different from primary, secondary or tertiary carbon. (between secondary and primary radical \( \sim 0.5 \) kcal). In contrast, with bromine radical this difference goes up to 3 kcal. Thus, bromine radical will have a clear preference for abstraction of tertiary H followed by secondary H and primary H. No such distinct preference is possible for chlorination (chlorine radical forms all the three type of alkyl radicals with equal ease). Thus, the less reactive the radical the more is its selectivity.

\[
\begin{align*}
\text{CH}_3 & \quad \text{CH}_3 \\
\text{CH}_3\text{CH}_2\text{CH}_3 + \text{Br}_2 \xrightarrow{\text{hv}} & \text{CH}_3\text{CH}_2\text{CH}_2\text{Br} + \text{CH}_3\text{CH} \quad \text{(>99%)} \\
& \text{CH}_3 \quad \text{CH}_3 \\
& \text{Br}
\end{align*}
\]

Due to its relative non-selectivity, chlorination is useful only when there is just one kind of hydrogen in the molecule e.g. cyclohexane, neopentane, ethane, methyl benzene (toluene) give a single product on halogenation.

\[
\text{CH}_3 + \text{Cl}_2 \xrightarrow{\text{hv}} \text{Cl} + \text{HCl}
\]

\[
\begin{align*}
\text{CH}_3 & \quad \text{CH}_3 \\
\text{CH}_3\text{CH}_2\text{CH}_3 + \text{Cl}_2 \xrightarrow{\text{hv}} & \text{CH}_3\text{CH}_2\text{CH}_2\text{Cl} + \text{HCl} \\
& \text{CH}_3 \\
& \text{CH}_3
\end{align*}
\]

\[
\begin{align*}
\text{CH}_3 - \text{CH}_3 & \quad \text{CH}_3 \\
\text{CH}_3\text{CH}_2\text{CH}_3 + \text{Cl}_2 \xrightarrow{\text{hv}} & \text{CH}_3\text{CH}_2\text{Cl} + \text{HCl} \\
& \text{CH}_3 \\
& \text{CH}_3
\end{align*}
\]
Reactions of Methane with Other Halogens

As mentioned before, halogens show a widespread relative reactivities with methane. Fluorine is so reactive that it causes a violent reaction, chlorine is less reactive, bromine is still lesser and iodine is so unreactive that for all practical purposes we can say that it does not undergo any reaction at all.

These reactivities can be understood by comparing $\Delta H^\circ$ and $E_{act}$ for each step of halogen reaction.

\[
\begin{align*}
\text{Initiation} & \quad F_2 \rightarrow F^* + F^* \quad \Delta H^\circ (\text{kcal/mol}) & E_{act} (\text{kcal/mol}) \\
\text{Propagation} & \quad F^* + CH_4 \rightarrow CH_3^* + HF & +38 & +38 \\
& \quad ^*CH_3 + F_2 \rightarrow CH_2F + F^* & 105 - 136 = -31 & +1.2 \\
& \quad \Delta H^\circ = -101 & 38 - 108 = -70 & \text{small}
\end{align*}
\]

\[
\begin{align*}
\text{Initiation} & \quad Cl_2 \rightarrow Cl^* + Cl^* \quad \Delta H^\circ (\text{kcal/mol}) & E_{act} (\text{kcal/mol}) \\
\text{Propagation} & \quad Cl^* + CH_4 \rightarrow CH_3 + HCl & +58 & +58 \\
& \quad ^*CH_3 + Cl_2 \rightarrow CH_2Cl + Cl^* & 105 - 103 = 2 & +3.8 \\
& \quad \Delta H^\circ = -24 & 58 - 84 = -26 & \text{small}
\end{align*}
\]

\[
\begin{align*}
\text{Initiation} & \quad Br_2 \rightarrow Br^* + Br^* \quad \Delta H^\circ (\text{kcal/mol}) & E_{act} (\text{kcal/mol}) \\
\text{Propagation} & \quad Br^* + CH_4 \rightarrow CH_3 + HBr & +46 & +46 \\
& \quad ^*CH_3 + Br_2 \rightarrow CH_2Br + Br^* & 105 - 87 = 12 & +18.6 \\
& \quad \Delta H^\circ = -6 & 46 - 70 = -24 & \text{small}
\end{align*}
\]

\[
\begin{align*}
\text{Initiation} & \quad I_2 \rightarrow I^* + I^* \quad \Delta H^\circ (\text{kcal/mol}) & E_{act} (\text{kcal/mol}) \\
\text{Propagation} & \quad I^* + CH_4 \rightarrow CH_3 + HI & +36 & +36 \\
& \quad ^*CH_3 + I_2 \rightarrow CH_2I + I^* & 105 - 71 = 34 & +33.5 \\
& \quad \Delta H^\circ = 13 & 36 - 57 = -21 & \text{small}
\end{align*}
\]

The chain initiating step for fluorine is very endothermic and may prompt us to think that fluorine is very unreactive. But we must not forget that in comparison to chain propagating steps, the chain initiating steps occurs very infrequently and one initiation is sufficient for thousands of propagation steps. We must, therefore, look into the $\Delta H^\circ$ and $E_{act}$ values of the next steps. The $E_{act}$ for both steps are very low. Moreover, the $\Delta H^\circ$ for overall propagation is very large. The two factors account for the high reactivity of fluorine towards methane (or alkanes, in general). The reactions with fluorine are poor in their selectivity.
due to the high reactivity of fluorine e.g., the ratio of primary to tertiary H abstraction is 1:1.4 while for the less reactive bromine this ratio is 1:1600. Fluorine reactions are so violent that they are difficult to control. Such reactions are invariably controlled by suppression of free radical pathways—which is done by dilution with inert gas, or by working at low temperatures and/or by use of free radical scavengers. The $\Delta H^0$ for chlorination is not as high (¼ of fluorination) as for fluorination which explains its lower reactivity. Also, $E_{act}$ values are higher and the energy required to break the Cl - Cl bond is also much higher. In contrast to chlorination, the hydrogen abstraction step in bromination has a very high $E_{act}$ value. Thus, only a very small fraction of collisions between bromine and methane molecule will be energetically effective. Bromine is, therefore, much less reactive. The overall reaction in iodination is endothermic. Here, the hydrogen abstraction step is the step with very high $E_{act}$. $E_{act}$ is so large that only two collisions out of every $10^{12}$ collisions have sufficient energy. Thus, iodine is not reactive at all.

Role of Temperature: At high temperatures, selectivity of any radical decreases e.g., at 600°C, the relative susceptibility to attack by CP of primary, secondary and tertiary is 1:2:1:2:6 (or compared with 1:3.8:5 at 300°C).

**Radical Substitution of Benzylic and Allylic Hydrogens**

We know that electron delocalisation stabilises a molecule—more the delocalisation more stable is the molecule and the faster is its formation. Accordingly, allyl and benzylic radicals are far more stable than alkyl radicals. The order of decreasing stability of radicals therefore becomes:

\[
\begin{align*}
&\text{CH} \equiv \text{CH} \equiv \text{CH} \\
&\text{CH} \equiv \text{C} \equiv \text{CH} \\
&\text{CH} \equiv \text{CH} \\
&\text{CH} \equiv \text{CH} \equiv \text{CH} \\
&\text{H} \equiv \text{C} \equiv \text{H}
\end{align*}
\]

If an alkene (with allylic hydrogen) is treated with Br₂ or N-bromosuccinimide (NBS) in a polar solvent (like DMSO/H₂O) we get addition reaction at the double bond i.e. dibromo product with Br₂, and halohydrin with NBS in polar solvent. Both reactions involve generation of bromonium ion as electrophile that adds to electron rich $\pi$ bond.

If, however, NBS is taken in a nonpolar solvent such as CCl₄, the alkene has its allylic hydrogen substituted by bromine and the double bond remains unaffected. The reaction is catalysed by peroxides, heat or light. The mechanism involves homolytic cleavage of $N$-Br bond to generate bromine radical needed to initiate the radical reaction.
Br$^+$ abstracts one allylic hydrogen to form one allyl radical that is stabilized by resonance (2 resonance structures)

\[ \text{Br}^+ + \text{CH}_2\text{CH} = \text{CH}_2 \rightarrow \text{H - Br} + \text{CH}_2\text{CH} = \text{CH}_2 \leftrightarrow \text{CH}_2 = \text{CH}^+ - \text{CH}_2 \]

HBr formed here reacts with NBS to give Br$_2$ and succinimide.

Thus, H - Br which is a product of the hydrogen abstraction reaction, is converted to bromine. Now, the allylic radical reacts with bromine molecule to give the substitution product.

\[ \text{CH}_2 = \text{CH} - \text{CH}_2 + \text{Br} \rightarrow \text{CH}_2 = \text{CHCH}_2\text{Br} + \text{Br}^+ \]

Br$^+$ starts the second cycle and so on. The overall reaction is:

\[ \text{CH}_2 = \text{CH} - \text{CH}_2 + \text{NBS} \xrightarrow{\Delta \text{CH}_2\text{Cl}_2} \text{CH}_2 = \text{CH} - \text{CH}_2\text{Br} \]

Similarly

\[ \text{Br}_2 \xrightarrow{\Delta \text{C}} \text{Br}_2 \]

Br$_2$ molecule formed here does not add to double bond since it is present in very low concentrations in the reaction mixture at any time. The addition reaction involves the formation of cyclic bromonium ion intermediate which then adds to bromide ion. But if bromide ion is not anywhere nearby, this intermediate formation step gets reversed and the reaction is not completed. This theory has been confirmed by running reactions with very low concentrations of molecular bromine, in which case allylic substitution, rather than an addition reaction, is seen. NBS competes with the bromonium ion for the bromide ion; so the allylic substitution reaction is favoured. This is also the reason why NBS is the preferred reagent for radical substitution since it allows the reaction even in very low amounts whereas if we take Br$_2$, we need larger amounts that could also add to the double bond.

In the example cited above, the allylic substitution gives a single product. This is because of structure of the starting alkene which gives two equivalent resonance stabilized allylic radicals. But if there are non equivalent allyl radicals formed due to resonance, we will get two substitution products.
As before, % substitution at allylic position is more in case of bromination than chlorination owing to the higher selectivity of Br₂ over Cl₂.

Why does bromination with NBS occur exclusively at an allylic position and not elsewhere in the molecule?

This is because if we look into the structure, the molecule possesses three kinds of C-H bonds with different strengths i.e. vinyl C-H, allylic C-H, alkyl C-H

\[
\begin{align*}
\text{vinyl} & \quad \text{allylic} \\
\text{CH}_3 & \quad \text{CH}_2=\text{CH} \quad \text{CH} = \text{CH}_2
\end{align*}
\]

Of the three, the allylic C-H bond has the least strength giving thereby, the most stable radical.

If we react toluene with bromine or chlorine in the absence of catalyst (in the presence of catalyst we get only ring substitution products) we get a substitution product where the methyl hydrogen is replaced by bromine.

\[
\text{CH}_3 + X_2 \xrightarrow{\Delta} \text{CCl}_4 \rightarrow \begin{align*}
\text{CH}_3X & \quad \text{OCH}_3 & \quad \text{OCH}_3 \\
\text{X} & = \text{Cl}_2 \text{ or } \text{Br}_2
\end{align*}
\]

The substitution is therefore at benzylic carbon, carbon adjacent to aromatic ring. Benzylic hydrogen atoms resemble allylic hydrogen atoms in reactivity. The substitution is termed as benzylic substitution. Br₂ abstracts a benzylic H to release a benzylic radical that gets stabilized via resonance. The benzylic radical reacts with Br₂ to give benzylic bromide.
Thus, in the presence of catalyst, bromine acts as an electrophile for substitution on ring and in the absence of catalyst it produces bromine radicals for radical substitution on side chain. Here also, NBS is used successfully to carry out benzylic substitution.

**Stereochemistry of Radical Substitution Reactions**

As a result of halogenation, depending on the structure of the alkene, a chiral centre in the alkyl halide product is created.

$$CH_3CH_2CH_2CH_3 + Br_2 \xrightarrow{hv} CH_3CH_2CHCH_3 + HBr$$

Consequently, two configurations of the product are formed viz. R and S enantiomer. This is because in the propagation step, an alkyl radical intermediate is formed which is sp³ hybridized. The three groups which carbon bearing unpaired electron are bonded, all lie in one plane. Therefore, the next step of bromine radical attack on the planar alkyl radical is equally probable from both top and bottom giving rise to equal amount of both products.

This result needs to be understood from another point-of-view. Consider any conformation of the achiral sec-butyl radical intermediate, for example I. Due to steric reasons, the attack of bromine radical is preferred from the bottom (otherwise eclipsing of bonds will cause steric strain). But a rotation by 180° about the single bond converts I to II.

The two conformations are of the same free radical and are mirror images. Hence, they are in equilibrium with each other. Attack by bromine radical is equally likely on II from the bottom side. Thus, the two conformations are attacked by Br⁺ to an equal extent giving the two enantiomers R (from I) and S (from II) in equal amounts (racemic modification). Achiral reactants give such racemic modifications due to 'random attack'.

Let us now take a substrate with one pre-existing chiral centre e.g. S-2-bromobutane. Abstraction of one H from C-3 by bromine radical will result in creation of another chiral centre. The carbon centre of the reactant which is responsible for S configuration is not the reaction centre now. Therefore this portion of the configuration of reactant is fixed. We expect two products to be formed: (R, S) and (S, S). These two are related as diastereomers.
Are these two products formed in equal amounts? For this, we again examine the free radical for the reaction: chiral 2-bromo butyl radical. This time, if we look into one conformation III, and the other conformation IV, obtained by 180° rotation about single bond from III, we will find that the two conformations are present in different ratios. They are, thus, not of equal energy and are not in equilibrium with each other. Therefore, random attack is not possible in such a case.

Attack from the bottom of III gives (R, S) isomer and that from IV gives (S, S) isomer. Since III is sterically more stable (lesser methyl crowding), it is more abundant than IV (methyl groups are closer). Therefore, reaction will occur on III with more yield hence (R, S) or the meso product will predominate over the (S, S) product.

PREPARATION METHOD II : ADDITION OF HALOGEN ACID TO ALKENE

An alkene on treatment with HX (hydrogen chloride, hydrogen bromide or hydrogen iodide) gives the corresponding alkyl halide. The reaction is an Electrophilic Addition wherein H and X add to double bond to form two new single bonds with the carbons.

\[
\begin{align*}
\text{HX} & \quad \text{HX} \\
\text{C=C} & \quad \text{C=C} \\
\text{H} & \quad \text{H}
\end{align*}
\]

HX is taken in the gaseous form. The reaction takes place in two steps. In the first step, the carbon - carbon double bond which is electron rich, can donate a pair of electrons to an electrophilic proton of HBr to
form a carbocation intermediate with a new $\sigma$ bond between the entering H and alkene C. This is the slow step of the reaction and hence the rate determining step. The carbocation formed is itself an electrophile which can accept an electron pair from nucleophilic Br to form a C-Br bond and yield a neutral addition product in the second step. That is why aqueous solutions of HX are avoided otherwise water will compete in the addition reaction.

\[ \begin{align*}
C=\overset{\text{slow}}{\text{+ HBr}} & \rightarrow C-C \quad \overset{\text{carbocation}}{\downarrow} \quad \overset{\text{fast}}{\text{+ Br}} \\
& \quad \downarrow \quad \downarrow \\
& \quad \text{C-C} \\
& \quad \text{Br} \quad \text{H}
\end{align*} \]

The rate of addition of each of the hydrogen halides to a particular alkene increases in the order HCl<HBr<HI. This is the order of their increasing acid strength (the dissociation constants $K_a$ are $10^7$, $10^9$ and $10^{10}$ mol dm$^{-3}$ at 298K, resp.) and the parallel suggests that the rate-determining step is the transfer of a proton form HX to alkene to form a carbocation. The next step of reaction between carbocation and anion ($X^-$) will be very rapid so that its rate is independent of $X^-$. The energy diagram for the electrophilic addition reactions (fig. 4) has two peaks (corresponding to two transition states) separated by a valley (carbocation intermediate). As mentioned before, the formation of carbocation is a slow step but once formed, it rapidly reacts with Br to yield bromoalkane product.

Reaction with HI, HCl and HBr is equally successful. HI is generated in the reaction mixture by heating potassium iodide with phosphoric acid.

\[ \begin{align*}
\text{CH}_3\text{C}=\text{CCH}_3 + \text{HCl} \quad \rightarrow \quad \text{CH}_3\text{C}=\text{CCH}_3 \\
\end{align*} \]

When the alkene is symmetrically substituted, it is easy to determine the product of the reaction. H$^+$ adds to one of the $sp^2$ carbons and $X^-$ to the other giving rise to a single product. When we take unsymmetrically substituted alkenes, we expect a mixture of products. However, we do not get a mixture of products — we still get a single product.
Many examples like this led the Russian chemist, Vladimir Markovnikov, in 1870, to formulate what is now known as Markovnikov’s rule. The rule states that in the addition of HX to an alkene, H attaches to the carbon atom of the double bond that already has greater number of hydrogen atoms.

**Explanation of Markovnikov’s Rule:**

Let us take the simplest unsymmetrical alkene - propene. In step 1, the addition of H⁺ to alkene can give us two possible carbocations: primary carbocation and secondary carbocation.

```
H

\[ \text{CH}_2\text{CH}=\text{CH}_2 + H^+ \rightarrow \text{CH}_3\text{CH}^+\text{CH}_2 \]
```

This is a slow step and hence the rate determining step for the overall reaction. The two carbocations will not be formed at the same rate. If the rate of formation of the two carbocations is different, then the one that is formed faster will be the preferred product of the first step. Also, the formation of the first step decides the product of the overall reaction. For knowing the product of the first step, we need to look into the stabilities of the carbocations and 

i.e. tertiary carbocation is more stable due to +1 effect of three alkyl groups and 10 ‘no-bond’ resonance structures contributing to the delocalisation and stabilisation. This is followed by secondary (7 ‘no-bond’ resonance structures), primary (4 ‘no-bond’ resonance structures) and methyl (1 structure) carbocation.

Let us now examine the structures of the transition state leading to the carbocation intermediate. Based on **Hammond Postulate**, the T.S. of the first step of this endergonic reaction resembles the products i.e. T.S.
will have a carbocationic character. Therefore, factors stabilizing the product (carbocations) will stabilize the T.S. leading to it. The more stable the T.S., the lower is the $E_w$ of the reaction pathway which implies that, the faster will be the formation of the product. Thus, the carbocation that is formed faster is the one that is more stable, and is therefore the preferred product.

Based on the above discussion, for the example given, the secondary carbocation will be formed faster than the primary carbocation. This is due to the higher stability of the secondary carbocation. The T.S. resembles the carbocation, hence T.S. leading to secondary carbocation will be more stable than T.S. leading to primary carbocation. This, in turn, means that for the pathway leading to secondary carbocation $E_w$ will be lower and so it will be formed faster. In other words, the secondary carbocation is a more stable intermediate, and is formed faster. Once formed, it quickly reacts with chloride ion to give the product 2-chloropropene. Primary carbocation is so unstable that it is formed with great difficulty. Due to the large difference in the stability and hence rate of formations of secondary and primary carbocations, the relative amount of the products of the overall reactions are drastically different. In fact, secondary carbocation alone is formed which further reacts to give 2-chloropropene. Primary carbocation is not formed; hence, 1-chloropropene is not formed.

$$\begin{align*}
\text{CH}_2=\text{CH}_2 & \quad \text{slow} \\
\text{H}^+ & \\
\text{CH}_2=\text{CH}_2 + \text{H}^+ & \quad \text{fast} \\
\text{CH}_3\text{CHCH}_3 & \\
\text{Cl}^- & \\
\text{CH}_3\text{CHCH}_3 \quad \text{(actual product)} & \quad \text{Cl}^- \\
\end{align*}$$

Therefore, the rate of addition of a hydrogen halide to an alkene increases in the order:

$$\text{CH}_2=\text{CH}_2 < \text{RCH} = \text{CH}_2 < \text{R}_2\text{C} = \text{CH}_2 < \text{RCH} = \text{CHR} < \text{R}_2\text{C} = \text{CHR} < \text{R}_2\text{C} = \text{CR}_2$$

This order is also consistent with the rate determining step being the formation of carbocation.

In other words, we can redefine Markovnikov’s rule as: in the addition of HX to alkene the more substituted carbocation is formed as the intermediate rather than the less substituted one.

In fact, with the understanding of the mechanism for the ionic addition of hydrogen halides to alkenes, the modern statement of Markovnikov’s rule is: In the ionic addition of an unsymmetrical reagent to a double bond, the positive portion of the adding reagent attaches itself to a carbon atom of the double bond so as to yield the more stable carbocation as an intermediate.

Some more examples are shown:
Electrophilic addition of HX is, therefore, a Regioselective Reaction (A reaction wherein two or more constitutional isomers can be produced but one predominates). When the difference in the stability of the possible intermediate carbocations is large, only one product (the more stable one) is formed. If the difference is small, the more stable intermediate predominates but the less stable one is also formed thereby leading to a mixture of major and minor products. Thus, the difference between 3° and 1° or between 2° and 1° is so large that only 3° and 2° carbocations are formed respectively. The 1° carbocation is not formed at all. Such reactions are said to be completely regioselective. The difference between 2° and 3° carbocation is not very large. Therefore, such reactions will lead to a mixture of two isomeric products in different quantities and will be highly regioselective but not completely regioselective.

In some cases, structure of alkene does not permit regioselectivity at all.

Here both the sp² carbons are substituted by one alkyl group each. Therefore, protonation of either of the two will result in secondary carbocation intermediates only, which will have equal stability. Hence both transition states will be of same energy. Both products are, therefore, formed in equal amounts.
Rearrangement of Carbocations

Sometimes, the product of addition of HX to alkene does not give the products as expected. Instead one gets a product where X⁻ is bonded to the C that did not bear the double bond in the reactant. Usually this product happens to be the major product.

\[
\begin{align*}
\text{CH}_3 & \quad \text{CH}_3 \quad \text{CH}_3 \\
\text{CH}_2=\text{CHCH}=\text{CH}_2 + \text{HBr} & \quad \rightarrow \quad \text{CH}_2=\text{CHCH}=\text{CH}_2 + \text{CH}_3=\text{C}-\text{CH}_2-\text{CH}_3 \\
\text{expected product (minor)} & \quad \text{unexpected product (major)}
\end{align*}
\]

These results were studied by Whitmore who was the first to suggest that the rearrangement of carbocations is responsible for such unexpected products. If the structure permits, a carbocation rearranges to form more stable carbocation.

