CHEMICAL PROPERTIES OF HALOALKANES

Chemical Properties of Haloalkanes (α, β,-Elimination Reaction)

Haloalkanes, also known as alkyl halides, can undergo α, β-elimination reactions, also called E_1 or E_2 reactions, depending on the conditions. These reactions involve the removal of an α-hydrogen and a β-halogen to form an alkene, along with the halide ion. The specific mechanism and products depend on factors such as the nature of the halogen, the structure of the haloalkane, the strength of the base, and the solvent used. Here are some key points regarding the chemical properties of haloalkanes in α, β-elimination reactions:

1) E_1 Reaction (Unimolecular Elimination)

- In E_1 reactions, the rate-determining step involves the formation of a carbocation intermediate.
- This reaction pathway typically occurs in the presence of weak bases or in polar protic solvents.
- It proceeds via a two-step mechanism: first, the leaving group departs, forming a carbocation, and then a base abstract a proton from the carbon adjacent to the carbocation to form the alkene.
- The stereochemistry of the product is generally not preserved.

2) E_2 Reaction (Bimolecular Elimination)

- E_2 reactions occur in one concerted step where the proton abstraction and the elimination of the leaving group happen simultaneously.
- These reactions are favored by strong bases and occur in polar aprotic solvents.
- The stereochemistry of the product can be influenced by the orientation of the reacting molecules, particularly in cases of stereochemistry at the reacting carbon center.
- E_2 reactions often exhibit Zaitsev's rule, where the more substituted alkene (the one with more alkyl groups attached to the double-bonded carbons) is favored.

3) Substrate Factors

- The nature of the halogen affects the reactivity of the haloalkane. Typically, more reactive halogens (e.g., iodine) will promote faster elimination reactions compared to less reactive ones (e.g., fluorine).
- The presence of substituents on the alkyl group can influence the ease of elimination. For instance, tertiary haloalkanes tend to undergo elimination more readily than secondary or primary haloalkanes due to the stability of the carbocation intermediate.

4) Base and Solvent Effects

- The choice of base and solvent can significantly influence the outcome of the elimination reaction. Strong bases like alkoxides or hydroxides favor E_2 reactions, while weaker bases may promote E_1 pathways.
- Polar aprotic solvents, such as DMSO or acetone, generally favor E_2 reactions by stabilizing the transition state.

Overall, understanding the specific conditions and mechanisms of α, β-elimination reactions in haloalkanes is crucial for predicting the products and designing synthetic routes in organic chemistry.

Chemical Properties of Haloalkanes (Wurtz Reaction)

The Wurtz reaction is a chemical reaction that involves the coupling of two alkyl halides (haloalkanes) in the presence of sodium metal to form a longer chain alkane. This reaction is named after its discoverer, Charles Adolphe Wurtz. Here are the key points regarding the chemical properties of haloalkanes in the context of the Wurtz reaction:

1) Reaction Mechanism

- The Wurtz reaction proceeds through a radical mechanism.
- Sodium metal undergoes homolytic cleavage to generate sodium radicals, which then abstract halogen atoms from the haloalkanes, producing alkyl radicals.
- The alkyl radicals subsequently combine to form a new carbon-carbon bond, resulting in the formation of a longer-chain alkane.

2) Conditions

- The Wurtz reaction is typically carried out in an inert solvent such as diethyl ether or tetrahydrofuran (THF), which helps dissolve the reactants and stabilize the reaction intermediates.
- Excess sodium metal is often used to ensure that enough sodium radicals are generated to react with the alkyl halides.

3) Scope and Limitations

- The Wurtz reaction is most commonly used for the synthesis of symmetrical alkanes, where both alkyl groups are identical.
- The reaction may also be applicable to the synthesis of unsymmetrical alkanes, but selectivity issues may arise due to the possibility of multiple products.
- Hindered alkyl halides or those containing β-hydrogens are less reactive in the Wurtz reaction due to steric hindrance or competing elimination reactions.

4) Stereochemistry

- The Wurtz reaction does not typically involve stereochemistry considerations, as it proceeds through radical intermediates where the configuration of the products is not controlled.

5) Safety Considerations

- The Wurtz reaction involves the use of highly reactive sodium metal, which can pose safety hazards if not handled properly.
- Precautions such as conducting the reaction under an inert atmosphere and using appropriate protective equipment are necessary to minimize risks associated with handling reactive metals and organic halides.

Overall, the Wurtz reaction provides a useful method for the synthesis of symmetrical alkanes from alkyl halides. However, its application may be limited by selectivity issues and safety considerations associated with the use of reactive metals.