In the example mentioned, the electrophile H⁺ adds to the sp² C bearing more Hs, in accordance with Markovnikov's rule. This results in the formation of secondary carbocation. If we closely look at the structure, the carbon adjacent to the positively charged carbon has a hydrogen that can shift as a hydride ion to the positively charged carbon and in the process form a more stable tertiary carbocation. This is referred to as carbocation rearrangement. In this case, the rearrangement has been achieved by a 1,2-hydride shift - i.e. H⁻ has shifted from one carbon to the adjacent electron deficient carbon. The new more stable carbocation now combines with the nucleophile X⁻ to yield final addition product.

\[
\begin{align*}
\text{CH}_3 & \quad \text{CH}_3 \quad \text{CH}_3 \\
\text{CH}_2=\text{CHCH}=\text{CH}_2 + \text{HBr} & \quad \rightarrow \quad \text{CH}_2=\text{CHCH}=\text{CH}_2 \quad \text{Br}^- \quad \rightarrow \quad \text{CH}_3-\text{C}-\text{CH}_2-\text{CH}_3 \\
1,2 \text{ hydride shift} & \quad \text{3\textsuperscript{rd} carbocation (more stable)} \quad \text{minor product} \\
\text{CH}_3 & \quad \text{CH}_3 \quad \text{CH}_3 \\
\text{CH}_2=\text{CHCH}=\text{CH}_2 & \quad \text{Br}^- \quad \text{CH}_3-\text{C}-\text{CH}_2-\text{CH}_3 \quad \text{Br}^- \\
\text{major product} & \quad \text{(without rearrangement)}
\end{align*}
\]

1,2-hydride shift does not alter the carbon skeleton. This is because, here one C-H bond is broken and a new C-H bond is formed. C-C skeleton is not disturbed.

\[
\begin{align*}
\text{C} & \quad \text{C} \quad \text{C} \quad \text{H} \\
\text{H} & \quad \rightarrow \quad \left[ \begin{array}{c} \text{C} \\ \text{H} \end{array} \right] ^+ \rightarrow \quad \text{C} \quad \text{C} \\
1,2\text{-hydride shift}
\end{align*}
\]
However, carbocations can undergo rearrangement in such a way that C-C bond breaks and a new C-C bond is formed. In such cases, the basic carbon skeleton gets altered. 1,2-Methyl shifts are examples of such rearrangement that cause change in carbon skeleton.

\[
\begin{align*}
\text{CH}_3 & \quad \text{CH} = \text{CH} \\
& \quad \text{CH}_3
\end{align*}
\] + HCl \rightarrow
\begin{align*}
\text{CH}_3 & \quad \text{CH} = \text{CH} \\
& \quad \text{CH}_3
\end{align*}

Thus we see that, the greater stability of tertiary carbocation compound over the initial secondary carbocation provides the driving force for the C-C bond cleavage, resulting in migration of Me group with its electron pair from one C to the adjacent carbon. Such changes in carbon skeleton involving carbocation are collectively called Wagner Meerwein Rearrangements. The C-skeleton change may even take place to the extent of ring expansion if it is giving a more stable carbocation intermediate.

Thus, carbocation, once formed, must be checked for rearrangement before proceeding to the next step. Another point is that, rearrangement should give a more stable carbocation otherwise, it is of no use and is not going to take place.
e.g. 4-methyl-1-pentene on protonation gives a secondary carbocation. If now, this carbocation undergoes a 1,2 hydride shift we still get a secondary carbocation of equal stability. In such cases, therefore, rearrangement does not occur.

\[
\begin{align*}
\text{CH}_3 & \quad \text{CH}_3 \\
\text{CH}_3\text{CHCH}_2\text{CH} = \text{CH}_2 & \quad + \text{HI} \\
\rightarrow & \quad \text{CH}_3\text{CHCH}_2\text{CHCH}_3 \\
\text{2° carbocation} & \\
\end{align*}
\]

\[
\begin{align*}
\text{CH}_3 & \quad \text{CH}_3 \\
\text{CH}_3\text{CHCH}_2\text{CHCH}_3 & \quad + \text{I}^- \\
\rightarrow & \quad \text{CH}_3\text{CHCHCH}_2\text{CH}_3 \\
\text{2° carbocation of equal stability} & \quad \text{no rearrangement}
\end{align*}
\]

**PREPARATION METHOD III: ADDITION OF HBr: PEROXIDE EFFECT**

We have studied in the earlier preparation method that, the major product of addition of an unsymmetrical alkene and a hydrogen halide is the one in which the hydrogen of HX gets attached to the carbon which carries the larger number of hydrogen atoms (Markovnikov’s Rule).

However, two chemists, M. S. Kharasch and F. R. Mayo, investigating the addition of hydrogen bromide to some alkenes, found that different samples of the same alkene gave different results of addition reaction. Some samples behaved as expected, giving mainly the product predicted by Markovnikov, but other samples reacted much more quickly and gave mainly the products in contradiction to Markovnikov’s Rule i.e. H adding to the carbon with lower number of hydrogens.

\[
\begin{align*}
\text{RCH} & \quad \text{RCH} \\
\text{H} & \quad \text{Br} \\
\rightarrow & \quad \text{RCHCH}_2\text{CH} = \text{CH}_2 \\
\text{Expected Markovnikov addition product (minor)} & \\
\end{align*}
\]

\[
\begin{align*}
\text{RCH} & \quad \text{RCH} \\
\text{Br} & \quad \text{H} \\
\rightarrow & \quad \text{RCH}_2\text{CH}_2 \\
\text{Anti Markovnikov addition product, Unexpected (major)} & \\
\end{align*}
\]

Eventually they noticed that the samples giving the expected product were the ones that had been freshly distilled and for which the reaction was done in absence of air. If the same sample was treated with HBr in presence of a small quantity of a peroxide (such as benzyol peroxide, \(\text{C}_6\text{H}_5\text{C}-\text{O}-\text{O}-\text{CC}_3\text{H}_3\)), or in general alkyl peroxide, ROOR) the unexpected product was formed. The reversal of the orientation of additions caused
by the presence of peroxides is known as PEROXIDE EFFECT. In presence of peroxide, the addition of HBr takes place by an entirely different mechanism — Free Radical Mechanism giving anti-Markovnikov addition product. If the addition is done in the absence of peroxides or in presence of inhibitors—such as hydroquinone or diphenyl amine—that inhibit the formation of radicals—the reaction follows the electrophilic addition route(preparation method II) to give Markovnikov addition product.

The free radical mechanism comprises of the Initiation Reaction, wherein the peroxide cleaves homolytically to give alkoxyl radical. With HBr, alkoxyl radical abstracts a hydrogen radical to release bromine radical.

\[
\text{ROOR} \rightarrow \text{RO}^* + \text{RO}^*
\]

\[
\text{RO}^* + \text{HBr} \rightarrow \text{ROH} + \text{Br}^*
\]

Bromine radical reacts with alkene and is regenerated in the Propagating Reactions. We have already studied, in preparation method I, that mechanism involving such step wise reactions that produce intermediates which cause the next step to occur are called Chain Reactions.

\[
\text{Br}^* + \text{RCH} = \text{CH}_2 \rightarrow \text{R}^*\text{CHCH}_2\text{Br}
\]

\[
\text{R}^*\text{CHCH}_2\text{Br} + \text{HBr} \rightarrow \text{RCH}_2\text{CH}_2\text{Br} + \text{Br}^*
\]

The chain reactions stop when any of the following termination reactions occur:

\[
\text{Br}^* + \text{Br}^* \rightarrow \text{Br}_2
\]

\[
\text{Br}^* + \text{R}^*\text{CHCH}_2\text{Br} \rightarrow \text{RCHCH}_2\text{Br}
\]

\[
2 \text{R}^*\text{CHCH}_2\text{Br} \rightarrow \text{R}^*\text{CH}^*\text{CH}^*\text{R}
\]

These compounds have also been isolated in small quantities from this reaction. This mechanism is further supported by the fact that anti-Markovnikov addition is caused not only by the presence of peroxides but also by irradiation with light of a wavelength that dissociates HBr to H* and Br*. Therefore, HBr addition to alkenes, in presence of either peroxide initiators or light of appropriate frequency, gives anti Markovnikov addition products.

\[
\text{RCH} = \text{CH}_2 + \text{HBr} \xrightarrow{\text{hv or peroxides}} \text{RCH}_2\text{CH}_2\text{Br}
\]

The reversal of orientation of addition product in the free radical mechanism can be explained by looking into the intermediate radicals formed. In the electrophilic addition, electrophile (H*) adds to alkene in such a way so as to produce the more stable carbocation. In the free radical addition, it is the bromine radical
(Br\textsuperscript{+}) that first adds to produce the more stable free radical. In the transition state of free radical formation, there is considerable radical character i.e. \( \pi \) bond is partly broken, C - Br bond is partly formed and the adjacent carbon has partly gained the odd electron it will carry in the intermediate free radical. Factors that stabilize free radical will therefore also stabilize the incipient free radical in the transition state. The decreasing order of stability of free radicals is: tertiary free radical > secondary > primary free radical.

Thus, for example, in the free radical addition of HBr to propene, the more stable intermediate is 2\textsuperscript{nd} free radical rather than the 1\textsuperscript{st} free radical. Corresponding T.S. leading to 2\textsuperscript{nd} free radical will be more stable and \( E_{\text{act}} \) of this pathway will be lower. Hence, this route will be the preferred route for radical addition.

\[
\begin{align*}
\text{CH}_2\text{CH} = \text{CH}_2 + \text{Br} & \quad \rightarrow \quad \begin{array}{c}
\text{CH}_3 \text{CH} = \text{CH}_2 \\
\text{Br}^* \\
\end{array} \\
\text{T.S. leading to 2}\text{radical} & \quad \text{2}\text{ free radical}
\end{align*}
\]

\[
\begin{align*}
\text{CH}_3 \text{CH} = \text{CH}_2 + \text{Br} & \quad \rightarrow \quad \begin{array}{c}
\text{CH}_3 \text{CH} = \text{CH}_2 \\
\text{Br}^* \\
\end{array} \\
\text{T.S. leading to 1}\text{radical} & \quad \text{1}\text{ free radical}
\end{align*}
\]

If we look into the transition state, the shared electrons will be displaced more towards electronegative Br thereby making the radical moiety of the transition state acquire polar character.

\[
\begin{align*}
\text{CH}_3 - \text{CH} = \text{CH}_2 + \text{Br} & \quad \rightarrow \quad \begin{array}{c}
\text{CH}_3 - \text{CH} = \text{CH}_2 \\
\text{Br}^* \\
\end{array} \\
\text{T.S. leading to 2}\text{radical} & \quad \text{2}\text{ free radical}
\end{align*}
\]

This polar character of T.S. will allow for that orientation which places the positive charge on the carbon that can best accommodate it. In this example Br\textsuperscript{+} will add to C-1 because the resulting secondary carboxylation character is more stabilizing than primary carboxylation character obtained if Br\textsuperscript{+} adds to C-2.

Finally, addition of a bulky free radical (Br\textsuperscript{+}) to less hindered C(C-1) is more favoured since it gives a less crowded and therefore more stable transition state.

\textbf{Stability of free radical, polar factors and steric factors - All three explain the anti Markovnikov addition product formation.}

\textbf{HCl and HI fail to undergo radical addition reactions with alkene.} This can be explained if we see the \( \Delta H^0 \) of the propagating steps for the various hydrogen halides.

\[
\begin{align*}
\Delta H^0 / \text{kJ mol}^{-1} \\
\text{X} = \text{Cl} & \quad -76 \quad -19 \quad +40 \\
\text{Br} & \quad -91 \\
\text{I} & \quad -91
\end{align*}
\]

\textbf{A statement:} In ionic addition (Markovnikov) \( \text{H}^+ \text{I}^- \) gets attached to the alkene carbon in the first step, while in free radical (anti-Markovnikov) addition it is Br\textsuperscript{+} which adds, gets attached to the alkene carbon in the first step, may help the reader to understand the basic difference between the two.
It is only for HBr that both the propagating steps are exothermic. With both HCl and with HI one of the two steps has very high activation energy and so is very slow step - too slow to compete with rapid termination steps.

**PREPARATION METHOD IV: ADDITION OF HALOGEN TO ALKENES.**

Bromine and chlorine both add readily to alkenes to yield 1,2-di-haloalkanes. Fluorine is too reactive and reaction is difficult to control whereas iodine is too unreactive with most alkenes.

When the electron rich alkene approaches a molecule of Br₂ or Cl₂, one of the halogen atoms take up the \( \pi \) electrons and in turn releases both of its shared electrons to the other halogen atom. Thus, in the formation of this new C-Br bond, both electrons are provided by the alkene. Hence, bromine molecule is described as an electrophile behaving as Br⁺ and Br⁻ (or Cl⁺ and Cl⁻ in case of Cl₂). This reaction is, therefore, an Electrophilic Addition Reaction. As a result, we expect a carbocation to be formed that could undergo further reaction with Br⁻ to yield the dibromo addition product.

\[
\text{H} \quad \text{Br - Br} 
\]

\[
\begin{align*}
\text{H} & \quad \text{Br} \\
\text{Br} & \quad \text{H}
\end{align*}
\]

However, this mechanism is not consistent with certain known facts of the reaction, particularly the stereochemistry of products. The mechanism proposed above gives no preference for a particular stereoisomer whereas actually, the reaction is very stereoselective.

George Kimball and Irving Roberts, in 1937, suggested a mechanism for this addition reaction which is consistent with the observed stereochemistry. They said that the true intermediate of the reaction is not a carbocation but is instead a cyclic bromonium ion (or cyclic chloronium ion). The latter is formed when a nonbonding pair of electrons on bromine forms a bond with the vacant \( p \) orbital of its neighbouring positively charged carbon (which would have otherwise been responsible for the existence of positively charged \( C \) of the carbocation). The bromonium ion is so formed due to its extra stability over the carbocation by having a complete octet (whereas the positively charged carbon of the carbocation does not have a complete octet). For this reason, the bromonium ion formation takes place in a single step. In the second step of the reaction, Br⁻ ion attacks one carbon atom of the cyclic bromonium ion. The three-membered ring opens up to release the strain and a vicinal dibromide is formed.
Stereochemistry of Addition of Halogens

Suppose we take 2 - butene and react with Br₂ in an inert solvent.

2 - butene exists as geometrical isomers - cis and trans and the saturated product of Br₂ addition has 2 chiral centres at C - 2 and C - 3.

The product, therefore, can exist as a pair of enantiomers and one meso compound.

It was found that cis - 2 - butene gave only racemic 2,3-dibromobutane and no meso product, whereas trans-2-butene gave only meso product and no racemic product. This clearly shows that the addition reaction is completely stereoselective and stereospecific. The observed result can be explained if we again look at the cyclic bromonium ion intermediate. The large bromine atom shields one side of the cyclic molecule from the attack by bromide ion. The attack of the bromide ion will, therefore, be from the side opposite to the side where Br is already present. Such opposite side addition is termed as Anti or Trans addition i.e. the net result is that the two bromine atoms add to the C=C from opposite sides. On this basis, cis - 2 - butene will always give racemic product only and trans 2 - butene will always give meso product only.
The electrophilic addition reaction is, as expected, favoured by electron releasing substituents on alkene. The stepwise mechanism of addition of the electrophile Br⁺ followed by the nucleophile Br⁻ is further supported by the fact that the reaction gives a variety of products in presence of nucleophiles added, in addition to Br⁻. Thus, when ethylene is reacted with aqueous solutions of Br₂ and NaCl, Cl⁻ and H₂O act as competing nucleophiles (otherwise NaCl is inert towards ethene) and we get several addition products. In all cases, the mode of addition remains trans.
Similarly, halogenation done in presence of aqueous solutions of sodium nitrite, sodium iodide, sodium fluoride and methanol give mixture of products due to presence of competing nucleophiles (ONO₂⁻, I⁻, F⁻, CH₃OH respectively).

\[
\text{CH}_2=\text{CH}_2 + \text{Cl}_2 + \text{CH}_3\text{OH} \rightarrow \text{CH}_2=\text{CH}_2 + \text{CH}_2=\text{CH}_2 \\
\text{Cl} \quad \text{OCH}_3 \quad \text{Cl} \quad \text{Cl}
\]

\[
\text{CH}_2=\text{CH}_2 + \text{Br}_2 + \text{NaNO}_3 \rightarrow \text{CH}_2=\text{CH}_2 + \text{CH}_2=\text{CH}_2 \\
\text{Br} \quad \text{ONO}_2 \quad \text{Br} \quad \text{Br}
\]

\[
\text{CH}_2=\text{CH}_2 + \text{Br}_2 + \text{NaF}+\text{H}_2\text{O} \rightarrow \text{CH}_2=\text{CH}_2 + \text{CH}_2=\text{CH}_2 + \text{CH}_2=\text{CH}_2 \\
\text{Br} \quad \text{F} \quad \text{Br} \quad \text{OH} \quad \text{Br} \quad \text{Br}
\]

\[
\text{CH}_2=\text{CH}_2 + \text{Cl}_2 + \text{NaI}+\text{H}_2\text{O} \rightarrow \text{CH}_2=\text{CH}_2 + \text{CH}_2=\text{CH}_2 + \text{CH}_2=\text{CH}_2 \\
\text{Cl} \quad \text{I} \quad \text{Cl} \quad \text{OH} \quad \text{Cl} \quad \text{Cl}
\]

Addition of I₂ to alkene is thermodynamically unfavourable. Vicinal diiodides are unstable at room temperature, decomposing back to alkene and I₂.

\[
\text{CH}_3\text{CH}=\text{CHCH}_3 + \text{I}_2 \rightleftharpoons \text{CH}_3\text{CHCHCH}_3 \\
\]

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PREPARATION METHOD V: REACTION OF ALCOHOLS WITH HYDROGEN HALIDES.
Alcohols react readily with hydrogen halides to give alkyl halides and water. The reaction is carried out either by passing the dry hydrogen halide gas into the alcohol, or by heating the alcohol with the concentrated aqueous acid. HBr and HCl can also be generated in presence of alcohol by reaction of H$_2$SO$_4$ with NaBr and NaCl respectively.

\[
\text{CH}_3\text{CH}_2\text{OH} \xrightarrow{\text{dry HBr}} \xrightarrow{\text{or}} \text{CH}_3\text{CH}_2\text{Br} \\
\text{NaBr} + \text{H}_2\text{SO}_4
\]

The order of reactivity of HX is HI > HBr > HCl (HF is unreactive).
The order of reactivity of alcohols towards HX is 3° > 2° > 1°-CH$_3$.
With HCl, due to its very low reactivity, the reaction is generally done in presence of zinc chloride as catalyst.
The reaction can take place on its own with aqueous hydrogen halides. However, the reaction gets catalysed by strong acids such as concentrated H$_2$SO$_4$.
The reaction is a Nucleophilic Substitution reaction wherein OH group is replaced by X. However, OH is a strongly basic group and cannot be displaced by a nucleophile.

\[
\text{CH}_3\text{OH} + \text{Br}^- \xrightarrow{X} \text{CH}_3\text{Br} + \text{OH}^-
\]
The alcohols can undergo nucleophilic substitution when OH group is converted to a weak base. One way is to protonate OH$^-$ (strong base) to H$_2$O (weak base). H$_2$O is a better leaving group and can be displaced more easily by nucleophiles. Heat is required to speed up the slow reaction.

\[
\text{CH}_3\text{OH} + \text{H}^+ \xrightleftharpoons{X} \text{CH}_3\text{OH} \xrightarrow{\Delta} \text{CH}_3\text{Br} + \text{H}_2\text{O} \\
\text{weak base, good leaving group}
\]

Thus, protonation of OH$^-$ is a must before it can be displaced by a nucleophile. We can use nucleophiles such as I$^-$, Br$^-$, Cl$^-$. These nucleophiles are strong nucleophiles (particularly I$^-$ and Br$^-$) but still not strong enough to carry out substitutions with alcohols themselves. We cannot use strongly basic nucleophiles such as NH$_3$, RNH$_2$, CH$_3$OH since these would be protonated in the acidic solution and would no longer be nucleophilic.

As we know, nucleophilic substitution is of two types - $S_{n}1$ and $S_{n}2$. The details of this class of reaction are discussed in the section on reactions of alkyl halides. The structure of the alcohol determines the mechanism of substitutions. With secondary, tertiary, allylic and benzylic alcohols, only one reactant - a carbocation intermediate is involved in the rate determining step - and the mechanism is said to be $S_{n}1$ (substitution, nucleophilic, unimolecular).
The alcohol first gets protonated and in the next step gives the carbocation by expulsion of H\textsubscript{2}O molecule. The carbocation intermediate has two possible fates:

It can combine with the nucleophile Br\textsuperscript{-} and form substitution product or it can lose a H\textsuperscript{+} and form an elimination product. However, the alkene so formed can undergo addition reaction with HX so that ultimately the same substitution product is actually obtained. Nevertheless, elimination products do form in such cases.

Primary alcohols and methanol do not form stable carbocations, hence they form alkyl halides by the S\textsubscript{2} mechanism (substitution, nucleophilic, bimolecular). Here the rate of the reaction depends on the concentration of both the reactants alcohol\textsubscript{a} and halide ion. Again, acid produces a protonated alcohol. The halide ion then displaces a water molecule from carbon to produce alkyl halide.

In case of chloride ion, the weaker nucleophilicity than bromide or iodide ion, makes it reactive with primary and secondary alcohols only in presence of zinc chloride or some other lewis acid. A complex is formed with alcohol and ZnCl\textsubscript{2}. The resulting leaving groups are even better than H\textsubscript{2}O.
Carbocation formed from S_{n}1 mechanism, can undergo rearrangement, as expected, to give a more stable structure.

\[
\begin{align*}
\text{CH}_3\text{H} & \quad \text{HCl} \quad \text{CH}_3\text{H} \\
\text{CH}_3\text{OH} & \quad \text{Cl} \quad \text{CH}_3\text{Cl} \\
\end{align*}
\]

*sole product (via 2° to 3° carbocation by 1,2-methyl shift)*

\[
\begin{align*}
\text{CH}_3\text{H} & \quad \text{HBr} \quad \text{CH}_3\text{H} \\
\text{CH}_3\text{OH} & \quad \text{Br} \quad \text{CH}_3\text{CH}_3\text{Br} \\
\end{align*}
\]

*sole product (via 2° to 3° carbocation by 1,2-hydride shift)*

**PREPARATION METHOD VI: ALKYL HALIDES FROM THE REACTION OF ALCOHOLS WITH PHOSPHORUS TRIHALIDES, THIONYL CHLORIDE, p-TOLUENESULPHONYL CHLORIDE**:

Alcohols, particularly primary and secondary alcohols, give good yields of alkyl halides with no rearrangement, when we use phosphorus trihalides.

The OH group of alcohol is converted into a neutral HOPX_{2} leaving group (by an initial S_{n}2 reaction at phosphorus).

\[
\begin{align*}
\text{R}^\delta_+ \text{H} + \text{P}^\delta_+ \text{X}^\delta^- \xrightarrow{\text{S_{n}2}} \text{X}^\delta^- + \text{R}^\delta_+ \text{P}^\delta_+ \text{X}^\delta^- \\
\text{X}^- \xrightarrow{\text{S_{n}2}} \text{RX} + \text{(RO)P(H)}^\delta_+ \text{O}^\delta^- \xrightarrow{\text{HX}} \text{RX} + \text{(RO)P(H)(OH)}^\delta_+ \xrightarrow{\text{HX}} \text{RX} + \text{H}_{3}\text{PO}_{3} \\
\end{align*}
\]

The HOPX_{2} can further react with two moles of alcohol to form P(OH)_{3}. Net reaction is

\[
\begin{align*}
3\text{ROH} + \text{PX}_{3} & \rightarrow (\text{RO})_{2}\text{P} + 3\text{HX} \\
\text{X}^- & \xrightarrow{\text{S_{n}2}} \text{RX} + (\text{RO})_{2}\text{P(H)}^\delta_+ \text{O}^\delta^- \xrightarrow{\text{HX}} \text{RX} + (\text{RO})\text{P(H)(OH)}^\delta_+ \xrightarrow{\text{HX}} \text{RX} + \text{H}_{3}\text{PO}_{3} \\
\end{align*}
\]

The reaction is done in presence of bases like pyridine or triethylamine, that act as solvents to prevent the formation of HCl and so to make the reaction move more in the forward direction.

Similarly SOCl_{2} gives an intermediate that possesses a chlorosulphite group which is easily displaced by Cl. This reaction is also called Darzen's procedure.
When we use an optically active alcohol it is found that in this reaction there is a complete retention of configuration. To rationalise this result, the mechanism proposed is $S_{N}1$ (substitution, nucleophilic, internal) via an alkyl chlorosulphite intermediate.

![Chemical structure](image)

The formation of an intimate ion pair can also explain the retention of configuration in the alkyl halide product. The intermediate alkyl chlorosulphite (ROSOC1) dissociates to form an intimate ion pair ($R'O^+OSOC1$) within a solvent cage. The OSOC1 anion then collapses to give SO$_2$ and Cl$^-$. Now Cl$^-$ attacks the carbocation from the same side that OSOC1 departs. The solvent shell prevents the Cl$^-$ from diffusing to the other face of the carbocation.

![Chemical structure](image)

-This reaction is done in absence of a nitrogen base so that HCl formed cannot provide Cl$^-$ as nucleophile to attack the alkyl chlorosulphite in a $S_{N}2$ reaction. Therefore, $S_{N}1$ mechanism operates.

- In presence of a nitrogen base (B), HCl gets converted to BH$^+$Cl$^-$. The Cl$^-$ can act as nucleophile and attack the alkyl chlorosulphite in an $S_{N}2$ reaction. In such a situation, Cl$^-$ carries out back side attack and therefore the configuration of the product gets inverted.

![Chemical structure](image)
React in with PX, also gives R - X

\[
\text{ROH} + \text{PX}_3 \rightarrow \text{RX} + \text{HX} + \text{POX}_3
\]

**PREPARATION METHOD VII: HUNSDIECKER OR BORDINE HUNSDIECKER REACTION**

Hundsiecker et al. found that silver salts of the carboxylic acids in carbon tetrachloride solution are decomposed by chlorine or bromine to give alkyl halides.

\[
\text{RCOOAg} + \text{Br}_2 \rightarrow \text{RBr} + \text{CO}_2 + \text{AgBr}
\]

The yield of the alkyl halide is primary > secondary > tertiary. Chlorine gives a poor yield. The mechanism involves formation of hypohalite which then decomposes into free radicals.

\[
\text{RCOOAg} + \text{Br}_2 \rightarrow \text{RCOOBr} + \text{AgBr}
\]

\[
\text{R}-\text{C}-\text{OBr} \rightarrow \text{Br}^- + \text{R}-\text{C}^-\text{O}
\]

\[
\text{R}^* + \text{CO}_2
\]

\[
\text{R}^* + \text{RC}^-\text{OBr} \rightarrow \text{RBr} + \text{RC}^-\text{O}
\]

A more convenient way to carry out the Hundsiecker reaction is to heat the acid with mercuric oxide and bromine (This reaction is called Cristol - Firth Modification)

\[
\text{RCOOH} + \text{Br}_2 + \text{HgO} \xrightarrow{\Delta} \text{RBr} + \text{CO}_2 + \text{HgBr}_2
\]

**PREPARATION METHOD VIII: PREPARATION OF ALKYL FLUORIDES AND ALKYL IODIDES**

As discussed, direct fluorination of alkanes is difficult to accomplish, since the reaction is highly exothermic and usually explosive; it almost always leads to a mixture of perfluorinated compounds.

If instead of fluorine, the less reactive metal fluorides, such as silver, mercury (I) or platinum fluorides are used as fluorinating agents and made to react with alkyl halides, halogen atom is exchanged with fluorine.

This reaction is called SWART'S REACTION.
$$2 \text{R} \rightarrow \text{X} + \text{Hg}_2\text{F}_2 \rightarrow 2 \text{R} \rightarrow \text{F} + \text{Hg}_2\text{X}_2$$

$$\text{X} = \text{Cl}, \text{Br}, \text{I}$$

In this halogen exchange reaction, the advantage of I\textsuperscript{−}, Br\textsuperscript{−}, Cl\textsuperscript{−} acting as good leaving groups for substitution reaction has been used.

Alkyl iodides are more conveniently prepared by heating the chloro or bromo derivatives with sodium iodide in methanol or acetone solution

$$\text{RCI} + \text{NaI} \rightarrow \text{R-I} + \text{NaCl}$$

This reaction of halide exchange is called Finkelstien Reaction.

Iodo group can also be introduced using a reagent such as ICl (iodine monochloride) the reagent adds to alkene in accordance with Markovnikov’s rule (refer to preparation method II). Because of the greater electronegativity of chlorine, the positive portion of this molecule is iodine.

**PHYSICAL PROPERTIES**

Alkyl halides, due to the presence of electronegative halogen atom, are moderately polar in nature with a permanent dipole moment. The molecules are held together by van der Waals forces or weak dipole-dipole interactions. The lower members are gases (CH\textsubscript{3}Cl, CH\textsubscript{3}Br and C\textsubscript{2}H\textsubscript{5}Cl) but methyl iodide and a majority of higher members are sweet smelling liquids. The dipole moment (or polarity) affects the boiling points of the compounds. Alkyl halides, due to higher molecular mass, have higher b.pt than alkanes with same number of C atoms. Amongst themselves, alkyl iodides with highest atomic mass of iodide group, has highest b.pt followed by bromides, chlorides and fluorides. With every increase in carbon atom there is a regular increase (by 20 - 30°C) in b.pt for a given halogen. Amongst isomeric alkyl halides, primary alkyl halide has highest b.pt followed by secondary and tertiary halide due to increase in branching of alkyl groups which decreases surface area (the molecule tends to assume shape of a sphere) and hence intermolecular forces of attraction.

If we compare alkyl halides with alkanes of comparable molecular mass, we surprisingly find that inspite of polarity of alkyl halide, their b pts are about the same as alkanes. This is because for a given molecular mass, alkane molecules have higher volumes than alkyl halide molecules. Alkanes will have much more number of C atoms in order to have same molecular mass as alkyl halide. Attractive forces between molecules-van der Waals forces or weak dipole dipole interaction forces - are greater for larger molecules.
which translate into higher b.pt.

Most alkyl halides have very low solubility in water due to lack of H-bonding but are miscible with each other and with other non-polar solvents e.g. benzene, ether, chloroform etc. While others are less dense, iodo, bromo and polychloro compounds are more dense than water.

Some physical properties are given in the table

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>mp °C</th>
<th>bp °C</th>
<th>sp gr (liq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl fluoride</td>
<td>CH₃F</td>
<td>-79</td>
<td>-14.2</td>
<td>0.877</td>
</tr>
<tr>
<td>Methyl chloride</td>
<td>CH₃Cl</td>
<td>-97</td>
<td>-23.7</td>
<td>0.920</td>
</tr>
<tr>
<td>Methyl bromide</td>
<td>CH₃Br</td>
<td>-93</td>
<td>4.60</td>
<td>1.732</td>
</tr>
<tr>
<td>Methyl iodide</td>
<td>CH₃I</td>
<td>-64</td>
<td>42.3</td>
<td>2.279</td>
</tr>
<tr>
<td>Ethyl chloride</td>
<td>CH₂CH₂Cl</td>
<td>-139</td>
<td>13.1</td>
<td>0.910</td>
</tr>
<tr>
<td>Ethyl bromide</td>
<td>CH₂CH₂Br</td>
<td>-119</td>
<td>38.4</td>
<td>1.430</td>
</tr>
<tr>
<td>n-Propyl chloride</td>
<td>CH₃CH₂CH₂Cl</td>
<td>-123</td>
<td>46.4</td>
<td>0.890</td>
</tr>
<tr>
<td>Isopropyl chloride</td>
<td>CH₃CHClCH₃</td>
<td>-117</td>
<td>36.5</td>
<td>0.860</td>
</tr>
<tr>
<td>n-Butyl bromide</td>
<td>CH₃CH₂CH₂Br</td>
<td>-112</td>
<td>101.6</td>
<td>1.275</td>
</tr>
<tr>
<td>Isobutyl bromide</td>
<td>(CH₃)₂CHCH₂Br</td>
<td>-120</td>
<td>91.3</td>
<td>1.250</td>
</tr>
<tr>
<td>sec-Butyl bromide</td>
<td>CH₂CH₂CH(Br)CH₃</td>
<td>-</td>
<td>91.0</td>
<td>0.871</td>
</tr>
<tr>
<td>tert-Butyl bromide</td>
<td>(CH₃)₃CBr</td>
<td>-20</td>
<td>73.3</td>
<td>1.222</td>
</tr>
</tbody>
</table>

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REATIONS OF ALKYL HALIDES

Alkyl halides have their sp\(^1\) hybridised carbon bonded to an electronegative halogen atom. Since halogen is more electronegative than carbon, the two atoms do not share their bonding electrons equally. The halogen atom has a larger share of the electrons and hence develops a partial negative charge whereas the carbon to which it is bonded bears a partial positive charge. The \(\text{C - X} \) bond in alkyl halides has therefore got a considerable polar character.

\[
\begin{align*}
\text{C} & \quad \delta^+ \\
\delta^- & \quad X
\end{align*}
\]

\(X = \text{F, Cl, Br, I}\)

This polar \(\text{C - X} \) bond is responsible for the high reactivity of alkyl halides and is characteristic of the functional group 'X'.

Alkyl halides are typically involved in polar reactions with nucleophiles and bases. With nucleophiles or bases they can undergo one of the following reactions:

I  
**Substitution**: \(X\) group replaced by nucleophile (\(\text{Nu}\))

\[
\begin{align*}
\text{Nu} & \quad \text{C} \quad \text{X} \\
\rightarrow & \quad \rightarrow \\
\text{X}^- & \quad \text{CNu}
\end{align*}
\]

\(\text{Nu} \rightarrow \text{C} \rightarrow X^- + \text{CNu}\)

II  
**Elimination**: Removal of \(\text{HX}\) to yield alkene, induced by a base.

\[
\begin{align*}
\text{Nu}^+ & \quad \text{H} \\
\rightarrow & \quad \rightarrow \\
\text{X}^- & \quad \text{NuH} \quad + \quad \text{C} \quad \rightarrow \\
& \quad \rightarrow \\
\end{align*}
\]

\(\text{Nu}^+ \rightarrow \text{H} \rightarrow \text{X}^- + \text{NuH} \rightarrow \text{C} \rightarrow X^- + \text{NuH}\)

Apart from these, alkyl halides also undergo the following type of reactions.

III  
**Formation of Grignard Reagents**

IV  
**Reduction**
SUBSTITUTION REACTIONS

Alkyl halides react with nucleophiles as follows:

\[ \text{Nu}^- + R - \overline{\text{X}} \rightarrow R - \text{Nu} + \overline{\text{X}}^- \]

Here, nucleophile, $\text{Nu}^-$, is any species with either unshared pair of electrons or a negative change. $R - \overline{X}$ is the organic molecule on which reaction takes place and is called substrate. $\overline{\text{X}}$ is the group that is displaced and is called the leaving group or nucleofugic group. Since the initial attacking species is a nucleophile $\text{Nu}^-$ which replaces $\overline{X}$ on substrate $R - \overline{X}$, this reaction is a Nucleophilic Substitution Reaction.

Alkyl halides owe the nucleophilic substitution reactions to the functional group, halogen. A halide ion is an extremely weak base i.e., it readily releases a proton to other bases which is understood from the high acidity of the hydrogen halides. Just as halide readily releases a proton, in alkyl halide it readily loses carbon to other bases. Thus, the weakly basic halide ion is an extremely good leaving group which makes alkyl halide good substrates for nucleophilic substitutions.

Nucleophilic substitution is an extremely useful class of organic reaction since it is a very potential synthetic tool. Listed below are a large number of nucleophiles which undergo substitution reactions with alkyl halide to give various products carrying different functional groups.

<table>
<thead>
<tr>
<th>Nucleophile</th>
<th>Product</th>
<th>Product Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{OH}^-$</td>
<td>ROH</td>
<td>Alcohol</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}$</td>
<td>ROH</td>
<td>Alcohol</td>
</tr>
<tr>
<td>$\text{OR}^-$</td>
<td>ROR</td>
<td>Ether</td>
</tr>
<tr>
<td>$\text{C}==\text{CR}^-$</td>
<td>RC==CR</td>
<td>Alkyne</td>
</tr>
<tr>
<td>$\text{I}^-$</td>
<td>RI</td>
<td>Alkyl Iodide</td>
</tr>
<tr>
<td>$\text{CN}^-$</td>
<td>RCN</td>
<td>Nitrile</td>
</tr>
<tr>
<td>$\text{RCOO}^-$</td>
<td>RCOOR</td>
<td>Ester</td>
</tr>
<tr>
<td>$\text{NH}_2^-$</td>
<td>RNH$_2$</td>
<td>Primary Amine</td>
</tr>
<tr>
<td>$\text{RNH}_2$</td>
<td>R$\text{NH}$</td>
<td>Secondary Amine</td>
</tr>
<tr>
<td>$\text{R}_2\text{NH}^-$</td>
<td>R$\text{N}$R</td>
<td>Tertiary Amine</td>
</tr>
<tr>
<td>$\text{SH}^-$</td>
<td>RSH</td>
<td>Thiol</td>
</tr>
<tr>
<td>$\text{SR}^-$</td>
<td>RSR</td>
<td>Thioether</td>
</tr>
<tr>
<td>$\text{P(C}_6\text{H}_5)_3^-$</td>
<td>RP$^+$ (C$_6$H$_5$)$_2$X</td>
<td>Phosphonium Salt$^+$</td>
</tr>
<tr>
<td>$\text{N}_3^-$</td>
<td>RN$_3$</td>
<td>Alkyl Azide</td>
</tr>
</tbody>
</table>

Nucleophilic substitution can take place in two ways:

(i) Nucleophile attacks the electrophilic carbon centre and $C - \overline{X}$ bond breaks.

\[ \text{Nu}^- \overset{\delta+}{\underset{\delta-}{\text{C}} - \overline{X} \rightarrow \text{Nu}^- \overset{\text{C}}{\underset{\text{X}^-}{\text{C}} + \overline{X}} \]
The carbon-halogen bond breaks and then the nucleophile attacks the positively charged C.

\[
\begin{align*}
\text{C}^{-} \text{X} & \rightarrow \text{C}^{+} + \text{X}^{-} \\
\text{C}^{+} + \text{Nu} & \rightarrow \text{C}^{-} \text{Nu}
\end{align*}
\]

In both cases the essential feature is that the carbon halogen bond breaks heterolytically, i.e. X departs with the electron pair as \(\text{X}^{2-}\).

Whether the reaction takes place by mechanism (I) or mechanism (II) depends on several factors viz

- Structure of Alkyl Halide
- Reactivity and structure of Nucleophile
- Concentration of Nucleophile
- Solvent in which reaction is carried out

To know the mechanism of a reaction, we should determine the factors that affect the rate of the reaction i.e. Kinetics of the reaction. Kinetic measurement on reactions in which alkyl halides are attacked by a wide variety of nucleophiles have revealed two essentially extreme types of mechanisms with the following rates of reactions:

(I) \[ \text{Rate} = K [\text{RX}] \left[\text{Nu}\right] \]

(II) \[ \text{Rate} = K \left[\text{RX}\right] \]

Thus, one case has rate of reaction dependent on both reactants whereas the other is independent of nucleophile. Let us discuss each of these cases in detail.

**S_N2 Reaction**

Take the nucleophilic substitution of the simplest alkyl halide i.e. reaction of methyl bromide with OH\(^{-}\) wherein OH\(^{-}\) displaces Br\(^{-}\).

\[
\text{CH}_3\text{Br} + \text{OH}^- \rightarrow \text{CH}_3\text{OH} + \text{Br}^{-}
\]

The rate of the reaction in this case is found to depend on the concentration of both \(\text{CH}_3\text{Br}\) and \(\text{OH}^-\). It was found that if concentration of either of the reactants is doubled the rate of nucleophilic substitution doubled and if either of the reactants have their concentrations halved the rate became half of the original rate. If both the reactants have their concentrations doubled, the rate of the substitution reaction gets quadrupled.

Rate law for the reaction, therefore, is

\[ \text{rate} \propto [\text{CH}_3\text{Br}][\text{OH}^-] \]
In general, the rate of such reactions depends on concentration of both the reactants

\[ \text{rate} \propto [\text{alkyl halide}][\text{nucleophile}] \]

or,

\[ \text{rate} = k[\text{alkylhalide}][\text{nucleophile}] \]

Thus, the reaction is a second order reaction. This essentially means that for the reaction to take place, a hydroxide ion and a CH$_3$Br molecule must collide. Also, the rate law tells us about the number of molecules involved in the transition state of the rate determining step. In the transition state, two molecules of the reactants are involved. Such a reaction is known as $S_{N2}$ reaction which stands for Substitution, Nucleophilic, Bimolecular.

$S_{N2}$ Reaction : Mechanism

In 1937, Edward D. Hughes and Sir Christopher Ingold proposed the mechanism for $S_{N2}$ reaction. They proposed a concerted mechanism wherein the reaction takes place in a single step without the formation of intermediates. The attack of nucleophile on the electrophilic carbon bearing the leaving group and the departure of the halide ion from this carbon, both take place simultaneously. This happens when the nucleophile attacks the carbon on the side opposite to the side bonded to the leaving group. Such an attack is, therefore, very reasonably called 'back side' attack or the rear attack. The orbital of the nucleophile that contains the nonbonding electron pair begins to overlap with the empty (antibonding) molecular orbital of the carbon atom bearing the leaving group. The orbital has its larger lobe on the side of the carbon directed away from the C-Br bond. Consequently, the best overlap of the interacting orbitals is achieved from back side attack.

As the reaction progresses the bond between the nucleophile and the carbon atom grows, and the bond between the carbon atom and the leaving group weakens.

In the transition state, the groups -OH and -Br are collinear and perpendicular to the plane containing carbon atom and the remaining three hydrogens. In other words, the sp$^3$ hybridized C of alkyl halides, which is otherwise tetrahedral with 3 Hs and 1 X disposed in the four corners of a tetrahedron, has to assume a trigonal planar sp$^3$ hybridization to have one C and 3 Hs in one plane in the T.S. In the sp$^3$ hybrid
state, the bond angles are 120°. The remaining p, orbital is used to hold the -OH and -Br groups (by means of its two lobes) through ‘half bonds’ or partial bonds separated by an angle of 180°. C-OH bond is not completely formed, hence OH has a diminished negative charge; C-Br bond is not completely broken, hence Br has partly removed pair of electrons from carbon and therefore has a partial negative charge. The negative charge, in the course of being transferred from OH to Br, is spread in T.S. The C-H bonds are thus arranged like the spokes of a wheel with the C-OH and C-Br bonds forming the axle of the wheel. This makes C pentavalent in the T.S. rather than tetravalent. Gradually, the nucleophile gets closer to the carbon and bromine moves farther away from it. As a result, the 3 C-H bonds also start moving in the same direction as that of bromine. Finally C-OH bond is fully formed and C-Br is completely broken. When Br gets ejected, C returns to the tetrahedral hybridization. Because the transition state involves both the nucleophile (OH-) and the substrate (CH₃Br), this mechanism accounts for the second-order kinetics. The energy necessary to effect the breaking of the C - Br bond is partly supplied by that produced in forming C - OH bond. The overall reaction is exergonic - i.e. has a negative free energy change. The equilibrium constant has a large value thereby indicating that the reaction goes to completion. The T.S. has a fleeting existence - lasts for the time required for one molecular vibration ~ 10⁻¹⁵ s. Reaction coordinate diagram for the hydrolysis of bromomethane is shown in fig.5.

Such a mechanism has being designated by Ingold as S₉².

**Stereochemistry of S₉² Reaction**

The ‘Backside’ mode of attack of OH⁻ on CH₃Br to displace Br⁻, is possible only when OH⁻ is on a side directly opposite to Br⁻. As a result, the configuration of C atom undergoing the displacement reaction will invert - just like the turning inside out of an umbrella in strong winds. Such a reaction that yields products whose configuration is opposite to that of reactants is said to proceed with inversion of configuration or Walden Inversion in honour of Paul Walden who discovered the stereochemical aspect of this reaction.

Obviously, due to lack of chiral centre, the inversion can not be observed in CH₃Br substitution. Nevertheless if we take a suitable substrate, e.g. S (+) - 2 - bromooctane and react it with sodium hydroxide, we get R(-) - 2 - octanol.

\[
\begin{array}{c}
\text{Br} \quad \text{CH₃} \quad \text{H} \\
\text{C} \quad \text{S₉²} \quad \text{NaOH} \\
\text{CH₃} \quad \text{H} \\
\text{S (+) - 2 - bromooctane} \\
\end{array}
\quad 
\begin{array}{c}
\text{H} \quad \text{C} \quad \text{OH} \\
\text{CH₃} \quad \text{S₉²} \quad \text{NaOH} \\
\text{CH₃} \quad \text{H} \\
\text{R (-) - 2 - octanol} \\
\end{array}
\]

Similarly if we take cyclic halide of a particular configuration, its S₉² reaction leads to complete inversion.

\[
\begin{array}{c}
\text{CH₃} \quad \text{Cl} \quad \text{H} \\
\text{H} \quad \text{OH} \quad \text{NaOH} \\
\text{cis - 1- chloro - 3 - methycyclopentane} \\
\end{array}
\quad 
\begin{array}{c}
\text{CH₃} \quad \text{H} \quad \text{OH} \\
\text{H} \quad \text{OH} \quad \text{S₉²} \\
\text{trans - 3 - methycyclopentanol} \\
\end{array}
\]

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In $S_n2$ reaction, every molecule, whether capable of visually showing inversion or not, does undergo complete inversion. This stereochemical outcome of $S_n2$ reaction proves another important feature of the reaction: The concerted nature of the reaction - involves simultaneous bond breaking and bond making.