Chemical Properties of Haloalkanes

Haloalkanes, also known as alkyl halides, exhibit several chemical properties due to the presence of halogen atoms (fluorine, chlorine, bromine, or iodine) attached to alkyl groups. Here are some important chemical properties of haloalkanes:

1) Nucleophilic Substitution Reactions

- Haloalkanes undergo nucleophilic substitution reactions, where the halogen atom is replaced by a nucleophile.
- The reaction rate and mechanism depend on factors such as the nature of the halogen, the structure of the haloalkane, and the strength of the nucleophile.
- Common nucleophilic substitution reactions include SN_1 (substitution nucleophilic unimolecular) and SN_2 (substitution nucleophilic bimolecular) mechanisms.

2) Elimination Reactions

- Haloalkanes can undergo elimination reactions, where a halogen atom and an adjacent hydrogen atom are removed to form a double bond.
- These elimination reactions can proceed via E_1 (unimolecular elimination) or E_2 (bimolecular elimination) mechanisms, depending on factors such as the strength of the base and the structure of the haloalkane.

3) Reduction Reactions

- Haloalkanes can be reduced to form alkanes or other functional groups using reducing agents such as lithium aluminum hydride ($LiAlH_4$) or hydrogen gas (H_2) in the presence of a metal catalyst.
- Reduction reactions involve the replacement of the halogen atom with hydrogen.

4) Grignard Reactions

- Haloalkanes can react with magnesium metal (Mg) to form Grignard reagents, which are highly reactive organ magnesium compounds.
- Grignard reagents can undergo various reactions, including nucleophilic addition to carbonyl compounds and other electrophiles.

5) Halogen Exchange Reactions

- Haloalkanes can undergo halogen exchange reactions, where the halogen atom is replaced by a different halogen.
- These reactions are often carried out using metal halides or other halogenating agents.

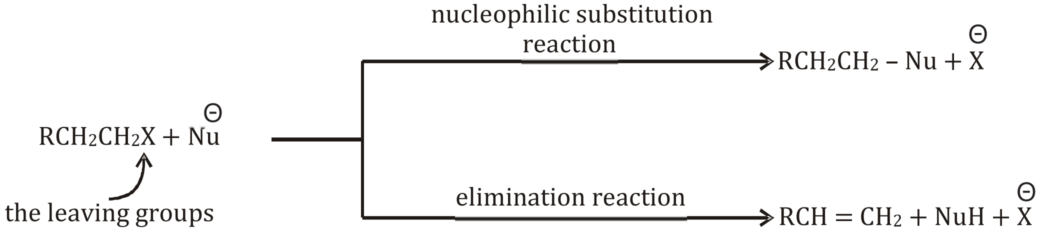
6) Reactivity Trends

- The reactivity of haloalkanes generally increases with increasing size of the halogen atom ($F < Cl < Br < I$) due to differences in bond strength and polarizability.
- Primary haloalkanes typically undergo SN_2 reactions readily, while tertiary haloalkanes prefer SN_1 or E_1 mechanisms due to steric hindrance.

Chemical Properties of Haloarenes (Nucleophilic Substitution Reaction)

Chemical Reactions of Alkyl Halide (Nucleophilic Substitution Reaction)

Organic compounds featuring an sp^3 hybridized carbon bonded to an electronegative atom or group can undergo two distinct types of reactions. First, there are substitution reactions where the electronegative atom or group is replaced by another atom or group. Second, there are elimination reactions in which the electronegative atom or group, along with a hydrogen atom from an adjacent carbon, is removed. The electronegative atom or group that undergoes substitution or elimination is referred to as the leaving group



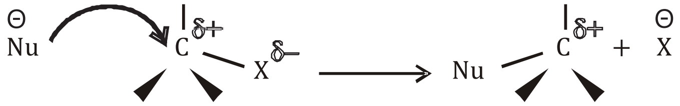
Due to the higher electronegativity of the halogen atom, it acquires a partial negative charge, while a partial positive charge is developed on the carbon atom.

8+ 8-
$RCH_2 - X$
$X = F, Cl, Br, I$

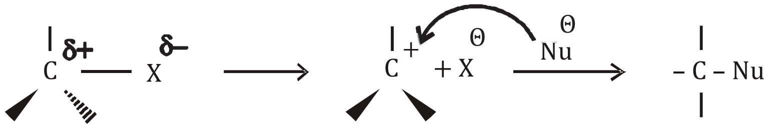
The polarity of the carbon-halogen bond in alkyl halides is responsible for their ability to undergo nucleophilic substitution and elimination reactions.