**Characteristics of $S_n2$ reaction**

**The Substrate**

When the substrate is $CH_3X$, the T.S. of $S_n2$ reaction is least crowded. But as we replace hydrogens progressively by methyl (or alkyl) groups, crowding at the reaction centre will go on increasing, making the back side attack increasingly difficult. This crowding will be more severe in the T.S., when the methyl groups are thrown closer to the -OH and -Br groups. Non bonded steric repulsions will raise the energy of the crowded T.S. $E_m$ will be higher and the reaction slows down. Thus, rate of $S_n2$ reaction is highest for the unhindered $CH_3X$ and progressively slows down as we replace Hs by bulky alkyl groups i.e. as we go from $CH_3X$ to $1^\text{st}$ to $2^\text{nd}$ to $3^\text{rd}$ alkyl halide, the rate of $S_n2$ reaction decreases. By the time, we replace all Hs by alkyl groups i.e. we have a tertiary alkyl halide, steric hindrance at the carbon increases so much that the back side attack becomes impossible and $S_n2$ reaction does not take place at all. Reaction coordinate diagram for such a reaction is shown in fig.6.

$$CH_3X > 1^\text{st} \text{ alkyl halide} > 2^\text{nd} \text{ alkyl halide} > 3^\text{rd} \text{ alkyl halide}$$

--- decreasing order of reactivity in $S_n2$ reaction ---

Even if the nature of alkyl halide is same (i.e. number of alkyl groups bonded to the carbon are same) - the size of the alkyl group effects the rate of $S_n2$ reaction - bulkier groups pose higher steric hindrance and hence decrease the rate of $S_n2$ reaction. Thus, between ethyl bromide and n-propyl bromide, the group $CH_3CH_2$ - on the $\alpha$ carbon in n-propyl bromide, is bulkier than $CH_3$ - in ethyl bromide, therefore the latter has higher reactivity in $S_n2$ reaction. Therefore, order of reactivity for primary halides with increasing steric hindrance caused by a single substituent will be:

$$CH_3CH_2Br > CH_3CH_2CH_2Br > CH_3CH=CH_2Br > CH_3C=CHBr$$

In the last case, the Hs of methyl branches pose severe van der Waal repulsion to both the nucleophile and the leaving group. $S_n2$ reaction is impossible in this case.

One might think about the role of polar factors in the reactivity order of alkyl halides. The T.S. has C with partial bond to OH and X and partial negative charges on each. The extent of breaking and making of bond is the same. Therefore, C does not have appreciably more or less charge. If C was more negative or more positive, polar factors (i.e. electron releasing effect of R group) would have played a key role.

In general, branching at $\alpha$-carbon i.e. going from primary to secondary to tertiary alkyl halide - retards the $S_n2$ reaction. Similarly branching at $\beta$-carbon retards the $S_n2$ reaction. The following table will make these points clear.
Table
(Effect of branching in the alkyl halide on the rate of a typical S,2 reaction)

<table>
<thead>
<tr>
<th>R⁻</th>
<th>Name of R</th>
<th>Relative Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₃</td>
<td>methyl</td>
<td>145</td>
</tr>
<tr>
<td>CH₂CH₂⁻</td>
<td>ethyl</td>
<td>1</td>
</tr>
<tr>
<td>(CH₃)₂CH⁻</td>
<td>isopropyl</td>
<td>0.0078</td>
</tr>
<tr>
<td>(CH₃)₂C⁻</td>
<td>tert- butyl</td>
<td>0.00005</td>
</tr>
<tr>
<td>CH₃CH₂CH₂⁻</td>
<td>propyl</td>
<td>0.82</td>
</tr>
<tr>
<td>(CH₃)₂CHCH₂⁻</td>
<td>isobutyl</td>
<td>0.036</td>
</tr>
<tr>
<td>(CH₃)₂C⁻CH₂⁻</td>
<td>neopentyl</td>
<td>0.000012</td>
</tr>
</tbody>
</table>

The Leaving Group

The nature of the leaving group displaced by the attacking nucleophile has an important role to play. The leaving group leaves with a negative charge i.e. as an anion. Any anion can be rated as a strong or weak base based on its stability. The best leaving groups or the best anions, therefore, are those that can stabilize or accommodate their negative charge. The more stable the anion the more difficult it is for it to share its electron, hence the weaker base it is. Therefore, the best leaving group should be the weakest base.

Let us look at the leaving groups in alkyl halides:

\[ \text{OH} \quad \text{R-F, R-Cl, R-Br, R-I} \]

Weakest bases can also be looked as the anions of strongest acids. Amongst all hydrogen halides, HI is the strongest acid; therefore I⁻ is the weakest base and the best leaving group.

\[ \text{HI} > \text{HBr} > \text{HCl} > \text{HF} \quad \text{order of acidity of HX} \]

\[ \text{I}^- < \text{Br}^- < \text{Cl}^- < \text{F}^- \quad \text{order of basicity of X}^- \]

\[ \text{I}^- > \text{Br}^- > \text{Cl}^- > \text{F}^- \quad \text{leaving ability of X}^- \]

Apart from halide ion, p-toluene sulphonate (tosylate ion) is a very well stabilized anion, hence a very weak base or a very good leaving group.
Stable anions are good leaving groups because they lower the energy of the transition state of the reaction. In the T.S., the negative charge is equally distributed over both the incoming nucleophile and the outgoing leaving group. If the leaving group bears a structure that can accommodate negative charge well, it can lower the energy of T.S. and increase rate of reaction.

In contrast, OH, 'NH₂, OR are poor leaving groups since they cannot stabilize the negative charge. Therefore, alcohols, amines, as well as alkyl fluorides do not normally undergo S₄₂ reactions.

<table>
<thead>
<tr>
<th>CH⁻</th>
<th>CH₂⁻</th>
<th>OR⁻</th>
<th>F⁻</th>
<th>Cl⁻</th>
<th>Br⁻</th>
<th>I⁻</th>
<th>TsO⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>200</td>
<td>10,000</td>
<td>30,000</td>
<td>60,000</td>
</tr>
</tbody>
</table>

*Less Reactive*  

| Leaving group reactivity | More Reactive |

**The Nucleophile**

Nature of Nucleophile attacking the substrate is another important variable. Any species with unshared pair of electrons (non bonded electrons) can act as a nucleophile. Thus, nucleophiles can be neutral or negatively charged. Neutral nucleophile on attacking substrate (which is an electron deficient atom other than proton) gives a positively charged product whereas negatively charged nucleophiles give a neutral product.

\[
\text{Nu} + \text{R} - \text{X} \rightarrow \text{Nu - R} + \text{X}^+ \]

\[
\text{Nu}^- + \text{R} - \text{X} \rightarrow \text{Nu - R} + \text{X}^+ \]

In case of S₄₂ reaction, nucleophilicity is a measure of how readily the nucleophile attacks an electron deficient sp³ hybridized carbon bonded to a leaving group. The affinity of a nucleophile for a carbon atom can also change from one reactant to other. Several common nucleophiles in the order of their reactivity for bromomethane substrate are given.
A base is also a species with non bonding pair of electrons that are used to attack electron deficient atom. In case of base, this electron deficient atom is a proton. Nucleophile always attacks an electron deficient atom other than proton.

Nucleophilicity might therefore be expected to correlate with its basicity, as both involve the availability of electron pair and the ease with which they are donated. But, there is never an exact parallel between the two. (Basicity involves an equilibrium situation whereas nucleophilicity a kinetic situation).

Basicity data being readily available, can be used as a guide to nucleophilicity, provided like is being compared to like.

* If the attacking atom is the same, nucleophilicity parallels basicity i.e. stronger bases are stronger nucleophiles and vice versa,

\[ \text{CH}_3\text{CH}_2\text{O}^- \rightarrow \text{CH}_3\text{C}^\text{O}^- \rightarrow \text{NO}_3^- \]

* Negatively charged nucleophiles are more reactive than their neutral counterparts.

\[ \text{HO}^- > \text{H}_2\text{O}^- \quad \text{HO}^- \quad \text{OH}^- \]

\[ \text{CH}_3\text{CH}_2\text{O}^- \quad \text{CH}_3\text{CH}_2\text{OH} \quad \text{NH}_3^+ \quad \text{NH}_3 \]

CH$_4$N$^-$
* When the attacking atoms are of approximately same size, the stronger bases are again stronger nucleophiles. Atoms across the second row of periodic table are of nearly the same size. The hydride anions of these have the following basicity order which is also the nucleophilicity order. The basicity and nucleophilicity order of the following is the same:

\[
\text{CH}_3^- > \text{NH}_4^+ > \text{OH}^- > \text{F}^-
\]

(The corresponding acids have the opposite trend in their strengths)

* If attacking atoms are of different size, the nucleophilicity and basicity parallel in gas phase. This is because of the increase in size in going down the group. The negative charge is increasingly better accommodated which makes the base increasingly more stable, or in other words as we go down the group the base becomes increasingly weaker. Accordingly, the nucleophilicity decreases down the group.

The relationship between basicity and nucleophilicity becomes inverted in a protic solvent i.e. As we go down a group, the anions show a decrease in their basicities, but increase in their nucleophilicities. Why does this order get inverted? This happens because protic solvents have partially positively charged hydrogens that get associated with the nucleophiles from all sides through H-bonding (protic solvents have hydrogen attached to O or N atom of the solvent). Anions are said to get solvated in such a situation.

A small sized, less polarizable nucleophilic anion gets highly solvated through the ion-dipole interactions. The heats of hydration (solvation energy) are very high. In order to participate in S_n reaction, the nucleophile has to come out of this cage. For this, at least one of the ion-dipole interaction must be broken. Strong bases (which are also mostly strong nucleophiles) interact with protic solvents more strongly than weak bases because they are better at sharing their electrons. Weak bases, therefore, require lesser energy to break the ion-dipole interaction and participate in S_n reaction; or in other words weak bases are better nucleophiles in protic solvents. In fact, larger atoms are better nucleophiles in protic solvents.

\[
\text{HS}^- > \text{HO}^- > \text{RS}^- > \text{RO}^- \\
\text{I} > \text{Br} > \text{Cl}
\]

In non-polar solvents, stronger bases are stronger nucleophiles. Between F^- and I-, F^- will be a stronger
nucleophile. This is due to absence of ion-dipole interactions. However, non-polar solvents do not dissolve most ions. But if we take polar aprotic solvents, this trend is retained. Aprotic solvents do not have hydrogen directly attached to O or N of the solvent molecule e.g. dimethyl sulfoxide, N, N-dimethyl formamide. Therefore, they cannot act as H-bond donors. Polar aprotic solvents have partial positive charge on the inside of the molecule which makes it less accessible for interaction with nucleophile. Therefore, the anion does not get solvated. They also have partial negative charge on the molecule which can solvate cations and thus increase solubility.

Another important factor that affects nucleophilicity is the steric factor. A nucleophile needs to approach the back side of an electron deficient carbon. For this not only does the carbon need to be sterically unhindered but also the nucleophile. Therefore, whereas increasing number of alkyl groups make the base stronger by their increasing electron releasing capability, there is an increasing steric hindrance that makes the approach of nucleophile difficult, therefore the nucleophilicity decreases. That is why t-butoxide ion is stronger base and weaker nucleophile than ethoxide ion.

The Solvent
We just studied the important role played by solvent in affecting the reactivity of the nucleophile. Protonic solvents, with strong dipoles, cage around the nucleophile and lower its ground state energy and hence its reactivity. This, in turn, decreases the rate of S_{n}2 reaction. Polar aprotic solvents, on the other hand, keep the anion unsolvated and bare so that their ground state energy remains high and hence their nucleophilicity is not reduced. This results in increase in the rate of S_{n}2 reaction. Polar aprotic solvents are, therefore, best suited for S_{n}2 reactions.

S_{n}1 Reaction
Let us now consider the nucleophilic substitution of the most substituted alkyl halide e.g. hydrolysis of tertiary butyl chloride wherein OH\(^{-}\) displaces Cl\(^{-}\).

\[
\begin{align*}
\text{CH}_3 &- \text{C} - \text{Cl} + \text{OH}^{-} \rightarrow \text{CH}_3 & - \text{C} - \text{OH} + \text{Cl}^{-} \\
\text{CH}_3 & & \text{CH}_3
\end{align*}
\]

The rate of the reaction is found to be independent of OH\(^{-}\) concentration. Doubling the concentration of alkyl halide doubles the rate of reaction but doubling the concentration of OH\(^{-}\) has no appreciable effect on the rate. Also, the rate of reaction remains same in water and in 0.05 N NaOH (i.e. 500,000 times higher concentration of OH\(^{-}\))

Rate law for the substitution reaction is dependent only on the alkyl halide.

\[
\text{rate} = k \left[ (\text{CH}_3)\text{C} - \text{Cl} \right]
\]
In general, rate of such reactions depend on concentration of only substrate

\[ \text{rate} = k \ [\text{alkyl halide}] \]

Transition state of the step that determines overall rate of reaction, involves molecules of only the alkyl halide and not of OH\(^+\). The reaction is, therefore, unimolecular and such reactions are termed as S\(_{n1}\) : Substitution Nucleophilic Unimolecular.

**S\(_{n1}\) Reaction : Mechanism**

The t-butyl choride molecule dissociates slowly by a heterolytic cleavage into a chloride ion and a cation derived from the t-butyl group—a carbocation. This constitutes the first step of the reaction. In the second step, the nucleophile, OH\(^-\), rapidly combines with the carbocation to yield t-butyl alcohol.

\[
\begin{align*}
\text{CH}_3\text{C}^-\text{Cl} & \underset{\text{slow}}{\xrightarrow{\text{slow}}} \text{CH}_3\text{C}^+ + \text{Cl}^- \\
\text{CH}_3\text{C}^+ + \text{OH}^- & \underset{\text{fast}}{\rightarrow} \text{CH}_3\text{C}^-\text{OH}
\end{align*}
\]

Because the rate of S\(_{n1}\) reaction depends only on the concentration of alkyl halide, the first step must be the slow step that determines the rate of the overall reaction (second step involves the participation of nucleophile). This step can be understood to be slow since it involves breaking of a bond, an energy demanding process. Since no other bonds are formed in this step, it is a highly endothermic step and must have a high free energy of activation. In fact, it takes place only because of the ability of the solvent (water) to stabilize the carbocation. Water molecules surround and stabilize the carbocations produced in this step. In gas phase, the free energy of activation is 7 times more than in aqueous solvents. The second step can be understood to be fast since it involves only formation of a bond, an energy releasing process. Although solvated, carbocation is still very reactive and readily forms bond—more with the nucleophile present in plentiful-water, than with OH\(^-\)

\[
\begin{align*}
\text{CH}_3\text{C}^+ + \text{H}_2\text{O} & \rightarrow \text{CH}_3\text{C}^-\text{OH} \\
\text{CH}_3\text{C}^-\text{OH} & \underset{\text{H}^+}{\xrightarrow{\text{H}^+}} \text{CH}_3\text{C}^-\text{OH}
\end{align*}
\]

The reaction coordinate diagram for the S\(_{n1}\) reaction is shown in fig.7.
The important transition state for the $S_N 1$ reaction is the transition state of the slow, rate determining step that leads to the formation of the carbocation. T.S., therefore, has the C-Cl bond being largely broken and ions beginning to develop.

$$\begin{align*}
\text{transition state for slow rate determining step} \\
\begin{array}{c}
\text{CH}_3 \\
\text{C}^{+} \cdots \cdots \text{Cl} \\
\text{CH}_3
\end{array}
\end{align*}$$

**Stereochemistry of $S_N 1$ Reaction**

The first step of $S_N 1$ reaction results in the formation of carbocation, i.e. leaving group leaves before the nucleophile attacks. Carbocations have a trigonal planar shape with sp$^2$ hybridised C. When this planar molecule is attacked by nucleophile, the attack can take place equally well on either the frontside or backside. If the attack is from the frontside i.e. the side same as the one from where the leaving group has departed, the relative configuration of product and reactant will be same. If the attack is from the backside, then the product will have configuration inverted from the configuration of reactant. Thus, both inverted configuration and retained configuration will be present in equal amounts. In a t-butyl carbocation we cannot observe the formation of the two type of products due to absence of chiral centre. However, if we take a suitable carbocation e.g. $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_3$, a secondary alkyl halide, we can appreciate this fact.

\[
\text{Cl} \quad \text{CH}_3\text{CH}_2 \quad \text{H} 
\quad + \quad \text{H}_2\text{O} \quad \xrightarrow{\text{conditions}} \quad \text{OH} 
\]

One therefore expects, with the above logic, equal amounts of both products to be formed giving net optical activity zero. Such an equimolar mixture of pair of enantiomers is called Racemic Modification and the process by which it is obtained is called Racemisation. When the amounts of the two products are equal, the reaction is said to have proceeded with complete racemisation.

However, in a typical $S_N 1$ reaction, complete racemisation does not take place. Instead 50 - 70% of inverted product is formed and product with retained configuration is lesser in amount. This is referred to as partial racemisation with more of inverted product i.e. reaction proceeds with racemisation plus some net inversion.

Saul Winstein was the first to explain why extra inverted product is formed in $S_N 1$ reaction. He proposed that the dissociation of the alkyl halide in the first step gives a structure in which the two newly formed ions are still loosely associated i.e. an intimate ion pair is formed. This ion pair then slowly allows a molecule or two of the solvent to come in between so that the distance between the positive and the negative ion increases and we get solvent separated ion pair. Further inclusion of more solvent molecules gives completely dissociated ions.
\[ \delta^+ \quad \delta^- \quad \overset{\text{intimate ion pair}}{\text{R} - \text{Cl}} \quad \overset{\text{solvent separated ion pair}}{\text{R}^+ \text{Cl}^-} \quad \overset{\text{completely separated ion}}{\text{R}^+ \quad \text{Cl}^-} \]

The attack of the nucleophile can occur at any of the stages A, B or C. An attack at stage A i.e. intimate ion pair or even at stage B i.e. the solvent separated ion pair, is an attack on a carbocation when it is still very well shielded by the leaving group. Therefore, although not bonded, the leaving group blocks the approach of the nucleophile from its own side. This results in an increase in backside attack and hence more of formation of inverted product. Attack at stage C will lead to racemisation since the carbocation is free to have attack from both sides. Which species predominates, depends on several factors but the more stable the carbocation \( R^+ \), the longer is its life and the longer it escapes the nucleophilic attack - leading to greater proportion of racemisation. But the nucleophilicity of the solvent makes the life of \( R^+ \) shorter and hence attack occurs earlier leading to more inverted product. e.g. If we take \( \text{C}_6\text{H}_5\text{CH}_2\text{Cl} \) and \( \text{C}_6\text{H}_5\text{CH}_2\text{Cl} \) and carry out their hydrolysis, we find that due to stabilization of benzyl cation, the extent of racemisation is much more than for \( \text{C}_6\text{H}_5\text{CH}_2^+ \) which shows no such resonance stabilization. \( \text{C}_6\text{H}_5\text{CH}_2\text{Cl} \) gives more of inverted product arising from the attack of the nucleophilic solvent on the substrate at the intimate ion-pair stage.

**Characteristics of \( S_n^1 \)**

**The Substrate**

According to the Hammond postulate, any factor that stabilizes a high-energy intermediate should also stabilize the transition state leading to the intermediate. For the \( S_n^1 \) attack, considerable charge separation has taken place in the T.S. i.e. C has partly gained the positive charge it is to carry in the carbocation.

\[ \text{R:}\text{X} \quad \overset{\delta^+ \quad \delta^-}{\text{R} \quad \text{X}} \quad \overset{\text{R}^+ \quad \text{X}^-}{\text{R}^+ \quad \text{X}^-} \]

Therefore, dissociation of substrate to yield a carbocation will be favoured whenever a stabilized carbocation intermediate is formed. In other words, the more stable the carbocation the faster it is formed. As we traverse from the lowest to the highly substituted alkyl halide there is increasing stabilization of the corresponding carbocation formed which in turn increases the rate of formation of the T.S. and hence the rate of \( S_n^1 \) reactions.

The stability order of alkyl carbocations is well known to us i.e.,

\[ 3^+ > 2^+ > 1^+ > \text{-CH}_3 \]  

This order arises from the operation of both inductive effect and hyperconjugation.
Apart from this order of stability, formation of carbocation with trigonal planar disposition of only three substituents about the sp$^3$ C is favoured since it releases the steric crowding in going from the initial halide, with a tetrahedral disposition of four substituents about its sp$^3$ C. The 3 substituents are as far apart from each other as they can get in the planar carbocation and the relative relief of crowding (halide → carbocation) will increase as the substituents increase in size (H → Me → Me$_2$C). The $S_{n}1$ reaction rate would thus be expected to increase markedly as the series of halides is traversed.

In addition to these substrates, benzyl and allyl halides also are very reactive for the $S_{n}1$ reaction. This is because the corresponding carbocations are especially stable. There are 5 resonance structures contributing to the stability of benzyl carbocation and 2 resonance structures contributing to the stability of allyl carbocation.

More the number of phenyl rings attached to the benzylic C, more will be the resonance stabilization of the corresponding carbocation and hence more will be the reactivities for $S_{n}1$ reaction.

The stability of allylic and benzylic cation is about the same as secondary carbocation.
Another important feature in the formation of carbocations is the occurrence of rearrangements. This rearrangement is possible only when we have a carbocation, which implies that only $S_{n2}$ reaction, and not $S_{n1}$, can experience rearrangement, wherever the structure of substrate permits. Rearrangements involving 1,2 shifts of hydride and alkyl group can occur only when the rearranged species is more stable than the starting one. Thus, wherever structure permits, a primary carbocation rearranges to secondary or tertiary carbocation. Similarly, secondary carbocation rearranges to tertiary carbocation. This rearrangement is then followed by combination of carbocation with nucleophile. Thus, the final product obtained bears the incoming nucleophile on a C atom different from the C atom from where the leaving group had departed.