There are two important mechanisms for the substitution reaction

(1) The partially positively charged carbon attracts a nucleophile. As the nucleophile approaches the carbon, it triggers heterolytic cleavage of the carbon-halogen bond, and the halogen retains both of the shared electrons.

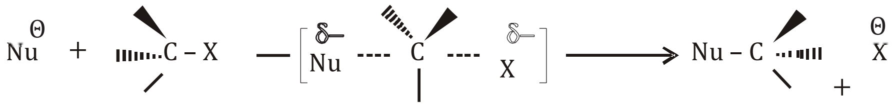


(2) The carbon-halogen bond undergoes heterolytic cleavage independently, aided by a polar protic solvent, resulting in the formation of a carbocation (solvolysis).
The produced carbocation subsequently reacts with the nucleophile to generate the substitution product.



(A) Bimolecular nucleophilic substitution reaction (S_N^2)

The mechanism of S_N^2 reaction



transition state

Characteristic of S_N^2

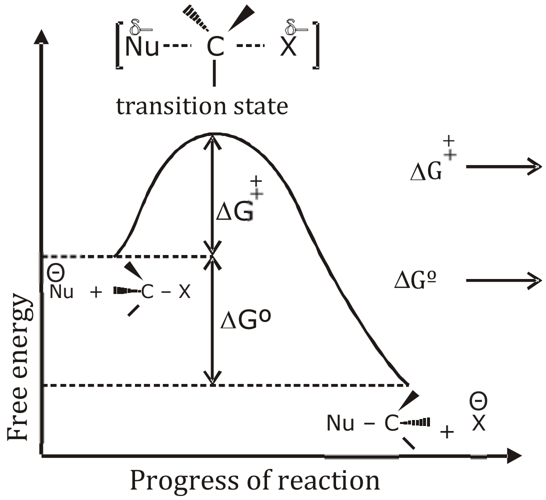
(1) It is bimolecular, unistep process

(2) It is second order reaction because in the Rds two species are involved

(3) Kinetics of the reaction → rate $\propto$ [alkyl halide] [nucleophile]
rate $\propto$ k [alkyl halide] [nucleophile]

When the concentration of the alkyl halide in the reaction mixture is increased twofold, the nucleophilic substitution reaction rate also doubles. Likewise, if the concentration of the nucleophile is doubled, the reaction rate doubles as well. However, when both concentrations are doubled, the reaction rate quadruples.

(4) Energetics of the reaction →



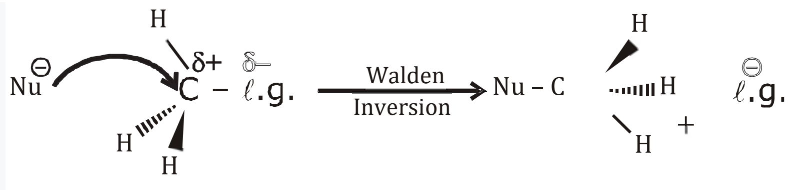
$\Delta G^{\ddagger}$ → The difference in free energy between the reactant and the transition state.

ΔG^{o} → The difference in free energy between the reactant and product.

Figure: A free energy diagrams for a hypothetical S_N2 reaction that takes place with a negative ΔG^{o}.

(5) No intermediates are formed in the S_N2 reaction, the reaction proceeds through the formation of an unstable arrangement of atoms or group called transition state.

(6) The stereochemistry of S_N2 reactions, as previously discussed, involves the nucleophile attacking from the rear side, which is the side directly opposite to the leaving group. This mode of attack results in an inversion of configuration at the carbon atom being targeted by the nucleophilic attack. This inversion is commonly referred to as Walden inversion.



(7) Factor's affecting the rate of S_N2 reaction → Number of factors affect the relative rate of S_N2 reaction, the most important factors are:

(i) Structure of the substrate
(ii) Concentration and reactivity of the nucleophile
(iii) Effect of the solvent
(iv) Nature of the leaving group

(i) Effect of the structure of the substrate

Order of reactivity in S_N2 reaction: $-CH_3 > 1^o > 2^o >> 3^o$ (unreactive)

The primary reason for this reactivity order is a steric influence. Extremely large and bulky groups can frequently impede the formation of the necessary transition state. This crowding effect increases the energy of the transition state and decelerates the reaction.

Table: Relative rates of reactions of alkyl halide in S_N2 reaction.

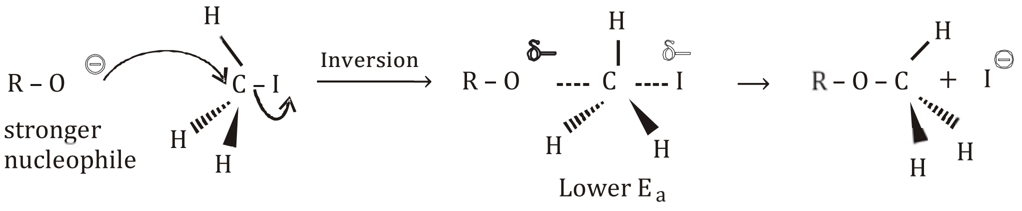
Substituent	Compound	Relative rate
Methyl	CH_3X	30
1°	$CH_3\,CH_2\,X$	1
2°	$(CH_3)_2\,CHX$	0.02
Neopentyl	$(CH_3)_3\,CCH_2X$	0.00001
3°	$(CH_3)_3\,CX$	~ 0

(ii) Concentration and reactivity of the nucleophile

In S_N2 kinetics, augmenting the nucleophile's concentration leads to a higher S_N2 reaction rate. The characteristics of the nucleophile significantly influence the reaction rate, with a more potent nucleophile demonstrating significantly greater effectiveness compared to a weaker one.

For example, we know that a negatively charged nucleophile is more reactive than its conjugate acid

e.g., $HO^{\ominus} > H_2O,\ RO^{\ominus} > ROH.$



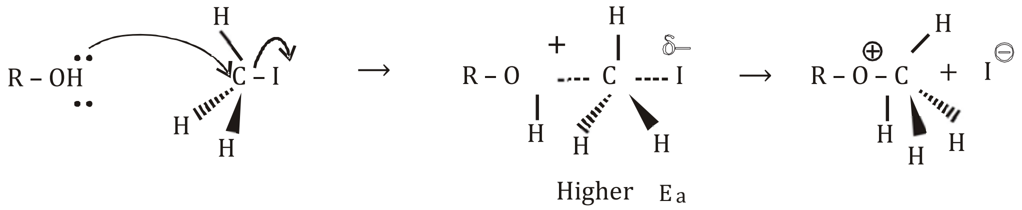
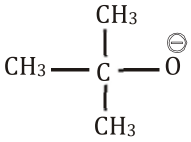


Table:

some common nucleophiles listed in decreasing order of nucleophilicity in hydroxylic solvent	
Strong nucleophiles $(CH_3CH_2)_3\ddot{P}$ $-\ddot{S}H^{\ominus}$ $I^{\ominus}$ $(CH_3-CH_2)_2\ddot{N}H$ $-CN^{\ominus}$ $(CH_3-CH_2)_2\ddot{N}$	Moderate nucleophile: $Br^{\ominus}$ $\ddot{N}H_3$ $(CH_3)_2\ddot{S}$ $Cl^{\ominus}$ $ACO^{\ominus}$ Weak nucleophile $F^{\ominus}$
$HO^{\ominus}$ $CH_3O^{\ominus}$	H_2O CH_3OH

Steric effects on nucleophilicity



$CH_3-\overset{CH_3}{\underset{CH_3}{C}}-O^{\ominus}$

t-butoxide
Stronger base, yet weaker
nucleophile cannot approach
the carbon atom so easily.

$CH_3-CH_2-O^{\ominus}$

ethoxide weaker base,
yet stronger nucleophile

(iii) Effect of the solvent

The solvent's influence: In polar protic solvents, sizable nucleophiles are effective, and the halide ions exhibit the following trend.

$$I^{\ominus} > Br^{\ominus} > Cl^{\ominus} > F^{\ominus}$$

(in polar protic solvent)

This phenomenon is connected to the intensity of the interaction between nucleophiles and solvent molecules in polar protic solvents, which form hydrogen bonds with nucleophiles in the subsequent fashion.

Because small nucleophile is solvated more by the polar protic solvent thus its nucleophilicity decreases and rate of SN^2 decreases.

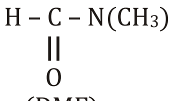
Relative nucleophilicity in polar protic solvent.

$$SH^{\ominus} > CN^{\ominus} > I^{\ominus} > OH^{\ominus} > N_3^{\ominus} > Br^{\ominus} > ACO^{\ominus} > Cl^{\ominus} > F^{\ominus} > H_2O$$

Hence, when the nucleophile is anionic, polar protic solvents are not conducive for $S_N{}^2$ reaction rates.

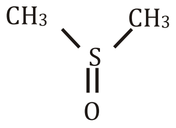
In contrast, polar aprotic solvents lack active hydrogen atoms, preventing them from forming hydrogen bonds with nucleophiles. Additionally, polar aprotic solvents have a congested positive center, leading to limited anion solvation. Consequently, $S_N{}^2$ reactions exhibit an increased rate when conducted in polar aprotic solvents.