A few examples of carbocation rearrangement are shown:

\[
\begin{align*}
\text{CH}_3\text{CHCH}_2\text{Br} & \xrightarrow{\text{OH}^-} \text{CH}_3\text{CH}^+\text{CH}_2^- \xrightarrow{S_{n2} \text{ condition}} \text{CH}_3\text{CH}^+\text{CH}_2\text{OH}^- \\
& \xrightarrow{1, 2\text{-hydride shift}} \text{CH}_3\text{CH}^-\text{CH}_2^- \\
& \xrightarrow{1'=\text{carbocation}} \text{CH}_3\text{CH}^-\text{CH}_2^- \\
\end{align*}
\]

\[
\begin{align*}
\text{CH}_3\text{C}^-\text{CH}_2\text{Cl} & \xrightarrow{H_2O} \text{CH}_3\text{C}^-\text{CH}_2\text{OH}^- \xrightarrow{\text{-H}^+} \text{CH}_3\text{C}^-\text{OH}^- \\
& \xrightarrow{1, 2\text{-hydride shift}} \text{CH}_3\text{CH}^-\text{CH}_2^- \\
& \xrightarrow{1'\text{'carbocation}} \text{CH}_3\text{CH}^-\text{CH}_2^- \\
\end{align*}
\]

\[
\begin{align*}
\text{CH}_3\text{C}^-\text{CH}_2\text{Br} & \xrightarrow{H_2O} \text{CH}_3\text{C}^-\text{CH}_2\text{OH}^- \xrightarrow{\text{-H}_2\text{O, H}^+} \text{CH}_3\text{C}^-\text{OH}^- \\
& \xrightarrow{1, 2\text{-methyl shift}} \text{CH}_3\text{C}^-\text{CH}_2^- \\
& \xrightarrow{1'\text{'carbocation}} \text{CH}_3\text{C}^-\text{CH}_2^- \\
\end{align*}
\]

\[
\begin{align*}
\text{CH}_2\text{Cl} & \xrightarrow{\text{OH}^-} \text{RING EXPANSION} \xrightarrow{1, 2\text{-alkyl shift}} \text{Cyclic Structure} \\
& \xrightarrow{57} \text{Cyclic Structure} \\
\end{align*}
\]
The Leaving Group

From $S_{n}2$ reactions, we have understood that the best leaving groups are the ones that are weak bases i.e. conjugate bases of strong acid. An identical order of reactivity is formed for $S_{n}1$ reaction because the leaving group is directly involved in the rate determining step.

$$R-I > R-Br > R-Cl > R-F$$

The rate of $S_{n}1$ reaction is also governed by the stability of T.S leading to carbocation intermediate. T.S. resembles the carbocation intermediate; therefore order of stability of carbocations will also be the order of stability of T.S leading to it. Accordingly, t-alkyl carbocation is most stable followed by secondary and primary carbocation. Therefore, t-alkyl halide is most reactive followed by secondary alkyl halide and primary alkyl halide.

The Nucleophile

Since nucleophile is not involved in the rate determining step, it has no effect on the rate of reaction. Therefore, whether we do reaction in solvent alone, or add a strong nucleophilic anion - the rate is unaffected.

$$(\text{CH}_3)_2C-OH + HX \rightarrow (\text{CH}_3)_2C-X + H_2O$$

Rate = same whether $X = I, Br$ or $Cl$.

Similarly,

$${C}_6{H}_5CH-Cl \xrightarrow{CH_3COOH} C_6H_5CH-OCOCH_3$$

Both routes have the same rate of reaction.
The Solvent

Solvents have a large effect on $S_n1$ reaction but the reason for the effects are not the same as for $S_n2$ reaction. In $S_n2$, the solvent molecules stabilize or destabilize the nucleophile reactant. In $S_n1$, the solvent molecules stabilize or destabilize the transition state. Since the T.S. resembles the intermediate carbocation, factors stabilizing intermediate carbocation will also stabilize the transition state and increase rate of $S_n1$ reaction. Carbocations are stabilized by the association or solvation with protic solvent molecules - i.e. interaction of the positively charged carbocation with electron rich ends of the solvent dipoles oriented around the former.

Such an association and stabilisation of carbocation is not possible with non polar solvents. Therefore, $S_n1$ reactions occur more rapidly in polar protic solvents such as H$_2$O, CH$_3$OH than in non polar solvents (such as hydrocarbon and ethers).

In the reaction of 2-chloro-2 methyl propane, there is a rate increase of 100,000 in changing from ethanol solvent to water. Water has a much higher dipole moment than ethanol.

\[
\text{CH}_3\text{CH}_2\text{Cl} + \text{ROH} \rightarrow \text{CH}_3\text{CH}_2\text{OR} + \text{HCl}
\]

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Relative Reactivity</th>
</tr>
</thead>
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<tr>
<td>EtOH</td>
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<tr>
<td>40% H$_2$O</td>
<td>100</td>
</tr>
<tr>
<td>60% EtOH</td>
<td>14,000</td>
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<tr>
<td>80% H$_2$O</td>
<td>20% EtOH 100,000</td>
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</table>

59
$S_{N\cdot2}$ Vs. $S_{N\cdot1}$: Comparison and Competition

Let us review and compare the features that characterize $S_{N\cdot2}$ and $S_{N\cdot1}$ reaction mechanism.

$S_{N\cdot2}$

- Second order kinetics.
- Bimolecular rate-determining transition state.
- One step mechanism.
- Absence of carbocation rearrangement.
- Backside attack of the nucleophile and inversion of configuration.

$S_{N\cdot1}$

- First order kinetics.
- Unimolecular rate-determining transition state.
- Two step mechanism.
- Carbocation rearrangement.
- Attack of nucleophile from both sides and racemisation of products with more of inversion of configuration.
- Reactivity order $3^o > 2^o > 1^o$ for $CH_3 X$.

We can see the distinct differences between the two mechanisms. But there are certain situations when one cannot predict readily, which mechanism will be followed. Therefore, we need to look into the relationship between the two mechanisms. For this, we once again take up each factor that affects the nucleophilic substitution reaction - now we discuss keeping in mind the relationship of the two mechanisms.

The Substrate

We know that methyl halides and primary alkyl halides undergo nucleophilic substitution by $S_{N\cdot2}$ pathway only. This is due to the fact that methyl carbocation and primary alkyl carbocation are too unstable to be formed. Tertiary alkyl halides undergo $S_{N\cdot1}$ reaction only since the bulky alkyl branches at $\alpha$ C pose severe steric hindrance to formation of a stable pentavalent T. S. Secondary alkyl halides, allyl and benzyl halides can undergo both $S_{N\cdot1}$ and $S_{N\cdot2}$ reaction since they form stable carbocations as well as relatively unhindered pentavalent T. S.

\[
\begin{align*}
S_{N\cdot2} \text{ increase} \\
RX = \text{CH}_3X & \quad \text{1}^o \quad \text{2}^o \quad \text{3}^o \\
& \quad S_{N\cdot1} \text{ increase}
\end{align*}
\]

It therefore becomes important to know when the pathway is predominately $S_{N\cdot2}$ and when it is predominately $S_{N\cdot1}$. Vinyl halides, Alkynyl halides and aryl halides - all three do not undergo $S_{N\cdot2}$ or $S_{N\cdot1}$ reaction. The C atom to which halogen is attached is sp$^2$ or sp hybridized. This makes these carbon atoms more electronegative, their C-X bonds stronger and bond lengths shorter. The C - X bond is, therefore, less
polar and hence less reactive. The corresponding carbocations are very unstable, even more unstable than primary carbocation. This, in turn, is because the resulting carbocation has the positive charge on sp carbon, which being more electronegative (than sp$^2$ C that carries alkyl carbocation) is more resistant to becoming positively charged. They therefore do not undergo $S_n^1$ reaction. Again, the π electrons of double bond, triple bond or the aromatic ring of the substrate repel the incoming nucleophile to approach for an $S_n^2$ back side attack. Therefore, they do not undergo $S_n^2$ reaction.

The Nature of Leaving Group

Leaving group is a part of the substrate itself and its ease of departure definitely affects the rate of substitution. Whichever pathway occurs - the nucleophilic attack ($S_n^2$) or heterolysis ($S_n^1$) - the bond to the leaving group is broken in the rate determining step - so the easier this cleavage the faster the reaction. Thus, both pathways $S_n^2$ and $S_n^1$ get affected to the same degree by a change in nature of leaving group. Therefore, leaving group has little effect on the predominance of mechanism.

The Nucleophile

From the rate laws for the two pathways, we have seen that whereas nucleophile participates in the bimolecular rate determining T.S. of $S_n^2$ reaction, it plays no role in the rate determining carbocation formation of $S_n^1$ reaction. It is only in the second step of $S_n^1$ reaction which is a fast bimolecular reaction, that nucleophile is involved. Nature and concentration of nucleophile will, therefore, affect only $S_n^2$ pathway. Increase in concentration of nucleophile as well as its reactivity increases the rate of $S_n^2$ reaction and has no effect on $S_n^1$ reaction. A good nucleophile present in high concentration speeds up the $S_n^2$
reaction. A poor nucleophile present in low concentration retards the $S_{N2}$ reaction and indirectly favours the $S_{N1}$ pathway.

**The Solvent**

Solvent is, by far, the most important factor in changing the predominance of a mechanistic pathway. Solvents usually employed for a reaction fall in three categories.

**Polar protic solvents**: Where H is directly attached to O or N making them hydrogen bond donors. e.g. H$_2$O, CH$_3$OH, HCOOH, CH$_3$CH$_2$OH. The unshared electron pairs solvate cation and acidic H solvate anions.

**Polar aprotic solvents**: Where H is not bonded to O or N. They are polar with high dipole moments, as large as that of water. These have negative poles on the oxygen atom that enables strong solvation of cation only. Due to absence of acidic H they do not solvate anions. e.g. DMF, DMSO, HMPT.

**Non polar solvents**: Hydrocarbons which have very low dipole moments. e.g. benzene, chloroform, ethers. Solvent helps to stabilize charges by ion - dipole interactions. If the reactants in the rate limiting step have formal charge on them, an increase in polarity of solvent will decrease the rate of the reaction. If none of the reactants in the rate limiting step is charged, increasing the polarity of the solvent will increase the rate of the reaction.

In the $S_{N2}$ reaction it is the nucleophile which is usually charged and gives rise to a T.S. that has its negative charge dispersed. In such a case, if we increase the polarity of polar protic solvent the fully charged anion gets more stabilized than the T.S.; therefore increasing polarity will increase the energy difference between reactants and T.S. thereby increasing activation energy or decreasing rate of reaction. If $S_{N2}$ reaction is done with neutral nucleophile, the polar solvent will be fully available to stabilize only T.S. Therefore, increasing polarity will decrease the activation energy and increase rate of $S_{N2}$ reaction.

For a polar aprotic solvent, even the charged nucleophile will see an increase in rate with increase in polarity. This is because there is no solvent association with anion. Polarity is, therefore, only to dissolve the reactants. Hence increasing polarity now stabilizes only T.S. and increases rate of reaction.

In the $S_{N1}$ reaction, heterolysis of alkyl halide is the rate limiting step which is facilitated by solvent. The energy required for dissociation of C - X bond is more than compensated by the energy released by ion - dipole interaction. This results in stabilization of carbocation by solvent. $S_{N1}$ reaction rates are, therefore,
increased in polar protic solvents. Polar solvents separate the ions and protic solvents solvate the ions. In non polar solvents or in gas phase, $S_{n}1$ reactions do not occur at all.

**ELIMINATION REACTIONS**

A second important reaction, after substitution of alkyl halides, is the Elimination Reaction. In substitution reactions, we studied the reaction of nucleophile with the substrate alkyl halide by attack on $\alpha - C$ to displace halogen group. If the attack of this nucleophile is on the neighbouring hydrogen (i.e. $\beta - H$) it causes elimination of a molecule of HX to form an alkene.

\[
\text{H} \quad \text{C} \cdots \linebreak \text{X} \quad \text{+ B} \quad \rightarrow \quad \text{C} = \text{C} \quad \text{+ BH + X}^\text{−}
\]

\[\text{:}\beta\text{-base}\]

$X = \text{Cl, Br, I}$

This elimination of the elements of hydrogen halide, HX, from the alkyl halide is called Dehydrohalogenation. Also, since the removal of H in HX is from $\beta - C$, these reactions are often called $\beta$ - elimination or 1,2 - elimination reactions. Dehydrohalogenation is a widely used method for the preparation of alkenes. The alkyl halide is heated with a strong base to cause this elimination.

\[
\text{H} \quad \text{CH}_{2}\text{CHCH}_{3} \quad \text{C}_{2}\text{H}_{5}\text{ONa} \quad \text{C}_{2}\text{H}_{5}\text{OH, 55°C} \quad \text{CH}_{2} = \text{CH-CH}_{3} + \text{NaBr + C}_{2}\text{H}_{5}\text{ONa}
\]

\[
\text{CH}_{3} \quad \text{CH}_{3} \quad \text{Br} \quad \text{C}_{2}\text{H}_{5}\text{ONa} \quad \text{C}_{2}\text{H}_{5}\text{OH, 55°C} \quad \text{CH}_{2} = \text{C - CH}_{3} + \text{NaBr + C}_{2}\text{H}_{5}\text{ONa}
\]

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As we can see, the same reagents can effect a substitution reaction. Therefore, elimination reactions are seen to compete with substitutions and vice versa. We shall first discuss the mechanism of elimination and then compare with substitution reactions.

**Type of Elimination Reactions**

There are three important mechanisms for an elimination reaction.

**E2 Reaction**

When we take ethylbromide and heat with a strong base such as hydroxide ion or alkoxide ion, elimination of HX occurs by E2 mechanism - E stands for Elimination and 2 for Bimolecular. Thus here, molecules of both reactants are involved in the rate determining T.S. The rate of reaction depends on the concentration of both reactants - hence, it follows second order kinetics.

\[
\text{CH}_3\text{CH}_2\text{Br} + \text{NaOH} \rightarrow \text{CH}_2 = \text{CH}_2 + \text{NaBr} + \text{H}_2\text{O}
\]

\[
\text{rate} = k \left[ \text{CH}_3\text{CH}_2\text{Br} \right] \left[ \text{OH}^- \right]
\]

or in general, rate law for E2 reaction is:

\[
\text{rate} = k \left[ \text{alkylhalide} \right] \left[ \text{base} \right]
\]

Considerable experimental evidence indicates that the reaction takes place in the following way:

![Mechanism of E2 Reaction]

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The mechanism, like $S_2$ reaction, involves one step concerted removal of a $\beta$ proton by a base and loss of halide ion. As the attacking base begins to abstract $H^+$ from the $\beta$ C, the C-H bond breaks, a C=C bond begins to form, and the leaving group begins to depart, taking with it the electron pair from the C-Br bond. Like $S_n^2$, E2 mechanism involves no intermediates.

Apart from the compliance with rate law, another strong evidence in support of this mechanism is the stereochemistry of E2 elimination. The bonds to the eliminating groups (H and X) must be in the same plane. This is because the sp$^3$ orbital of the carbon bonded to H and the sp$^3$ orbital of the carbon bonded to X become overlapping p orbitals in the alkene product. Therefore, the orbitals must overlap in the T.S. This overlap is optimal when the orbitals are parallel, and for this the four atoms (H, 2 Cs, X) must be in the same plane.

There are two ways in which H, 2 Cs and X together can be in one plane. One way is when both the departing groups are on the same side of the molecule - Syn periplanar position. This is achieved by having the alkyl halide in eclipsed conformation. The other way is when the two departing groups are situated on the opposite side - Anti periplanar position. For this, the conformation of the molecule is staggered (dihedral angle = 180$^\circ$) Between the two, elimination from the anti periplanar conformation is preferred. This is because staggered conformation is sterically more stable. Therefore, T.S. leading to elimination from staggered conformation is more stable. Also, viewed from one end, we can see that the removal of $H^+$ by base in staggered conformation results in backside attack on C carrying X. The incoming base faces no repulsion from the halide ion in such a situation. In the Syn elimination, the departing groups being eclipsed, T.S. is not so stable. Also, base must attack the C bearing X from the front side. The base will be therefore repelled by halide ion which is on the same side.

Another stereochemical feature of the elimination reaction is the stereoselectivity of the reaction. Anti Elimination may result in the formation of two geometric isomers of the alkene product in equal amounts. However, the reaction is stereoselective since out of the two isomers, the isomer with bulkiest groups on opposite side is more stable and will be formed in greater yield.
2-Pentene can exist both as E and Z isomers

\[
\text{Me} - C = C - \text{Et} \quad \text{Z} \quad \text{H} - C = C - \text{Et} \quad \text{E}
\]

Out of the two, E - isomer is the major product.

Sometimes, there is no possibility of having both isomers formed i.e. there is only one \( \beta \) H and hence only one conformation from where the groups eliminated are anti.

\[
\text{C}_6\text{H}_5\text{C} - \text{CH} - \text{CH} - \text{C}_6\text{H}_5 \quad \text{can exist in four configurations}
\]

If we take any one of the configurations, there is only one conformation possible that can provide anti elimination. Therefore, only one alkene is obtained.

\[
\text{E isomer (single product)}
\]

\[
\text{Z isomer (single product)}
\]

**Regioselectivity of E2 Reactions**

Dehydrohalogenation generally gives a mixture of isomeric alkenes.

2 - Bromopropane has 2 \( \beta \) - carbons but removal of H from either of them, gives the same product.
\[ \text{CH}_3\text{CHBrCH}_3 + \text{OH}^- \rightarrow \text{CH}_3\text{CH} = \text{CH}_2 + \text{CH}_3\text{OH} + \text{Br} \]

On the other hand, the following alkyl halide has 2 \( \beta \) carbons which give two alkene product. This is due to the structural difference of the 2 \( \beta \) carbons.

\[ \text{CH}_3\text{CH}_2\text{CHBrCH}_3 + \text{KOH} \rightarrow \text{CH}_3\text{CH}_2\text{CH} = \text{CH}_3 + \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH} = \text{CH}_2 \]

\( 71\% \) \hspace{1cm} \hspace{1cm} \hspace{1cm} 29\%

\[ \text{CH}_3\text{CH}_2\text{CBrCH}_3 + \text{KOH} \rightarrow \text{CH}_3\text{CH} = \text{CH}_3 + \text{CH}_3\text{CH}_2\text{C} = \text{CH}_2 \]

\( 71\% \) \hspace{1cm} \hspace{1cm} \hspace{1cm} 29\%

Which of the two alkenes is the predominant product, can be understood if we know which of the two alkenes will be formed easily. In fact, if we observe carefully, the predominant alkene is the one that is more substituted. We know that more the alkyl substituents on the double bond, more stable is the alkene (Hyperconjugation explains why more substituted alkenes are more stable). The T.S. of the dehydrohalogenation has partly broken bonds of C - H and C - X and partly formed double bond of C - C. The extent of formation and extent of cleavage of bond is equal, thereby giving T.S. an 'alkene like' character. Therefore, factors stabilizing the alkene will also stabilize T.S. Hence, if more alkyl groups on the two sp\(^3\) carbons stabilize the alkene, more alkyl groups on the two sp\(^3\) carbons will also stabilize the T.S. Hence a more substituted alkene will be the major product.

\textit{Two possible T. S. of dehydrohalogenation of 2 bromopentane}

\[ \text{CH}_3\text{CH}_2\text{CH} = \text{CH}_2 \]

\text{Transition state leading to 2 pentene (more stable)}

\[ \text{CH}_3\text{CH}_2\text{CH}_2\text{CH} = \text{CH}_2 \]

\text{Transition state leading to 1- pentene (less stable)}

Therefore, Elimination reactions are regioselective
From these observations, a Russian chemist Saytzeff formulated a rule called ‘Saytzeff Rule’ that predicts the predominant product of dehydrohalogenations. According to the Saytzeff rule - in dehydrohalogenation the preferred product is the alkene that has greater number of alkyl groups attached to the doubly bonded carbon atoms. In other words H is removed from that $\beta\ C$ which already has lower number of H atoms. Ease of formation of alkenes and their stability follows the order:

$$R_2C = CHR > R_2C = CH_2, RCH = CHR > RCH = CH_2 > CH=CH_2$$

From this order of stability we can also determine the reactivity of alkyl halides towards elimination. As we proceed from 1° to 2° to 3° alkyl halide, structures by definition become more branched at the $\alpha\ C$. This provides more number of $\beta\ H$s to be attacked by base for elimination as well as gives more highly branched and stable alkene.

Reactivity order of alkyl halides for dehydrohalogenation is therefore:

$$3° > 2° > 1°$$

However, there are some exceptions to this rule.

The rule is not followed in the following conditions. In all the cases that we discuss now, the preferred product is the less substituted alkene. This product is called the Hofmann product which is in accordance with Hofmann Rule that describes the direction of elimination of quaternary ammonium hydroxides.

I. When the attacking base is large
II. When the alkyl halide is an alkyl fluoride
III. When the alkyl halide contains one or more double bonds.
IV. When the alkyl group in alkyl halide or the leaving group is bulky.

1. **When the attacking base is large**: A bulky base will find it difficult to access a $\beta\ H$ in the interior of the alkyl halide. It will preferentially remove the more accessible $\beta\ H$ i.e. H from a relatively unsubstituted $\beta\ C$. This results in the less substituted alkene as the major product.
\[ \text{CH}_3\text{C}^\text{O}^- + \text{CH}_3\text{C}^-\text{CH}_2\text{Br} \rightarrow \text{CH}_3\text{C}^-\text{CH}_2\text{CH}_3 + \text{CH}_3\text{C}^\text{CHCH}_3 \]

\( \text{t-} \text{butoxide ion} \)  
(bulky base)

\((\text{CH}_3)_2\text{C}^- \text{OH}\)

In fact, as the bulkiness of base increases, the abstraction of more exposed \( \beta \text{H} \) increases thereby resulting in increase in formation of less substituted alkenes.

\[
\text{CH}_3\text{C}^-\text{CH}_3 + \text{RO}^- \rightarrow \text{CH}_3\text{C}^-\text{C}^\text{CH}_3 + \text{CH}_3\text{C}^-\text{CH} = \text{CH}_3
\]

more substituted product  
less substituted product

\( \text{RO}^- = \text{CH}_3\text{CH}_2\text{O}^- \)

80%  
20%

27%  
73%

19%  
81%

II. When the alkyl halide is an alkyl fluoride: Fluoride ion is the strongest base and hence the poorest leaving group. Therefore, it exerts a powerful electron-withdrawing effect making the \( \beta \text{H} \) acidic and more removable by base than its own removal. Thus the \( \text{C}^- \text{H} \) bond breaks to a larger extent than \( \text{C}^- \text{F} \) bond thereby giving the T. S. a 'carbanionic' character. Since carbanions are destabilized by electron releasing groups like alkyl groups, therefore the more stable carbanions will be the one formed from the removal of \( \text{H} \) from less substituted \( \beta \text{C} \).

\[
\text{H}^\text{5-} \text{OCH}_3 \rightarrow \text{CH}_3\text{CH}_2\text{CH} = \text{CH}_3
\]

major (less substituted alkene)

\[
\text{CH}_3\text{CH}_2\text{CH} = \text{CH} = \text{CH}_3
\]

minor (more substituted alkene)

In fact, as the basicity of halide ion increases, its leaving ability decreases and carbanionic character of its T. S. increases thereby increasing the predominance of less substituted alkene products.
\[
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 + \text{CH}_3\text{O}^- \rightarrow \text{CH}_2=\text{CHCH}_2\text{CH}_2\text{CH}_3 + \text{CH}_3\text{CH} = \text{CHCH}_2\text{CH}_3
\]

\[X \quad \text{1-hexene} \quad \text{2-hexene}\]

<table>
<thead>
<tr>
<th>X</th>
<th>1-hexene</th>
<th>2-hexene</th>
</tr>
</thead>
<tbody>
<tr>
<td>I^-</td>
<td>19%</td>
<td>81%</td>
</tr>
<tr>
<td>Br^-</td>
<td>28%</td>
<td>72%</td>
</tr>
<tr>
<td>Cl^-</td>
<td>33%</td>
<td>67%</td>
</tr>
<tr>
<td>F^-</td>
<td>70%</td>
<td>30%</td>
</tr>
</tbody>
</table>

III. When the alkyl halide contains one or more double bonds

If the structure of the alkyl halide is such that the removal of \(\beta\) H results in an alkene where either conjugated double bonds come into existence or there is extension of conjugation, then the reaction moves in favour of formation of such products.

**Major product (less substituted alkane)**

newly formed double bond is in conjugation with phenyl ring

\[\text{Br} \quad \text{CH}_3 \quad \text{CH}=\text{CHCH}_2\text{CH}_3 \quad \text{CH}_3 \quad \text{CH}_3\]

**Minor product (more substituted alkane)**

newly formed double bond is isolated from phenyl ring, i.e. no extra stabilization

\[\text{O} \quad \text{CH}_2 \quad \text{HC} = \text{C} \quad \text{CH}_3 \quad \text{CH}_3\]

\[
\text{CH}_2=\text{CHCH}_2\text{CH} = \text{CH} = \text{CHCH}_2\text{CH}_3
\]

**Major (extended conjugation)**

\[
\text{CH}_2 = \text{CHCH}_2\text{CH} = \text{CH} = \text{CHCH}_2\text{CH}_3
\]

**Minor (isolated double bond)**

\[
\text{CH}_2 = \text{CHCH}_2\text{CH} = \text{C} - \text{CH}_2\text{CH}_3
\]

\[
\text{CH}_3
\]
When the alkyl group of alkyl halide is highly branched: As the alkyl group gets bulky, there is an increase in steric repulsion in that T.S. which leads to more substituted alkene (due to eclipsing of alkyl groups) whereas steric repulsion is minimised in T.S. that leads to less substituted alkene. Hence less substituted alkene predominates. We can understand this from the Newman projection formula.

(leads to a more sterically hindered T.S.)

The same results are obtained if the leaving group is bulky.
Thus if any of the three species - the base, the alkyl substrate or the leaving group - is bulky, the elimination favours formation of less substituted alkene.

E1 Reaction

If we take a bulky alkyl halide such as tertiary butyl chloride and a solvent which is a less strong base, such as water, the elimination is seen to follow first order kinetics. The rate of elimination depends on the concentration of tertiary butyl chloride and not on water.
\[
\begin{align*}
\text{CH}_3 \quad \text{Cl} & \quad \text{CH}_3 \\
\text{CH}_3 & + \text{H}_2\text{O} \quad \rightarrow \quad \text{CH}_3 & \quad \text{H}_2\hat{\text{O}} & + \text{Cl}^- \\
\text{CH}_3 &
\end{align*}
\]

rate = \( k \ [(\text{CH}_3)_2\text{C-Cl}] \)

or in general, rate law is

rate = \( k \ [(\text{RX}] \)

Such reactions are seen only with tertiary and secondary alkyl halides and when the base is weak or in low concentration.

These reactions are called \( E_1 \) reaction i.e. elimination unimolecular. Here, the elimination takes place in two steps. The first step is a slow step of heterolysis of the alkyl halide to give a carbocation. This is the rate determining step for the overall reaction where T. S. involves only the alkyl halide molecule. In the second step, a base quickly removes a \( \beta \) H to form alkene as the product of elimination. The concentration of base does not effect the rate of elimination reaction since the reaction step whose rate we are measuring does not involve base.

\( E_1 \) reactions are very close analogs of \( S_n \) reaction just as \( E_2 \) and \( S_n \) are analogous. Both \( E_1 \) and \( S_n \) begin with dissociation of alkyl halides to form carbocation. In \( S_n \), nucleophile attacks carbocation to form a substitution product by combination. In \( E_1 \), the base attacks the carbocation to form an elimination product by removal of \( \text{H}^+ \). In fact \( E_1 \) and \( S_n \) reaction normally occur in competition.

As stated earlier, \( E_1 \) reactions require a weak base or a low concentration of strong base. The solvent alone can also bring about the elimination. Such reactions are termed as solvolysis. A non basic nucleophile in a protic solvent favours elimination. Since the rate determining step is exactly same, both \( S_n \) and \( E_1 \) reactions are favoured by the ease of formation of the carbocation. The more stable the carbocation the more easily it is formed. Hence tertiary alkyl halide giving the tertiary carbocation and secondary alkyl halide giving the secondary carbocation, are best substrates for \( E_1 \); tertiary better than secondary.

**order of reactivity of alkyl halide for \( E_1 \)**

\( 3^\text{\textit{th}} \text{benzylic} > 3^\text{\textit{th}} \text{allylic} > 2^\text{\textit{th}} \text{benzylic} > 2^\text{\textit{th}} \text{allylic} > 3^\text{\textit{st}} > 1^\text{\textit{th}} \text{benzylic} > 1^\text{\textit{th}} \text{allylic} > 2^\text{\textit{st}} > 1^\text{\textit{st}} \)

**Rearrangements in \( E_1 \) Reaction**

Again, like in \( S_n \), carbocations can rearrange to more stable carbocations before they undergo elimination to give alkenes. Rearrangements can involve \( 1, 2 \), hydride shifts or \( 1, 2 \) methyl shifts, as studied earlier.
Orientation in E1 Reaction
Elimination by E1 mechanism shows strong preference for Saytzeff orientation. Therefore, when more than one alkene can be formed, the reaction proceeds in favour of the more substituted alkene.

\[
\text{CH}_3\text{C-CH-CH}_2\text{Br} + \text{H}_2\text{O} \rightarrow \text{CH}_3\text{CH=CH-CH}_2\text{CH}_3 + \text{CH}_3\text{CH=CH}_2 + \text{H}_2\text{O} + \text{Cl}^-
\]
We have already discussed that more substituted alkene is more stable and arises from the more stable transition state. The more stable T.S. is formed more rapidly and this is achieved by removal of H from more substituted β C. (see fig. 8)

\[
\begin{aligned}
\text{CH}_3\text{C=CH}_2 + \text{H}_3\text{O}^- + \text{Cl}^- & \rightarrow \text{CH}_3\text{C} = \text{CH}_2 + \text{CH}_3\text{COOH} + \text{H}_2\text{O} \\
\text{More substituted alkene-like T.S.} & \text{ (More stable)} \\
\text{Less substituted alkene-like T.S.} & \text{ (Less stable)}
\end{aligned}
\]

\(\text{CH}_3\text{C=CH}_2\) 

\(\text{CH}_3\text{C} = \text{CH}_2\)

\(\text{CH}_3\text{COOH}\)

\(\text{H}_2\text{O}\)

\(\text{H}_3\text{O}^+\)

\(\text{Cl}^-\)

\(\beta\text{-base}\)

\(\beta\text{-base}\)

**Competition between E2 and E1**

Which mechanism, E2 or E1, is followed has to be understood seeing various factors:

**Substrate:** As we go from 1st to 2nd to 3rd alkyl halides, reactivity by both E2 and E1 increases. But 1st alkyl halides undergo only E2 elimination. Secondary and tertiary alkyl halides can react via both E2 and E1 mechanism. E2 is favoured along the sequence 1st → 2nd → 3rd because of the stability of the more substituted alkene formed. Whereas E1 is favoured along the same sequence 1st → 2nd → 3rd because of the stability of the carbocation being formed in the rate determining step. Primary halides form very unstable carbocation, therefore primary halides do not show E1 reaction.

<table>
<thead>
<tr>
<th>Primary Alkyl halides</th>
<th>E2 only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary Alkyl halides</td>
<td>E1 and E2</td>
</tr>
<tr>
<td>Tertiary Alkyl halides</td>
<td>E1 and E2</td>
</tr>
</tbody>
</table>

**Base:** Since base is involved in the rate determining step of E2 and not of E1, its nature and concentrations affects E2 and not E1. E2 is favoured by strong base and high concentration of base. Both factors help in pulling the \(\beta\) H faster. A strong base in polar aprotic solvent favours E2

E1 is not affected by strength and concentration of base. Strong or weak, base waits till carbocation is formed. Therefore ideal conditions for E1 are non basic nucleophile or weak base in polar protic solvent.
Summary of Reactivity $S_{n1}, S_{n2}, E1, E2$

As we have seen the same reactants are used for both substitution and elimination. How can we predict what will happen in any given case? One favourable point is that conditions that favour $S_{n2}$ also favour $E2$ and not $E1$ and conditions that favour $S_{n1}$ also favour $E1$ and not $E2$. Thus, we need to decide whether the combination will be $S_{n2} / E2$ or $S_{n1} / E1$.

Primary Alkyl Halide: $S_{n2}$ reaction is highly favoured whereas $E2$ is much less favoured. In the presence of a good/strong nucleophile, (such as RS⁻, I⁻, CN⁻, NH₃, Br⁻) $S_{n2}$ reaction is most likely via the back side attack at $\alpha - C$.

If the primary alkyl halide or the nucleophile is sterically hindered, the backside attack at carbon is very difficult and $E2$ elimination occurs predominantly.

Alkyl halide Reactivity order for $S_{n2}$

1° > 2° > 3°

Alkyl halide Reactivity order for $E2$

3° > 2° > 1°

$\text{CH}_3\text{CH}_2\text{CH}_2\text{Br} + \text{CH}_3\text{O}^- \xrightarrow{\text{CH}_3\text{OH}} \text{CH}_3\text{CH}_2\text{OCH}_3 + \text{CH}_3\text{CH} = \text{CH}_2$

(90%) (10%) $\text{S}_{n2}$ favoured

Secondary Alkyl Halides: $S_{n2}$ and $E2$ are always in competition. Strength of base and bulk of nucleophile play key role in relative amounts of the products in mixture.

Weakly basic nucleophile in polar aprotic solvents favours $S_{n2}$ reaction. Strong and bulky base favour $E2$ reaction.
Secondary alkyl halide, particularly benzylic and allylic, undergo $S_{n}1$ and $E1$ reaction if weakly basic nucleophiles are used in protic solvents such as ethanol or acetic acid.

**Tertiary Alkyl Halides**: Least reactive for $S_{n}2$ and most reactive for E2. With a base like OH⁻ or RO⁻ we get only alkene product.

$$\text{CH}_3\text{C}^\cdots\text{Br} + \text{CH}_3\text{CH}_2\text{OH} \rightarrow \text{CH}_3\text{C} = \text{CH}_2 + \text{CH}_3\text{CH}_2\text{CH}_3$$

If this reaction is done in neutral condition (e.g. pure ethanol), both products are formed but by $S_{n}1$ and $E1$ reactions.

$$\text{CH}_3\text{C}^\cdots\text{Br} \rightarrow \text{CH}_3\text{C} = \text{CH}_2 + \text{CH}_3\text{CH}_2\text{CH}_3$$

**Effect of Temperature**: Increase in temperature increases rate of both substitution and elimination. However, rate of elimination is increased much more. Should entropy argument be given to justify this?

Let us see some more example to predict the reaction products and mechanism.

**Example 1**:

$$\text{Cl}\text{C}_5H_{11} \rightarrow \text{CH}_3\text{ONa}^- + \text{CH}_3\text{OH}$$

The substrate is a cyclic secondary alkyl halide. CH₃O⁻ is a strong base present in polar protic solvent CH₃OH. Therefore, both factors - strong base and polar protic solvent, favour E2 reaction.
The substrate is a secondary benzylic substrate. HCOOH is a weak base in polar protic solvent H₂O. Therefore, condition are suitable for S₈ 1 with some E₁ reaction.

**E₁cB Mechanism**

Heterolysis of the alkyl halide can also take place by cleavage of C - H bond first. This results in the formation of a carbanion intermediate. Such reactions are referred to as E₁cB reactions (elimination, from conjugate base). Examples of reactions proceeding by this mechanism are very rare. For this mechanism to operate, the substrate must have highly electron-withdrawing substituents on the β C to make the δ hydrogen very acidic. This, in turn, would stabilise the carbanion and hence enable its formation. One such example is shown below:

\[
\begin{align*}
B: & \xrightarrow{\text{H}} \quad X_C & \xrightarrow{\text{CF}_2} & \xrightarrow{\text{CF}_2} & X_C = \text{CF}_2 \\
\end{align*}
\]

The substrate has two electronegative halogen atoms on the β C which stabilise the carbanion through electron withdrawal. Also, F is a poor leaving group and three such fluorine atoms promote the cleavage of C - H to form the carbanion.

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FORMAION OF ORGANO METALLIC COMPOUNDS

Compounds that contain carbon-metal bonds are called organometallic compounds. Alkyl halides are the starting materials for preparation of two of the most useful organometallic compounds.

A. Grignard Reagents  B. Organolithium Reagents

Other than these we will also study in this section

C. Reaction with Sodium  D. With Metal Alloys

Grignard Reagents

Grignard reagents are among the most versatile and important reagents in organic chemistry. Victor Grignard developed many applications of these reagents and was awarded Nobel Prize in 1912 for his contribution.

Grignard Reagent is an organomagnesium halide compound of the form R-Mg-X where X = Br, Cl, I.

\[
\text{CH}_2\text{CH}_2\text{MgBr} \quad \text{ethylmagnesium bromide}
\]

e.g.

\[
\text{[Cyclohexyl]MgCl} \quad \text{cyclohexylmagnesium chloride}
\]

Grignard reagent is generally prepared by the reaction between magnesium and alkyl halide in dry, alcohol free ether.

\[
R-X + Mg \xrightarrow{(C_2H_5)_2O} R-Mg-X
\]

A free radical mechanism is proposed for the above reaction.

Magnesium atoms of the metal first abstract a halogen atom from the alkyl halide to form an alkyl radical \(R^+\) at or near the magnesium surface.

\[
R - Br: \quad R: \text{Mg} \quad \rightarrow \quad R^+ \quad + \quad \text{Mg-Br:}
\]

The product radicals combine before the alkyl radicals can diffuse away

\[
R^+ \text{Mg-Br:} \quad \rightarrow \quad R-Mg-Br:
\]

This is not a chain reaction as against most other free radical mechanisms.
The solubility of Grignard reagents in ether solvents plays a crucial role in their formation. Grignard reagents are formed on the surface of the magnesium metal. As they form, these reagents are dissolved from the metal surface by the ether solvent. As a result, a fresh surface of metal is continuously exposed to the alkyl halide. Grignard reagents are soluble in ether solvent due to the association of ether with metal in a Lewis acid - base type interaction.

Other solvents besides ether such as tertiary amines, tetrahydrofuran (THF) and the dimethylether of ethylene glycol - are also used. THF is a better solvent than diethylether, particularly for aryl halides and alkenyl halides.

Reactivity order of alkyl halides for the formation of Grignard reagents is:

alkyl iodide > alkyl bromide > alkyl chloride

As the number of alkyl groups increases, the formation of Grignard reagents becomes difficult. Nevertheless all types of alkyl halides (1°, 2°, 3°) do form Grignard reagents.

**Reactivity of Grignard Reagents**

The C - Mg bond is polar, making the carbon atom both nucleophilic and basic.

\[ \overset{\delta-}{C} \quad \overset{\delta+}{\text{MgX}} \]

In a formal sense, a Grignard reagent can be thought of as the magnesium salt e.g. \(R\text{MgX}\), of a hydrocarbon acid, \(R\cdot\text{H}\). But because hydrocarbons are very weak acids, the conjugate bases, i.e. carbanions, are very strong bases. Therefore, Grignard reagents (i.e. carbanion) react with weak acids like \(\text{H}_2\text{O}, \text{ROH}, \text{RCOOH}, \text{RNH}_2\) to become protonated and yield hydrocarbons.
\[ \text{ROH} + \text{R-Mg-X} \rightarrow \text{RH} + \text{MgX (OR)} \]
\[ \text{HOH} + \text{R-Mg-X} \rightarrow \text{RH} + \text{MgX (OH)} \]
\[ \text{RCOOH} + \text{R-Mg-X} \rightarrow \text{RH} + \text{MgX (OCOR)} \]
\[ \text{RNH}_2 + \text{R-Mg-X} \rightarrow \text{RH} + \text{MgX (NHR)} \]

As a nucleophile, these reagents are capable of producing a variety of compounds such as alcohols, carbonyl compounds etc.

Organo Lithium Reagents

These reagents are typically formed by reaction of alkyl halides with lithium metal taken in a hydrocarbon solvent. The general formula of these compounds is R-Li.

\[ \text{R-Br} + 2 \text{Li} \xrightarrow{\text{hexane}} \text{R-Li} + \text{LiBr} \]

Mechanism of formation is like that of Grignard reagents. Like Grignard reagent, organo lithium reagents are very strong bases and abstract hydrogen more acidic than the hydrogen atoms of the hydrocarbon.

\[ \text{R}^+ \xrightarrow{\text{Alkyllithium}} \text{R} \xrightarrow{\text{organometallic compound}} \text{R}^+ \xrightarrow{\text{alkyl lithium}} \text{R-H} \]

Alkyl lithiums can be converted to another useful organometallic compound, lithium dialkyl cuprate. This reagent is useful in the synthesis of alkanes and other hydrocarbons.

Alkyl lithium is heated with cuprous iodide to get lithium dialkyl cuprate.

\[ \text{R-Li} + \text{CuI} \rightarrow \text{R}_2\text{CuLi} + \text{LiI} \]

\( \text{R}_2\text{CuLi} \) when heated with another alkyl halide causes a coupling of one alkyl of lithium dialkyl cuprate and alkyl group of alkyl halide. The alkyl group to be coupled with alkyl group of the organo copper compound is preferably methyl or primary or a secondary cyclo alkyl group.

\[ \text{R}_2\text{CuLi} + \text{R}^+ \xrightarrow{\text{X}} \text{R} - \text{R}^+ + \text{RCu} + \text{LiX} \]

This reaction was developed by Corey, Posner and Whitesides, House and is popularly called Corey House Synthesis of alkanes.

Both Grignard and Organolithium reagents react violently with oxygen and vigorously with water. For this reason, these reagents must be prepared under rigorously oxygen-free and moisture-free conditions.

C. An ethereal solution of alkyl halide (preferably the bromide or iodide), when treated with sodium
metal results in the formation of higher alkanes. This reaction is called WURTZ REACTION and is extremely useful for the preparation of alkanes.

\[ RX +RX + 2Na \rightarrow R - R' + 2NaX \]

The mechanism again involves free radicals:

\[ C_2H_5Br + Na \rightarrow C_2H_5^- + NaBr \]

\[ \cdot C_2H_5 + \cdot C_2H_5 \rightarrow C_3H_7 - C_2H_5 \]

D. With certain metallic alloys, alkyl halides form organometallic compounds.

e.g. ethyl chloride gives tetraethylead, on heating with sodium-lead alloy.

\[ 4C_2H_5Cl + \frac{Na/Pb}{\Delta} \rightarrow (C_2H_5)_4Pb + 4NaCl + Pb \]

**REDUCTION OF ALKYL HALIDES**

(i) Using zinc in aqueous acid, alkyl halides are reduced to alkanes. This reaction is called FRANKLAND REACTION

\[ 2R-X + Zn + 2 \text{H}^+ \rightarrow 2R-H + ZnX_2 \]

(ii) Catalytic reduction is done using Pd - C. Raney Nickel is also effective for this reduction.

\[ RX + H_2 \xrightarrow{\text{Pd-C}} RH + HX \]

(iii) Reduction can also be carried out with lithium aluminium hydride or sodium borohydride.

**MISCELLANEOUS REACTIONS**

(i) When heated to 300°C or to lower temperature in presence of AlCl₃ as catalyst, alkyl halides undergo rearrangement.
(ii) Alkyl halides are used in the Friedel Crafts reaction to give alkyl benzenes.

Friedel Crafts reaction is discussed in detail in the unit on Aromatic hydrocarbons.
ARYL HALIDES

INTRODUCTION

We have studied alkyl halides in the previous section and have realized the vast importance of this class of compounds, especially in the preparation of organic compounds with different functional groups. We shall now discuss the halogen derivatives of benzene - ARYL HALIDES, which though less reactive, than alkyl halides, have their own pattern of chemical reactivity and are also extremely useful class of compounds. In fact, with respect to the benzene ring there are three types of halogen compounds -

(i) Addition Compounds  (ii) Nuclear Substitution Products
(iii) Side - Chain Substitution Products

Addition compounds of benzene are formed by the saturation of the 3 double bonds of the ring. Benzene hexachloride and benzene hexabromides are examples of this class of compounds. These addition compounds are formed when benzene is heated with chlorine or bromine in the presence of sunlight.

\[
\text{Cl}_2 \xrightarrow{hv} 2\text{Cl}^* \\
\text{C}_6\text{H}_6 + 2\text{Cl}^* \rightarrow \text{C}_6\text{H}_5\text{Cl} \xrightarrow{\text{Cl}^* \text{etc.}} \text{C}_6\text{H}_5\text{Cl}_6
\]

*benzene hexachloride*

Benzene hexachloride (BHC) exists in eight stereoisomeric forms, but only seven are known - \(\alpha, \beta, \gamma, \delta, \epsilon, \eta, \sigma\). Out of these, \(\gamma\) - isomer is a powerful insecticide.

We shall discuss the other two categories of halogen compounds i.e. nuclear substitution and side chain substitution in detail in the following sections.

It is the nuclear substitution products that are called Aryl Halides.