Examples of polar aprotic solvent.



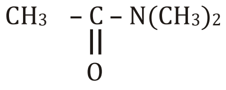
$H-\underset{O}{\underset{\|}{C}}-N(CH_3)$

(DMF)



$CH_3-\underset{O}{\underset{\|}{S}}-CH_3$

(DMSO)



$CH_3-\underset{O}{\underset{\|}{C}}-N(CH_3)_2$

(DMA)

In DMSO, the relative order of reactivity of halide ions is

$$F^{\ominus} > Cl^{\ominus} > Br^{\ominus} > I^{\ominus}$$

(iv) Nature of the leaving group

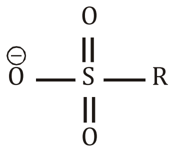
The characteristics of the leaving group: The most suitable leaving groups are those that transform into the most stable ion once they depart. Since leaving groups generally depart as negative ions, effective stabilization of the negative charge is a key factor. Weaker bases are particularly adept at achieving this, making them excellent leaving groups.

A proficient leaving group consistently stabilizes the transition state, reducing its free energy of activation and thus accelerating the reaction rate.

Order of leaving ability of halide ion

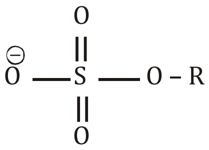
$$I^{\ominus} > Br^{\ominus} > Cl^{\ominus} > F^{\ominus}$$

Other leaving groups are



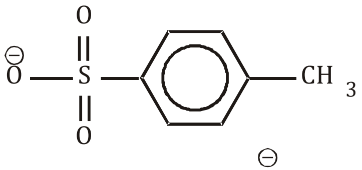
$\overset{\ominus}{O}-\underset{\underset{O}{\|}}{\overset{\overset{O}{\|}}{S}}-R$

Alkane sulphonate ion



$\overset{\ominus}{O}-\underset{\underset{O}{\|}}{\overset{\overset{O}{\|}}{S}}-O-R$

Alkyl sulphate ion



Tosylate ion ($\overset{\ominus}{OTs}$)

$CF_3SO_3^{\ominus}$

Triftlate ion

(a super leaving group)

Strongly basic ions rarely act as leaving group →

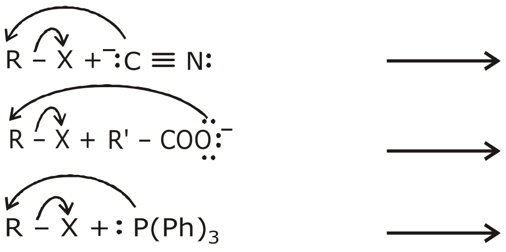
$$\overset{\ominus}{Br} + R - OH \not\longrightarrow R - X + \overset{\ominus}{OH} \quad \text{(strong base and bad lg)}$$

$$\overset{\ominus}{Nu} + CH_3 - CH_3 \not\longrightarrow CH_3 - Nu + \overset{\ominus}{CH_3} \quad (\overset{\ominus}{CH_3} \text{ is strong base})$$

Table: Examples of SN^2 reactions of alkyl halide →

$$\overset{\ominus}{\ddot{N}u} + CH_3 - X \xrightarrow{SN^2} \ddot{N}u - R + \overset{\ominus}{X} \quad (\overset{\ominus}{X} \text{ is not } \overset{\ominus}{F})$$

Nucleophile		**Product**	**Class of Product**
$R - X + {}^{-}:\ddot{I}:$	$\longrightarrow$	$R - \ddot{I}:$	Alkyl halide
$R - X + {}^{-}:\ddot{O}H$	$\longrightarrow$	$R - \ddot{O}H$	Alcohol
$R - X + {}^{-}:\ddot{O}R'$	$\longrightarrow$	$R - \ddot{O}R'$	Ether
$R - X + {}^{-}:\ddot{S}H$	$\longrightarrow$	$R - \ddot{S}H$	Thiol(mercaptan)
$R - X + {}^{-}:\ddot{S}R'$	$\longrightarrow$	$R - \ddot{S}R'$	Thioether (sulphide)
$R - X + :NH_3$	$\longrightarrow$	$R - :NH_3X^{-}$	Amine
$R - X + {}^{-}:\ddot{N} = \overset{+}{N} = \ddot{N}:^{-}$	$\longrightarrow$	$R - \ddot{N} = \overset{+}{N} = \ddot{N}:^{-}$	Azide
$R - X + {}^{-}:C \equiv C - R'$	$\longrightarrow$	$R - C \equiv C - R'$	Alkyne