BONDING IN ARYL HALIDES

Aryl halides, with general formula \(\text{Ar} - X\), have the halogen atom directly attached to the benzene ring.
If the halogen atom is not directly attached to the phenyl ring, it does not belong to the category of aryl halides. Instead, the structure and properties of the compound are simply of substituted alkyl halides. Typical example here is of benzyl chloride

\[ \text{O} - \text{CH}_2\-\text{Cl} \]

Aryl halides have the halogen atom bonded to the doubly bonded \( sp^2 \) carbon of the benzene nucleus. This makes the carbon-halogen bond shorter and stronger and hence less chemically reactive. In this respect, the aryl halides resemble vinyl halides where halogen is again bonded directly to doubly bonded \( sp^2 \) carbon.

\[ \text{C} - \text{Cl} \ \text{Bond Dissociation Energies} \]

<table>
<thead>
<tr>
<th>Compound</th>
<th>Bond Dissociation Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{CH}_3\text{CH}_2-\text{Cl} )</td>
<td>339 ( \text{kJ/mol} )</td>
</tr>
<tr>
<td>( \text{CH}_2 = \text{CH}-\text{Cl} )</td>
<td>368 ( \text{kJ/mol} )</td>
</tr>
<tr>
<td>( \text{C}_6\text{H}_5-\text{Cl} )</td>
<td>406 ( \text{kJ/mol} )</td>
</tr>
</tbody>
</table>

As a result of similarity in bonding, vinyl halides and aryl halides resemble in many other areas e.g. Both are relatively unreactive towards nucleophilic substitutions.

**PREPARATION OF ARYL HALIDES**

Two basic methods are employed in the preparation of Aryl Halides. However, these methods are very different from the ones used in preparing alkyl halides - due to the basic difference in the substrate used. Let us examine these methods.

**DIRECT HALOGENATION OF BENZENE**

We have studied halogenation of alkanes wherein we saw that, due to the non-polar nature of alkanes, their reactivity is very low and hence halogen reacts under high temperature or photochemical conditions or in presence of radical initiators. The mechanism of halogenation of alkanes is free radical substitution.
Benzene, on the other hand, is very susceptible to substitution but the mechanism is Electrophilic Aromatic Substitution. Chlorination and bromination is very conveniently carried out at ordinary temperature in presence of metallic iron or lewis acids such as chlorides or bromides of Fe, Al, Sb.

\[
\begin{align*}
\text{H} & \quad \text{Br}_2 \quad \text{Fe} \quad \text{Br} \quad \text{HBr} \\
\text{bromobenzene} \quad (70\%) 
\end{align*}
\]

**Mechanism of Halogenation**

We know that bromine (or chlorine) rapidly adds to alkenes (electrophilic addition). However, it is too weak an electrophile to react at an appreciable rate with benzene. Benzene itself is not as reactive as alkene. As a result, benzene needs the assistance of Fe or other lewis acids that act as catalyst.

\[
2 \text{Fe} + 3 \text{Br}_2 \rightarrow 2\text{FeBr}_3
\]

The active catalyst is FeBr₃ and not Fe alone. FeBr₃, forms a Lewis base - Lewis acid complex making bromine more electrophilic so that it readily attacks benzene.

**Step 1**

\[
\begin{align*}
\text{Br}^- & \quad \text{Br}^{-} \quad + \quad \text{FeBr}_3 \quad \text{→} \quad \text{Br}^- \quad \text{Br}^{-} \quad \text{FeBr}_3 \\
\text{Lewis Base} & \quad \text{Lewis Acid} \quad \text{Lewis Acid-Lewis Base Complex}
\end{align*}
\]

The rate law for catalytic halogenation of benzene is:

\[
\text{rate} = k \left[ \text{benzene} \right] \left[ X_2 \right] \left[ \text{Lewis Acid} \right]
\]

This shows that lewis acid plays a role in the electrophilic attack of halogen on benzene. It enables the transfer of bromine, without its electrons, from the complex directly to the ring.

This is the key step of aromatic halogenation. The reaction progresses with the loss of the better leaving group FeBr₄.

**Step 2**

\[
\begin{align*}
\text{H} & \quad \text{Br}^- \quad \text{Br}^- \quad \text{FeBr}_3 \quad \text{slow} \quad \text{Br}^+ \quad \text{H} \quad + \quad \text{Br}^- \quad \text{FeBr}_3 \\
\text{Benzene} & \quad \text{Bromine - Iron (III) bromide complex} \quad \text{Cyclohexadienyl cation intermediate} \quad \text{Tetrabromo ferrate ion}
\end{align*}
\]
The intermediate cyclohexadienyl cation is stabilized via resonance. This intermediate is also called Wheland intermediate, the T-complex or the benzenonium cation.

\[
\begin{align*}
\text{Br} & \text{H} \quad \longleftrightarrow \quad \text{Br} & \text{H} \\
& \quad \longleftrightarrow \quad \text{Br} & \text{H} \\
& \quad \text{equivalent to} \quad \text{Br} & \text{H}
\end{align*}
\]

It may also be possible that a positively charged halogen is produced which then attacks the benzene ring.

\[\text{Br} \quad \text{Br} \quad \text{FeBr}_3 \quad \longleftrightarrow \quad \text{Br}^+ \quad \text{FeBr}_4^-\]

Both the mechanisms can run simultaneously. Which one predominates depends on factors like strength of lewis acid — a strong lewis acid will encourage the liberation of positively charged halogen.

**Step 3**
The cation is no longer benzenoid and has lower resonance energy than benzene. It therefore, quickly reverts back to the benzenoid state by the expulsion of a proton with the assistance of the base, FeBr_. This removal of proton gives the product, bromobenzene.

\[
\begin{align*}
\text{Br} & \quad \text{H} \\
& \quad \text{fast} \\
& \quad \text{Br}^+ \quad \text{FeBr}_3^- \\
& \quad \longleftrightarrow \\
& \quad \text{FeBr}_3^- + \text{H} \quad \longrightarrow \quad \text{Br}^- \\
\end{align*}
\]

Chlorination can be easily carried out in the same way.
Fluorination and iodination of benzene, are rarely performed for the same reason studied in the alkylhalide preparation - fluorine is too reactive to control the reaction and iodine is too unreactive for a favourable equilibrium constant. These compounds are best obtained by transformation of pre-existing functional groups.

In this context, an electron releasing group already present on the benzene ring directs the incoming halogen to ortho and para position while electron withdrawing group directs the halogen to meta position.

\[
\begin{align*}
\text{CH}_3 & \quad \text{Cl} \\
& \quad \text{Cl}_2\text{FeCl}_3 \\
\end{align*}
\]

\[
\begin{align*}
\text{CH}_3 & \quad \text{Cl} \\
& \quad \text{Cl} \\
& \quad \text{Cl} \\
\end{align*}
\]

\[
\begin{align*}
\text{CH}_3 & \quad \text{Cl} \\
& \quad \text{Cl} \\
& \quad \text{Cl} \\
\end{align*}
\]

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DECOMPOSITION OF ARYLDIAZONIUM SALTS

Aryl amines when treated with acidified sodium nitrite (producing HNO₂) at low temperature (0 - 5°C), result in the formation of Aryldiazonium salts.

\[
\text{O} \quad \text{NH}_2 \quad \xrightarrow{\text{NaNO}_2, \text{HCl}} \quad \text{O} \quad \text{N=NCI}^-
\]

Similar reaction with aliphatic diazonium salts are not seen due to their highly unstable nature. Diazonium salts incorporate one of the best leaving groups - molecular nitrogen. For this reason, aliphatic diazonium salts react immediately, as they are formed, by S₈,1, E1 or S₈,2 mechanism, to give substitution and elimination products with the release of N₂ gas. In case of aromatic system, benzene ring bearing good leaving groups do not readily undergo S₈,1 or S₈,2 reactions. For this reason, aryl diazonium salts can be isolated as versatile intermediates in a variety of reactions. They produce a host of ring - substituted aromatic compounds. By using these compounds, aromatic ring can have functional groups that are otherwise difficult to be introduced. These reactions involve the replacement of diazo group, N₂⁺, by another univalent group and hence are called Replacement Reactions.

Replacement by Chloro or Bromo group: SANDMEYER REACTION

When a diazonium salt solution is run into a solution of cuprous halide dissolved in the corresponding halogen acid, the diazo group is replaced by a halogen atom.

\[
\text{NH}_2 \quad \xrightarrow{\text{NaNO}_2, \text{HCl}} \quad \text{N=NCI}^- \quad \xrightarrow{\text{CuCl/HCl}} \quad \text{Cl}
\]

\[
\text{NH}_2 \quad \xrightarrow{\text{NaNO}_2, \text{HBr}} \quad \text{N=NB} \quad \xrightarrow{\text{CuBr/HBr}} \quad \text{Br}
\]
Mechanism: Involves Radical Ion mechanism

\[ \text{CuCl} + \text{Cl}^- \rightarrow \text{CuCl}_2^- \]

\[ \text{ArN}_2^+ + \text{Cl}^- \rightarrow \text{N}_2 + \text{Ar}^+ + \text{Cl}^- \rightarrow \text{ArCl} + \text{CuCl} \]

**Gattermann Reaction**

This reaction simply requires the diazonium salt to be warmed in presence of copper powder when it decomposes to give the halobenzene.

Here, the diazonium salt is prepared using the halogen acid that will provide the halogen for the ring.

**Replacement by Fluoro group : SCHIEMANN REACTION**

This is a very convenient method for introducing fluorine atom in the ring. Addition of fluoroboric acid to aryldiazonium salt solution gives the insoluble diazonium fluoroborate, which on gentle heating gives the aryl fluoride.

\[ \text{O} - \text{N}_2^+ \text{Cl}^- + \text{HBF}_4 \rightarrow \text{O} - \text{N}_2^+ \text{BF}_4^- + \text{HCl} \]

\[ \rightarrow \text{O}^+ + \text{BF}_4^- + \text{N}_2 \]

\[ \rightarrow \text{O}^- \text{F} + \text{BF}_3 \]
Alternate methods are shown below:

\[
\begin{align*}
\text{ArNH}_2\text{Cl}^- + \text{HPF}_6 & \rightarrow \text{HCl} + \text{ArN}_2^+\text{PF}_6^- \\
& \text{hexafluoroposphoric acid} \\
& \Delta \\
\text{ArF} + \text{PF}_5 & \leftrightarrow \text{Ar}^+ + \text{PF}_6^- + \text{N}_2
\end{align*}
\]

\[
\begin{align*}
\text{ArN}_2^+\text{Cl}^- + \text{HAsF}_6 & \rightarrow \text{HCl} + \text{ArN}_2^+\text{AsF}_6^- \\
& \text{hexafluoroarsenic acid} \\
& \Delta \\
\text{AsF}_5 + \text{ArF} & \leftrightarrow \text{Ar}^+ + \text{AsF}_6^- + \text{N}_2
\end{align*}
\]

**Replacement by Iodo group**

Iodo compounds may be prepared by boiling the diazonium salt solution with aqueous potassium iodide.

\[
\text{ArN}_2^+\text{Cl}^- + \text{aq KI} \xrightarrow{\Delta} \text{Arl} + \text{KCl} + \text{N}_2
\]

This is the best method to introduce iodine into the benzene ring.

Mechanism of the reaction seems to involve the displacement of diazo group by the strong nucleophile, iodide ion or triiodide ion. Triiodide ion is produced by oxidation of \( I^- \) to \( I_2 \) by diazonium ion or nitrous acid present in the solution.

\[
I_2 + I^- \xrightarrow{\text{oxidation}} I_3^-
\]

**MISCELLANEOUS METHODS**

(i) Silver salts of aromatic acids react with bromine to form aryl bromides.

\[
\text{O-COOAg} + \text{Br}_2 \rightarrow \text{O-Br} + \text{AgBr}
\]

(ii) Aromatic hydroxy compounds on treatment with HX, PX, and SOCl, do not give Aryl halides (which are used easily with alcohols to get alkyl halides). Only PCl, gives chlorobenzene in poor yields.
A modification of this method involves the use of phenols with electron attracting groups on aromatic ring.

\[
\text{ArOH} + \text{PCl}_3 \xrightarrow{\Delta} (\text{ArO})_2\text{PCl}_3 + 3\text{HCl} \xrightarrow{\Delta \text{ArOH},\Delta} (\text{ArO})_3(\text{Ar'O}) \text{PCl} \xrightarrow{\Delta} \text{Ar'OCl} + (\text{ArO})_3\text{PO}
\]

where \(\text{Ar'O}\) contains more powerful electron attracting groups than does \(\text{Ar}\).

**PHYSICAL PROPERTIES**

Aryl halides resemble alkyl halides in many of their physical properties e.g. the b.pts of aryl halides and alkyl halides, with same number of carbon atoms, are nearly the same. All are practically insoluble in water and most are dense than water. Some physical contents are listed in the table.

<table>
<thead>
<tr>
<th></th>
<th>M.pt/°C</th>
<th>B.pt/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorobenzene</td>
<td>-45</td>
<td>85</td>
</tr>
<tr>
<td>Chlorobenzene</td>
<td>-45</td>
<td>132</td>
</tr>
<tr>
<td>Bromobenzene</td>
<td>-31</td>
<td>156</td>
</tr>
<tr>
<td>Iodobenzene</td>
<td>-31</td>
<td>189</td>
</tr>
<tr>
<td>Difluorobenzene</td>
<td>-34 (ortho)</td>
<td>-59 (para)</td>
</tr>
<tr>
<td>Dichlorobenzene</td>
<td>-17</td>
<td>-24</td>
</tr>
<tr>
<td>Dibromobenzene</td>
<td>6</td>
<td>-7</td>
</tr>
<tr>
<td>Diiodobenzene</td>
<td>27</td>
<td>35</td>
</tr>
</tbody>
</table>

The isomeric dihalobenzenes have a considerable difference in their m.pts. The para isomer has the highest m.pt because of being a symmetrical structure that gets filled in the crystal lattice better. Between alkyl halides and aryl halides, latter has a lesser polar character. This is due to the phenyl carbon being sp\(^3\) hybridized that reduces the difference in electronegativity between C and X. Also, there is donation of hydrogen bond from the longest bond.
REACTIONS OF ARYL HALIDES
LACK OF REACTIVITY FOR S<sub>2</sub> AND S<sub>1</sub> SUBSTITUTION

One of the most important differences between aryl halides (or vinyl halides) and alkyl halides is their reactivity towards nucleophilic substitution reaction; i.e. with OH, OR, NH<sub>2</sub>, CN etc, aryl halides show very low reactivity. As studied earlier, two most important mechanisms in nucleophilic substitutions of alkyl halides are S<sub>2</sub> and S<sub>1</sub>. Such reaction mechanisms are absent in aryl halides.

E.g. When ethyl bromide is allowed to react with sodium chloride in ethanol, S<sub>2</sub> reaction proceeds to completion in an hour with excellent yield

\[ \text{CH}_3\text{CH}_2\text{Br} + \text{CH}_3\text{CH}_2\text{ONa} \xrightarrow{\text{C}_2\text{H}_5\text{OH}} \text{CH}_3\text{CH}_2\text{OCH}_3 + \text{NaBr} \]

But when bromobenzene or vinyl bromide is subjected to the same conditions, nothing happens even for several days.

\[ \text{Br} \xrightarrow{\text{NaOC}_2\text{H}_5, \text{C}_2\text{H}_5\text{OH}} \text{No substitution} \]

\[ \text{CH}_2=\text{CH Br} + \text{NaOC}_2\text{H}_5 \xrightarrow{\text{C}_2\text{H}_5\text{OH}} \text{No substitution} \]

We have explained earlier the reason for this contrasting chemical reactivity.

In aryl and vinyl halides, carbon - halogen bond is shorter and stronger. This is, in turn, due to sp<sup>2</sup> hybridization of C that enables the electrons to come closer to the nucleus as compared to sp<sup>3</sup> C in alkyl halide. Moreover, resonance, of the type shown, strengthens the carbon-halogen bond by giving it double bond character.

In S<sub>2</sub> reactions, to reach the transition state, the carbon in the carbon - halogen bond of aryl or vinyl halides would have to be rehybridized from sp<sup>2</sup> to sp as against the carbon of alkyl halide which rehybridizes from sp<sup>3</sup> to sp<sup>2</sup>. Conversion of sp<sup>3</sup> C to sp C requires much more energy (21 kJ/mol) than conversion of sp<sup>2</sup> C to sp<sup>2</sup> C. This makes the T. S. caused by sp hybridization very high in energy and very low in stability. Another reason is that for S<sub>2</sub> reaction, back side attack of incoming nucleophile in the plane of the ring is required on the halogen bearing carbon. This would require the nucleophile to go through the plane of the benzene ring - an impossible task. S<sub>2</sub> reaction, by virtue of the mechanism, makes the carbon atom bearing
the halogen have an inversion in configuration. This would make the reaction necessarily yield a benzene derivative containing a twisted and highly strained double bond.

![Chemical structure](image)

Twisted double bond

Similar difficulties are encountered in vinyl halides. Here the leaving group $X^-$ and the incoming nucleophile $Nu^-$ face van der Waal repulsions from the neighbouring groups due to the back side attack in-plane of alkene.

![Chemical structure](image)

van der Waals Repulsion

Aryl halides and vinyl halides are equally inert to $S_n,1$ reactions. In $S_n,1$ reactions, a carbocation is formed in the first step. Here, we shall have the formation of a phenyl carbocation with a vacant orbital, which is very difficult. This electron deficient carbon will be bonded to two groups—the two carbons of the ring on either side of the electron deficient carbon. The most favourable geometry, therefore, is a linear geometry but such a geometry will introduce too much strain in the ring and is unachievable. As a result, the vacant orbital cannot be $2p$ orbital. This leaves only the $sp^3$ orbital to be the vacant orbital. So, both hybridization and the geometry is not favourable and hence the energy is very high or it is a highly unstable intermediate. To add to the instability, is the electron withdrawing effect of the ring double bonds. $S_n,1$ reactions are impossible to take place.

![Chemical structure](image)
Similarly, formation of vinyl cation is very difficult. Here the electron-deficient carbon is also part of a double bond. Electron deficient carbon is connected to two groups (carbon of the double bond and H) hence the geometry at this carbon is linear and the electron deficient carbon is therefore sp-hybridized. The 2p orbital is vacant and is not conjugated with the \( \pi \) -electron system of the double bond; it would have to be coplanar with the double bond \( \pi \) -system. Furthermore, the electron withdrawing polar effect of the double bond destabilizes the positive charge at vinylc carbon. Apart from this, the carbon-halogen bond bears a partial double bond character as well as the fact that halogen is bonded to \( s^2p^2 \)C which has more s character and so makes it stronger. All these factors raise the energy of vinyl cation to a very large extent.

This discussion clearly explains that nucleophilic substitution is impossible in Aryl halides. Of course, this is true for \( S_{N1} \) and \( S_{N2} \) type reaction. But it is still possible to observe nucleophilic substitution reactions in certain aryl halides by other mechanisms.

**\( (S_{NAR}) : \text{ADDITION - ELIMINATION MECHANISM} \)**

Aryl halides that have one or more electron withdrawing groups at ortho or para position to the halogen, undergo nucleophilic aromatic substitution under relatively mild conditions. Thus, groups like - \( NO_2 \), -CN, -N\((CH_3)\), -SO\(_2\)H, -COOH, -CHO, -COR, -X etc., enable the displacement of halogen by a nucleophile. These groups must be present at ortho or para position to the halogen. As the number of these groups increases, the conditions used for the nucleophilic substitution reaction become milder.

\[
\begin{align*}
\text{Cl} & \quad \text{6-8\% NaOH, 350^\circ C, 4500 lb/in}^2 \quad \rightarrow \quad \text{OH} \\
\text{Cl} & \quad \text{15\% NaOH, 160^\circ C} \quad \rightarrow \quad \text{OH}
\end{align*}
\]
As we go from the relative rate of substitution reaction at 50°C increases from 1.0 to more than $2.4 \times 10^{15}$.

These reactions are examples of nucleophilic aromatic substitution. These reactions involve nucleophiles and leaving groups and obey second-order rate laws,

$$\text{rate} = k [\text{aryl halide}] [\text{nucleophile}]$$

However, Nucleophilic Aromatic Substitutions do not involve a concerted backside attack as explained before. The generally accepted mechanism is a two step Addition - Elimination mechanism. In the first step, the nucleophile attacks the halide bearing carbon below (or above) the plane of the aromatic ring to yield a resonance stabilized anion, Meisenheimer Complex. This is the addition stage of the reaction. The negative charge in this complex is delocalized throughout the $\pi$ electron system of the ring. This is also the rate limiting step. In the second step, the Meisenheimer complex breaks down by loss of the halide ion. This is the elimination stage of the reaction.

Step 1: Addition Stage

$$\text{O}_2\text{N}^- + \text{Cl} \rightarrow \text{O}_2\text{N}^- \rightarrow \text{O}_2\text{N}^- \rightarrow \text{O}_2\text{N}^-$$
Resonance stabilization of negative charge of meisenheimer complex

Step 2: Elimination stage

This mechanism is consistent with the following experimental facts:

1. Kinetics: The rate determining step involves both aryl halide and nucleophile which is the requirement for second order reaction.

2. Effect of groups present in the ring: The addition of nucleophile in the first step is a slow step because of the formation of cyclohexadienyl anion at the expense of the aromaticity of the ring. The intermediate so formed, will have low activation energy for formation only when the negative charge is well dispersed. This can be effected by the presence of electron withdrawing groups. The negative charge is stabilized by the inductive effect but more so by the -R effect of the groups. For the latter, it is necessary that the group be present at ortho or para position to halogen.

This resonance structure contributes maximum to the required stabilization of the intermediate anion.
When the electron withdrawing group is present at meta position, negative charge remains restricted to carbon atoms of the ring and does not extend out to the group. No extra stabilization is therefore seen.

On this basis, presence of electron releasing groups such as -NH₂, -OH, -OR, -R will destabilize the intermediate, more so at ortho and para position.

Thus we see that just like Electrophilic Aromatic substitution, in nucleophilic aromatic substitution a group exerts its strongest influence at ortho and para portion.

3. **Effect of Leaving Group**: In contrast to S₉₂ reaction, alkyl fluorides react fastest in nucleophilic aromatic substitutions. The reactivity of aryl halides is:

$$\text{Ar–F} \gg \text{Ar–Cl} \approx \text{Ar–Br} \approx \text{Ar–I}$$

The exceptionally high reactivity of aryl fluorides may be explained by looking at the negatively charged intermediate once again. Fluorine, due to its high electronegativity, exerts polar effect in stabilizing the anion which is much more than other halogens. The loss of halide ion is not the rate limiting step (which is the rate limiting step in both S₉₂ and S₉₁), hence the basicity, or equivalently the strength of C - X bond is not important in determining the reaction rate.

Thus, order of leaving group reactivity in nucleophilic aromatic substitution is the opposite of that seen in aliphatic substitution. Fluoride is the most reactive leaving group, iodide is the least reactive.