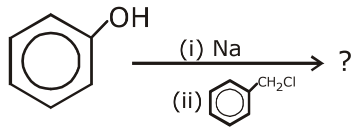
$R - C \equiv N:$ Nitrile

$R - COO - R$ Ester

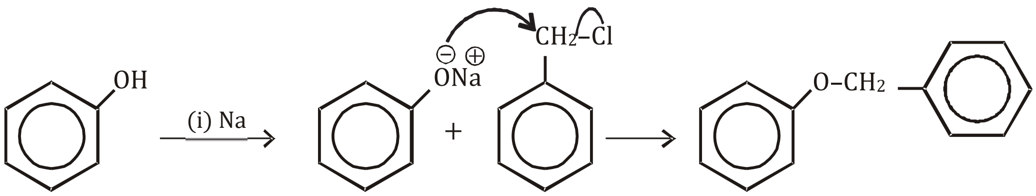
$[R - PPh_3]^+$ Posphonium salt

Ex. Complete the following reactions with mechanism

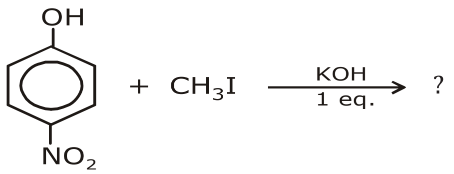
(a)



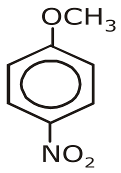
Sol.



(b)

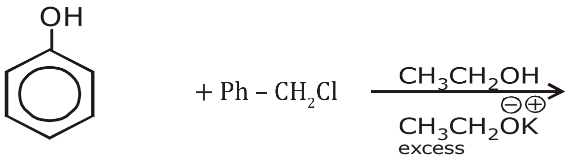


Sol.



(p-Nitro anisole)

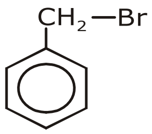
(C)



Sol. $CH_3-CH_2-O^{\ominus}$ is present in excess and it is stronger nucleophile than $Ph - O^{\ominus}$ so product is $Ph-CH_2 - OEt$

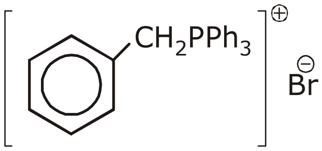
(d) $CH_3 - C \equiv CH \xrightarrow{Na} X \xrightarrow{CH_3 - CH_2 - I} Y$

Sol.



(e) $+ Ph_3\ddot{P} \rightarrow$ Salt

Sol.



Ex. When the concentration of alkyl halide is tripled and the concentration of OH^- ion is reduced to half, the rate of S_N2 reaction increases by:

(A) 3 times (B) 2 times (C) 1.5 times (D) 6 times

Ans. C

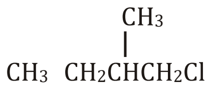
Ex. In the given reaction, $CH_3CH_2 - X + CH_3SNa \rightarrowtail$ The fastest reaction occurs when 'X' is:

(A) – OH (B) – F (C) – $OCOCF_3$ (D) $OCOCH_3$

Ans. C

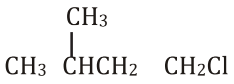
Ex. Correct decreasing order of reactivity towards S_N2 reaction

(I)



$CH_3\ CH_2\overset{CH_3}{\overset{|}{C}}HCH_2Cl$

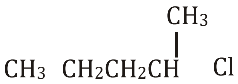
(II)



$CH_3\ \overset{CH_3}{\overset{|}{C}}HCH_2\ CH_2Cl$

(III) $CH_3CH_2CH_2CH_2Cl$

(IV)



$CH_3\ CH_2CH_2\overset{CH_3}{\overset{|}{C}H}\ Cl$

(A) IV > I > II > III (B) III > II > I > IV (C) IV > I > III > II (D) II > I > IV > III

Ans. B

(B) Unimolecular nucleophilic substitution reaction (S_N1)

$$(CH_3)_3C - Cl \ + \ \overset{\ominus}{OH} \xrightarrow[H_2O]{Acetone} (CH_3)_3C - OH\ +$$

Mechanism of S_N1 reaction

Step - 1 Formation of a carbocation (Rate determining step)

$$R - X \rightleftharpoons \overset{\oplus}{R} + \overset{\ominus}{X}$$

Step - 2 Nucleophilic attack on the carbocation (fast)

$$\overset{\oplus}{R} + Nu^{\ominus} \longrightarrow R - Nu$$

Characteristics of S_N1 reactions

1. It involves a two-step unimolecular process with the formation of an intermediate (carbocation).
2. The reaction follows a first-order kinetics.