### Difference between Nucleophilic Aromatic and Nucleophilic Aliphatic Substitution

<table>
<thead>
<tr>
<th>Features</th>
<th>S₉₁</th>
<th>S₉₂</th>
<th>S₉₁Ar</th>
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<tbody>
<tr>
<td>1. Timing of departure of leaving group</td>
<td>Before the attack of Nucleophile</td>
<td>At the same time as the attack of Nucleophile</td>
<td>After the attack of Nucleophile</td>
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<tr>
<td>Features</td>
<td>$S_n1$</td>
<td>$S_n2$</td>
<td>$S_nAr$</td>
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<tr>
<td>-------------------------------</td>
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<tr>
<td>3. Nature of Leaving group.</td>
<td>Iodides are most reactive, fluorides least.</td>
<td>Iodides most reactive, fluorides least.</td>
<td>Fluorides most reactive, iodides least.</td>
</tr>
<tr>
<td>6. Structure of intermediate/T.S.</td>
<td>$\text{R} + \begin{array}{c} \text{Z} \ \text{R} \ \text{X} \end{array}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ELIMINATION ADDITION MECHANISM: BENZYLNE**

So far, we have studied the $\beta$ elimination of alkyl halides. This is a reaction that takes place quickly to give rise to alkenes. If instead of alkyl halides, we take vinyl halides, then the same $\beta$-elimination requires vigorous conditions to produce alkenes. On the same analogy, if we take aryl halides, their $\beta$-elimination, which is ortho elimination, would give an interesting 'alkyne' called Benzylne or Dehydrobenzene.

```
\[
\text{H} \quad \text{Cl} \quad \text{Elimination} \quad -\text{HCl} \quad \text{H} \quad \text{Cl}
\]
```

This is the species involved when nucleophilic substitution of aryl halides is seen even in spite of the absence of powerful electron withdrawing groups on the aromatic ring. In such cases, the aryl halides are treated with very strong bases and the nucleophilic substitution takes place by the Elimination - Addition mechanism (or the Benzylne Mechanism). Structure of Benzylne has one triple bond. One of the two $\pi$ bonds in the triple bond of benzene is perpendicular to the $\pi$ electron system of the aromatic ring. The $\pi$ electron system of the aromatic ring is made by the lateral overlap of the $p$ orbital on each carbon. This extra $\pi$ bond of the triple bond is unusual, because it is formed from the sideways overlap of $sp^2$ orbitals on two adjacent carbons - one originally holding halogen and other holding hydrogen.
Alkynes require a linear geometry which is difficult to attain in benzene. Benzene has, therefore, a strained geometry. The new $\pi$ bond has no interaction with $\pi$ electron cloud of the ring. The sideways overlap is weak and hence benzene is a highly unstable molecule (205 kJ/mol unstable than alkyne). This, in turn, makes it very reactive and is attacked by strong bases to give an overall substitution product.

$$\text{Cl} + K^+\text{NH}_2^- \xrightarrow{\text{NH}_2, \text{liq.}} \text{NH}_2^- + K^+\text{Cl}^-$$

Therefore, benzene mechanism involves two steps

- First step where Elimination of $H$ and $X$ occurs to give benzene

- Second step where Addition of Nucleophile and $H$ occurs to give overall substitution product.

Elimination itself comprises of two steps.

(i) Abstraction of a hydrogen ion by the strong base such as amide ion to form ammonia and carbonion I, with negative charge at the ortho portion. Since there is no interaction with $\pi$ electron cloud therefore charge remain localised to the C where it has been generated.

(ii) Loss of halogen ion to form benzene.

Addition also involves two steps

(i) Attack of amide ion to form a new carbonion. Because benzene is symmetrical the carbons of the triple bond are indistinguishable Hence. $\text{NH}_2^-$ attacks equally well at either carbons.

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(ii) Protonation of anion by reaction with acid, ammonia etc. to give the neutral product.

Evidence for Benzyne Mechanism

(A) Robert and coworkers carried out isotopic labelling experiment to prove the above mechanism. Experiment: Chlorobenzene with the carbon bearing chlorine was labelled with radioactive isotope $^{14}C$ and was treated with $\text{KNH}_2$ in liq. $\text{NH}_3$. The aniline product so obtained was a 50:50 mixture of two isomers: one in which $\text{NH}_2$ was attached to labelled C and other in which NH$_2$ was ortho to labelled C.

Inference: As discussed, after formation of benzyne the two adjacent carbons bearing Cl and H each, become indistinguishable and NH$_2$ adds randomly to one or the other.
(B) The benzync mechanism accounts for the fact that when ayl halide bears a ring substituent, more than one product is observed.

Substitution at site different from the one occupied by the leaving group is called cine-substitutions. Therefore, Benzyne mechanism provides a mixture of direct and cine-substitution products.

(C) If the aryl halide has two groups ortho to halogen, the compound fails to give substitution reaction. This is due to absence of ortho hydrogen that can be eliminated.

(D) α-Deuteriofluorobenzene is converted to aniline very slowly. Instead it rapidly loses deuterium to yield ordinary fluorobenzene. This shows that C-D cleavage is the first step of the reaction but before strong C-F bond cleavage occurs, the carbanion abstracts H from NH$_3$ to regenerate fluorobenzene.
Both _m_-bromoanisole and _o_-bromoanisole give the same product _m_-anisidine (_m_-aminoanisole) _o_-Bromoaniline has only one ortho hydrogen. Therefore, it will give only one elimination product or only one benzene. _m_-Bromoanisole has two ortho hydrogens. Therefore, two benzyne is possible but the carbanion that receives the electron withdrawing inductive effect of methoxyl group will be more stable and hence preferred. Corresponding benzyne will therefore be preferred. That is why, both starting compounds give the same benzene. This benzyne will now have addition preferentially on the carbon that leads to a more stable carbanion - this again will be the meta attack, so that negative charge is ortho to electron withdrawing methoxyl group.

Thus, a single product — _m_-anisidine is obtained

Benzyne may also be generated by organolithium compound e.g. _C_6_H_5-Li. Here _C_6_H_5 is the base that enables the formation of benzyne. The benzyne is subsequently attacked by _C_6_H_5-Li to form carbanion which, attaches to Li⁺ due to unavailability of H⁺. Addition of water yields the final product.
Summary of Nucleophilic Substitution Reaction of Aryl Halides

1. Aryl halides, with electron withdrawing substituents at ortho and para position react by nucleophilic aromatic substitution reactions. This type of reaction involves a resonance - stabilized anionic intermediate resulting from a nucleophilic attack of the aromatic ring. This intermediate then loses halide ion to form the substitution product.

2. Ordinary aryl Halides undergo substitution by the benzyne mechanism only in the presence of very strong bases such as alkali metal amide and organolithium reagent or somewhat weaker bases under vigorous conditions (high temperature, longer reaction times).

SUBSTITUTION IN THE RING : ELECTROPHILIC AROMATIC SUBSTITUTION

Halogens show an anomalous behaviour towards Electrophilic Substitution reactions of the benzene ring - they are deactivating and yet ortho, para directing.

Normally, a substituent is ortho and para directing if it is an activating group and vice versa. In case of halogens, electrons are withdrawn through the -I effect which in turn is due to their high electronegativities. This makes them deactivating groups. On the other hand, lone pair on halogen enables the release of electrons through the +R effect. The electron density is increased at ortho ad para position. [-I and +R effects nearly balance evenly and hence both are operational] This line may be omitted.

\[ \begin{array}{cc}
\text{H} & \text{Z} \\
\text{Cl} & \\
\end{array} \]

- I effect

\[ \text{Z is electrophile} \]
\[ \text{The attack of electrophile results in an intermediate (positively charged) which is destabilised by the -I effect of X} \]

\[ \begin{array}{ccc}
\text{H} & \text{Z} & \text{Cl} \\
\text{Cl} & \\
\end{array} \rightarrow \begin{array}{ccc}
\text{H} & \text{Z} & \text{Cl} \\
\text{Cl} & \\
\end{array} \rightarrow \begin{array}{ccc}
\text{H} & \text{Z}^+ & \\
\text{Cl} & \\
\end{array} \]

para attack

Extra stabilization by structure

\[ \begin{array}{cc}
\text{H} & \text{Z} \\
\text{Cl} & \end{array} \rightarrow \begin{array}{cc}
\text{H} & \text{Z} \\
\text{Cl} & \end{array} \]

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Similarly **ortho attack** has additional structure for stabilization of intermediate

This additional structure is not possible in **meta attack**. Thus, only $\pi$ effect operates that destabilizes the intermediate.

Inductive effect is stronger than resonance effect and causes net electron withdrawal and hence deactivation for attack at all positions. The resonance effect opposes the inductive effect at ortho and para position and makes the deactivation less for ortho, para attack than for meta attack.

![Chemical reaction diagram](image)

**Nitration**

**Friedel Craft Acylation**

**FORMATION OF GRIGNARD REAGENTS**

Aryl halides react with magnesium in dry ether to form aryl magnesiumhalides - Grignard Reagent. Aryliodides are most reactive whereas aryl fluorides are least reactive.

Similarly aryllithium reagents are formed when aryl halides react with lithium
SOME MORE REACTIONS

Ullmann Reaction

Aryl halide is made to react with acetonilide and potassium carbonate in presence of copper powder to produce diphenyl amine

\[
\text{Ph NH CO CH}_2 + \text{Ph} \rightarrow \text{Br} + \text{K}_2 \text{CO}_3 \xrightarrow{\text{Cu}} (\text{Ph})_2 \text{NH} + \text{CO}_2 + \text{CH}_3 \text{COOK} + \text{KBr}
\]

Wurtz Fittig Reaction

This is a useful method for preparing alkyl benzenes. This is an extension of Wurtz reaction. Aryl halide and alkyl halide are warmed in an ethereal solution with sodium.

\[
\text{C}_6\text{H}_5\text{Br} + \text{C}_2\text{H}_5\text{Br} + 2\text{Na} \rightarrow \text{C}_6\text{H}_5\text{C}_2\text{H}_5 + \text{NaBr}
\]

Small amounts of \( \text{C}_4\text{H}_5 \rightleftharpoons \text{C}_2\text{H}_4 \) and \( \text{C}_6\text{H}_5 \rightleftharpoons \text{C}_2\text{H}_6 \) are also formed.

Hydrogenation

Using Pd/C/H\(_2\) or Mg / isopropanol, Aryl halides are converted to benzene.

\[
\text{+ Mg} \quad \text{(CH}_3\text{)}_2 \text{CHOH} \rightarrow \text{+ (CH}_3\text{)}_2 \text{COMgX}
\]

Heck Reaction

This reaction brings about coupling of alkane with aryl bromide or aryl iodide under the influence of Pd(O) catalyst.

\[
\text{CH}_3\text{Br} + \text{CH}_2 = \text{CH}_2 \xrightarrow{\text{Catalyst}} \text{CH}_3 \text{CH} = \text{CH}_2 + \text{HBr}
\]
POLYHALOALKANES

The most important of this class of compounds are the dihalogenomethanes (methylene halides), the trichloromethanes (haloforms, chloroform, bromoform and iodoform) and tetrachloromethane and fluorinated alkanes.

PREPARATION

Dihalogenomethanes are prepared by the partial reduction of haloforms, for example, diiodomethane is obtained in good yield by the reaction of iodoform with a solution of sodium arsenite.

\[ \text{CHI}_2 + \text{Na}_2\text{AsO}_3 + \text{NaOH} \rightarrow \text{CH}_2\text{I}_2 + \text{NaI} + \text{Na}_2\text{AsO}_4 \]

Dichloromethane is made industrially by the chlorination of methane.

Chloroform (trichloromethane) is made industrially by the chlorination of methane or by the following methods:

(a) By the action of bleaching powder (*calcium hypochlorite*) on ethanol (or acetone) in aqueous solution.

The hypochlorite first converts the ethanol into acetaldehyde, and then into trichloroacetaldehyde (*chloral*). This is then split by hydroxide ions into chloroform and formate ions.

\[ \text{H}_3\text{C} \text{CH}_2\text{OH } + \text{Cl}_2 \xrightarrow{-2\text{HCl}} \text{H}_3\text{C} \text{C} = \text{CH}_2 \xrightarrow{\text{Cl}_2} \text{Cl}_3\text{C} = \text{C} = \text{OH}^\circ \rightarrow \text{CHCl}_3 + \text{HCOO}^\circ \]

**Ethanol** **Acetaldehyde** **Chloral** **Chloroform** **Formate ion**

Starting from acetone, this is first chlorinated to give trichloroacetone, which is then split to give chloroform and acetate ions.

\[ \text{H}_3\text{C} \text{CO} \text{CH}_3 + 3\text{Cl}_2 \xrightarrow{-3\text{HCl}} \text{H}_3\text{C} \text{CO} \text{CCl}_3 + \text{OH}^\circ \rightarrow \text{CHCl}_3 + \text{CH}_3\text{COO}^\circ \]

**Acetone** **Trichloroacetone** **Chloroform** **Acetone ion**

*Bromoform, CHBr, and iodoform, CHI, can be prepared in an analogous way.*

(b) Very pure chloroform can be obtained by heating either chloral hydrate or trichloroacetic acid with alkali:
\[
\text{Cl}_2\text{C} - \text{CH(OH)}_2\text{C} + \text{NaOH} \rightarrow \text{CHCl}_3 + \text{HCOONa} + \text{H}_2\text{O}
\]

*Chloral hydrate*  
*Chloroform*

\[
\text{Cl}_2\text{C} - \text{COOH} + \text{NaOH} \rightarrow \text{CHCl}_3 + \text{NaHCO}_3
\]

*Trichloroacetic acid*

**Tetrachloromethane** (carbon tetrachloride) is obtained industrially by chlorination of heated chlorine-containing organic residues. This chlorination/pyrolysis has been called *chlorolysis*.

\[
\text{C}_2\text{H}_6 + 7 \text{Cl}_2 \xrightarrow{870 \text{ K}, \ 200 \text{ mbar (20 Mpa)}} 7 \text{Cl}_2 \rightarrow \text{CCl}_4 + \text{Cl}_2\text{C}=\text{CCl}_2 + 6 \text{HCl}
\]

**Tetrachloroethylene** is formed as a by-product in such chlorolyses; the proportion of the products is controlled by a temperature-dependent equilibrium.

\[
2 \text{CCl}_4 \rightleftharpoons \text{Cl}_2\text{C} = \text{CCl}_2 + 2 \text{Cl}_2
\]

**PROPERTIES AND USES**

Polyhalogenated alkanes have chemical properties similar to those of alkyl halides. Because they are poisonous, care is needed in handling them.

**Dichloromethane** (*methylene chloride*), \text{CH}_2\text{Br}_2\,(\text{b.p. 96.5}^{\circ}\text{C}) and **diiodomethane** (b.p. 181°C) are colourless liquids which do not burn. Together with dichloromethane they are often used as starting materials in organic syntheses.

**Chloroform**, \text{CHCl}_3, is a colourless sweet-smelling liquid of b.p. 61.2°C, which is only slightly soluble in water but is totally miscible with ethanol and ether.

**Chloropicrin** (*Nitrochloroform*), a liquid which boils at 112°C, is formed by the action of conc. nitric acid on chloroform, and is used as an insecticide.

\[
\text{CHCl}_3 + \text{HNO}_3 \rightarrow \text{Cl}_2\text{C} = \text{NO}_2 + \text{H}_2\text{O}
\]

**Bromoform**, \text{CHBr}_3, boils at 149.5°C, and closely resembles chloroform in its chemical properties. It is found in sea water at a concentration of ng/l (10⁻⁶g/l), and, as a metabolic product from algae, passes into the atmosphere.

**Iodoform**, \text{CHI}_3, forms leaflets of m.p. 119°C. It has a characteristic smell, and is insoluble in water but soluble in ethanol and ether. Its formation serves as a *test for ethanol, acetone or other compounds containing an acetyl, H,C—CO—* group.
Iodoform test. The liquid to be tested is treated with iodine and aqueous potassium hydroxide. If the test is positive a yellow crystalline precipitate of iodoform settles out:

\[ \text{C}_2\text{H}_5\text{OH} + 4 \text{I}_2 + 6 \text{KOH} \rightarrow \text{CH}_3 + \text{HCOOK} + 5 \text{KI} + 5 \text{H}_2\text{O} \]

\[ \text{R} \rightarrow \text{COCH}_3 + 3 \text{I}_2 + 4 \text{KOH} \rightarrow \text{CH}_3 + \text{R} \rightarrow \text{COOK} + 3 \text{KI} + 3 \text{H}_2\text{O} \]

Tetrachloromethane (carbon tetrachloride), CCl₄, is a colourless liquid, b.p. 76.7°C, with a sweetish smell. It is non-flammable and is used as a solvent, and for the extraction of fats, oils and resins. It is also used as an ingredient in cleaning-fluids and was used as the filling for fire-extinguishers.

FLUORINATED HYDROCARBONS

Some chlorofluorocarbons derived from methane and ethane (CFCs), because of their low boiling points, non-toxicity and chemical inertness, have been used as coolants (refrigerants) in refrigerators and cooling plants, as propellants for aerosols and foams, and as dry-cleaning fluids. They have been described as freons or as CFCs. The commonest coolants include trichlorofluoromethane, CCl₃F, (CFC 11), b.p. 24.9°C, dichlorodifluoromethane, CCl₂F₂ (Halon 121), b.p. -30°C, 1,2,2-trichloro-1,1,2-trifluoroethane, CCIF₃—CCIF₂, b.p. 48°C and 1,2-dichloro-1,1,2,2-tetrafluoroethane, CCIF₃—CCIF₂, b.p. 3.5°C.

Because of their great volatility and chemical stability, CFCs are transported to the higher layers of the earth’s atmosphere, the stratosphere, where they react with ozone in the following way:

\[ \text{CF}_3\text{Cl} \xrightarrow{\text{hv}} \text{CF}_2\text{Cl} + \text{Cl} \quad \text{Cl} + \text{O}_3 \rightarrow \text{ClO} + \text{O}_2 \quad \text{ClO} + \text{O} \rightarrow \text{Cl} + 2\text{O}_2 \]

There is therefore a danger that the shielding action of the ozone layer, which protects the earth from the influx of UV radiation from outer space, will be impaired. In addition, because CFCs absorb IR radiation much more strongly than CO₂ does, their increasing presence in the atmosphere may lead to its heating up in the same way that CO₂ does. If a compound contains hydrogen, as in the case of chlorodifluoromethane, CHClF₂ (CFC 22, b.p. -40°C), its decomposition occurs in lower layers of the atmosphere, in the troposphere. Its action on the ozone layer of the stratosphere is thus less than that of other chlorofluorocarbons.

PREPARATION

The direct fluorination of alkanes is only accomplished with difficulty, since the reaction is highly exothermic and usually explosive; it almost always leads to a mixture of perfluorinated compounds.

Swarts Reaction. In this, instead of fluorine, the less reactive metal fluorides, such as silver, mercury(II) or potassium fluorides are used as fluorinating agents. These react with alkyl halides, with exchange of the halogen atom by fluorine; mercury(II) fluoride is best for converting them into alkyl fluorides:

\[ 2 \text{R} \rightarrow \text{X} + \text{HgF}_2 \rightarrow 2 \text{R} \rightarrow \text{F} + \text{Hg}_2\text{X}_2 \]

\[ \text{X} = \text{Cl, Br, I} \]
In industry, chlorofluoroalkanes are obtained by fluorination of suitable chloroalkanes with dry hydrogen fluoride over a catalyst bed consisting of aluminium or chromium fluorides:

\[
\begin{array}{c}
\text{CCl}_4 \xrightarrow{\text{Catalyst}} \text{CCl}_2F_2 + \text{CCl}_3F \\
\text{HCl} \\
\text{Dichlorodifluoromethane} \quad \text{Trichlorofluoromethane}
\end{array}
\]

Tetrafluoroethylene is prepared industrially by pyrolysis of chlorodifluoromethane (CFC 22), which is itself obtained by reaction of chloroform with dry hydrogen fluoride in the presence of antimony (V) chloride:

\[
\begin{aligned}
2 \text{CHCl}_3 & \quad + 2 \text{HF(SbCl}_3) & \quad 2 \text{CHClF}_2 & \quad \text{(975 K)} & \quad \text{F}_2\text{C} = \text{CF}_2 \\
-2 \text{HCl} & & -2 \text{HCl} & & \\
\text{Chloroform} & & \text{Chlorodifluoromethane} & & \text{Tetrafluoroethylene}
\end{aligned}
\]

A generally applicable method is that of electrofluorination (Simons). Anodic fluorination is carried out by applying a voltage across dry hydrogen fluoride which is not great enough to liberate elementary fluorine. It leads to perfluorinated compounds.

e.g.

\[
\text{H}_2\text{C} - \text{COOH} \xrightarrow{4 \text{F}^\ominus} \text{F}_2\text{C} = \text{COF} \\
-8^\ominus - \frac{1}{2} \text{O}_2 - 4 \text{H}^\ominus \\
\text{Trifluoroacetyl fluoride}
\]

The main advantage of this method is that functional groups remain unchanged in the fluorination. A valuable fluorinating agent is sulphur tetrafluoride, SF\(_4\), which replaces oxygen atoms in ketones or in carboxylic acids by fluorine atoms.

\[
\begin{array}{c}
\text{R} - \text{C} - \text{R}' + \text{SF}_4 \xrightarrow{} \text{R} - \text{CF}_2 - \text{R}' + \text{SOF}_2 \\
\text{Ketone}
\end{array}
\]

\[
\begin{array}{c}
\text{R} - \text{C} = \text{O} \xrightarrow{+ \text{SF}_4} \text{R} - \text{C} = \text{O} \xrightarrow{- \text{SOF}_2} \text{R} - \text{C} = \text{F} \\
\text{OH} \quad \text{Carboxylic acid} \quad \text{Acyl fluoride} \\
- \text{HF} - \text{SOF}_2
\end{array}
\]

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**Fig. 1** Reaction coordinate diagram for alkene chlorination.

**Fig. 2** Reaction coordinate diagram for bromination.
Reaction is endothermic; transition states resemble products

**Fig. 3** Reaction coordinate diagram for chlorination.
Reaction is exothermic; transition states resemble reactants
Fig. 4 Reaction coordinate diagram for the electrophilic addition of halogen acid to alkene (HBr to 2-methylpropene); the reaction takes place in two steps; $\Delta G_i$ activation energy for first step, $\Delta G_i$ activation energy for second step.

Fig. 5 Reaction coordinate diagram for an S$_2$ reaction.

Fig. 6 The effect of changes in energy levels of transition state on reaction rate of S$_2$ reaction. Higher transition state energy level corresponds to slower reaction $\Delta G_i > \Delta G_i$. 
Fig. 7 Reaction coordinate diagram for an S$_1$ reaction.

Fig. 8 Reaction coordinate diagram for an E1 Reaction of an alkyl halide (2-chloro-2-methylbutane)