3. Kinetics of the reaction

Rate $\propto$ [Alkyl halide]

Rate = $k[(CH_3)_3C{-}X]$

Rate of SN^1 reaction is independent of concentration and reactivity of nucleophile.

4. Energetics of the $S_N{}^1$

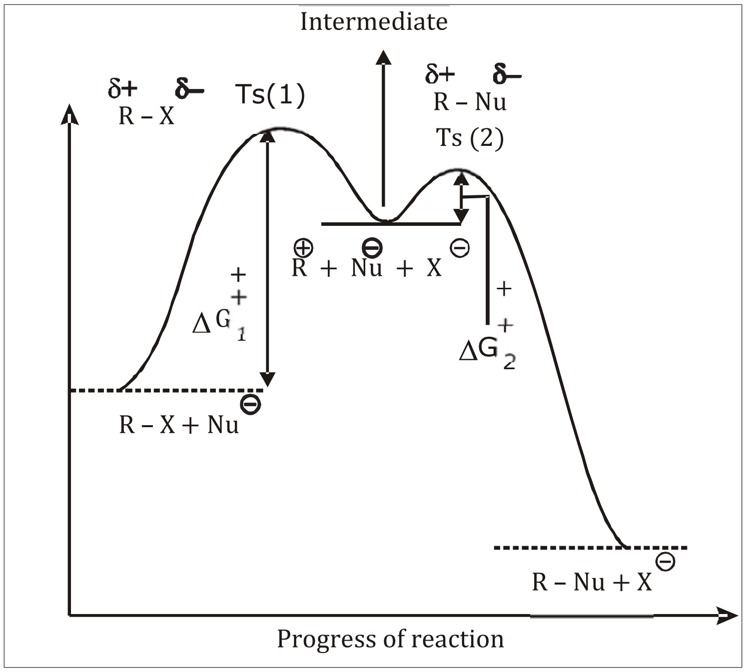


Figure: free energy diagram for the SN^1 reaction.

5 Factor's affecting the rates of $S_N{}^1$

(i) The structure of the substrate

In the $S_N{}^1$ reaction, the rate-determining step is the ionization step, which leads to the formation of a carbocation. This ionization is a highly endothermic process, and the rate of the $S_N{}^1$ reaction is significantly influenced by the stability of the carbocation. The carbocation, being the reaction's intermediate, ultimately determines the activation energy of the reaction.

$$S_N{}^1 \text{ reactivity: } 3^\circ > 2^\circ > 1^\circ > CH_3-X$$

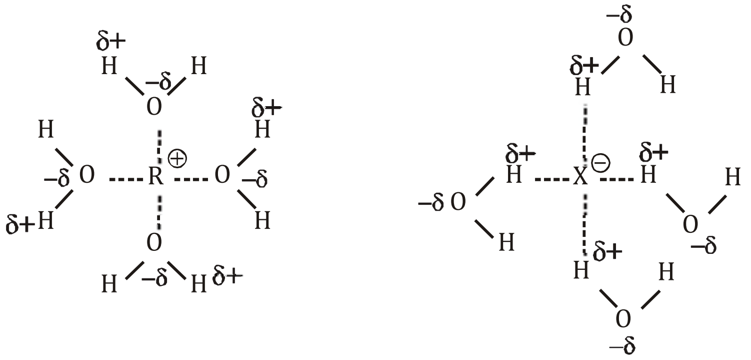
(ii) Concentration and reactivity of the nucleophile

The rate of $S_N{}^1$ reactions remains unaltered by both the concentration and the characteristics of the nucleophile.

(iii) Effect of the solvent $\rightarrowtail$ the ioizing ability of the solvent

The employment of a polar protic solvent significantly enhances the ionization rate of an alkyl halide in any $S_N{}^1$ reaction due to its efficient solvation of cations and anions. This effect arises from solvation, which stabilizes the transition state leading to the formation of the intermediate carbocation and halide ion more effectively than it does for the reactant. Consequently, this results in a lower activation energy.

$$R - X \quad \rightleftarrows \quad \overset{\oplus}{R} + \overset{\ominus}{X} \quad \text{(Solvolysis)}$$



Solvated ions

Table: Dielectric constants (∈) and ionization rates of t-Butyl chloride in common solvents

Solvent	∈	Relative rate
H_2O	80	8000
CH_3OH	33	1000
C_2H_5OH	24	200
$(CH_3)_2CO$	21	1
CH_3CO_2H	6	-

(iv) The nature of the leaving group

In the $S_N{}^1$ reaction, as the transition state is approached, the leaving group begins to acquire a negative charge. The stabilization of this emerging negative charge on the leaving group serves to stabilize the transition state, thus reducing the free energy of activation and subsequently enhancing the reaction rate.

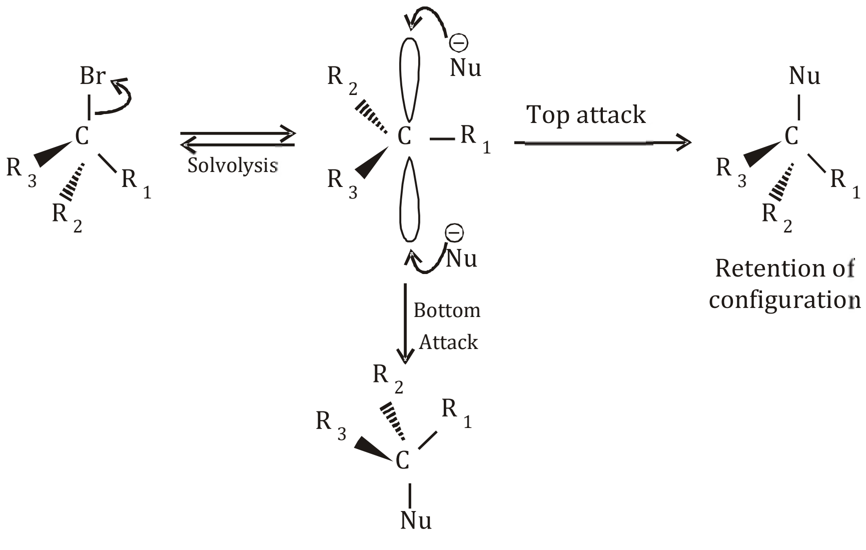
leaving ability of halogen is:

$$\overset{\ominus}{I} > \overset{\ominus}{Br} > \overset{\ominus}{Cl} >> \overset{\ominus}{F}$$

6. Stereochemistry of $S_N{}^1$ reactions

In the $S_N{}^1$ mechanism, the carbocation intermediate possesses $S_N{}^2$ hybridization and a planar geometry. A nucleophile has the ability to approach the carbocation from either side. If the reactant is chiral, nucleophilic attacks from both sides yield both enantiomers of the product, resulting in what is referred to as racemization.

Mechanism of racemization ($S_N{}^1$) →



Inversion of configuration

Chemical Properties of Haloarenes (Electrophilic substitution reaction)

Haloarenes, also known as aryl halides, are aromatic compounds containing one or more halogen atoms (fluorine, chlorine, bromine, or iodine) attached to an aromatic ring. Their chemical properties are significantly influenced by the presence of the halogen substituents, particularly in the context of electrophilic aromatic substitution (EAS) reactions. Here are the key chemical properties of haloarenes focusing on electrophilic substitution reactions:

Electrophilic Aromatic Substitution (EAS)

- Haloarenes are highly reactive towards EAS due to the electron-rich nature of the aromatic ring.
- The halogen substituent acts as an ortho/para-director, meaning it directs incoming electrophiles to the ortho and para positions relative to the halogen atom.
- The reaction proceeds through the formation of a sigma complex intermediate, followed by deprotonation to regenerate aromaticity.

Regioselectivity

- The regioselectivity of EAS in haloarenes is determined by the nature of the halogen substituent.
- Ortho and para positions are favored for substitution due to the stabilizing effect of resonance.
- Halogens are ortho/para directors due to their electron-withdrawing nature, which stabilizes the carbocation intermediate formed during the substitution process.

Reactivity Trends

- The reactivity of haloarenes in EAS reactions varies depending on the nature of the halogen atom and its position on the aromatic ring.
- Generally, halogens with higher electronegativity (e.g., fluorine and chlorine) are more activating toward EAS than those with lower electronegativity (e.g., bromine and iodine).
- Electron-donating substituents on the aromatic ring increase the rate of EAS, while electron-withdrawing substituents decrease reactivity.

Halogenation

- Haloarenes can undergo halogenation reactions, where a halogen atom replaces a hydrogen atom on the aromatic ring.
- Halogenation of haloarenes typically requires more reactive halogens (e.g., bromine or chlorine) and a Lewis acid catalyst such as iron (III) chloride.

Functional Group Compatibility

- Some functional groups on the aromatic ring may affect the reactivity or regioselectivity of EAS in haloarenes.
- Electron-donating groups enhance the reactivity of the aromatic ring towards electrophiles, while electron-withdrawing groups decrease reactivity.