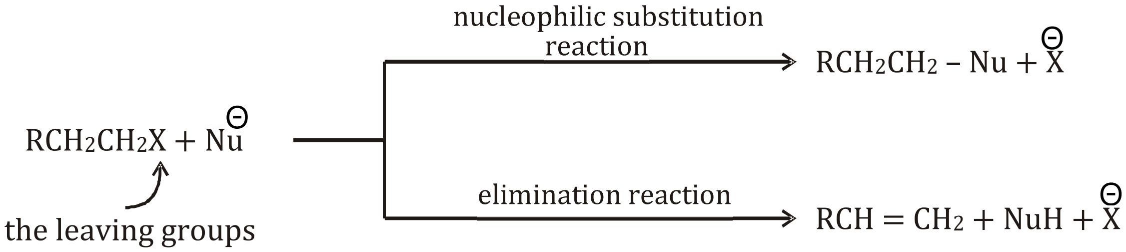
HALOALKANES AND HALOARENES

CHEMICAL PROPERTIES OF HALOALKANES

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.



$$RCH_2CH_2X + \overset{\ominus}{Nu} \xrightarrow{\text{nucleophilic substitution reaction}} RCH_2CH_2 - Nu + \overset{\ominus}{X}$$

$$RCH_2CH_2X + \overset{\ominus}{Nu} \xrightarrow{\text{elimination reaction}} RCH = CH_2 + NuH + \overset{\ominus}{X}$$

the leaving groups

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.

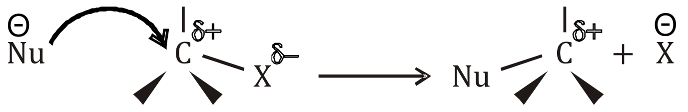
$$\overset{8+}{RCH_2} - \overset{8-}{X}$$

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.

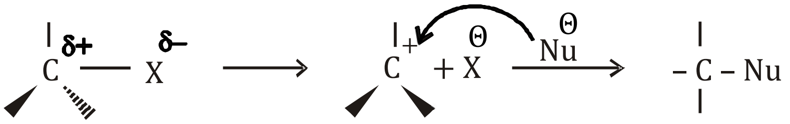
There are two important mechanisms for the substitution reaction

(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.



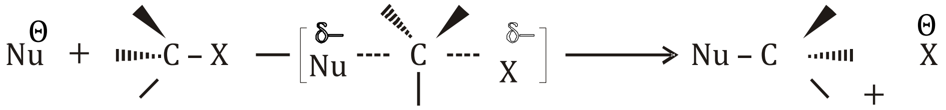
(2) The carbon-halogen bond undergoes heterolytic cleavage independently, aided by a polar protic solvent, resulting in the formation of a carbocation (solvolysis).
The produced carbocation subsequently reacts with the nucleophile to generate

the substitution product.



(A) **Bimolecular nucleophilic substitution reaction (S_N2)**

The mechanism of S_N2 reaction



transition state

Characteristic of S_N2

(1) It is bimolecular, unistep process

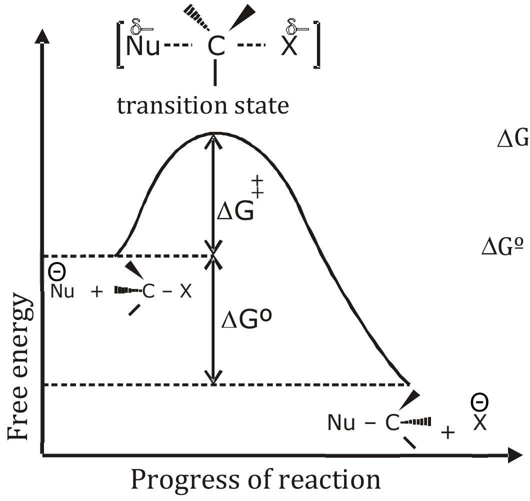
(2) It is second order reaction because in the Rds two species are involved

(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 →



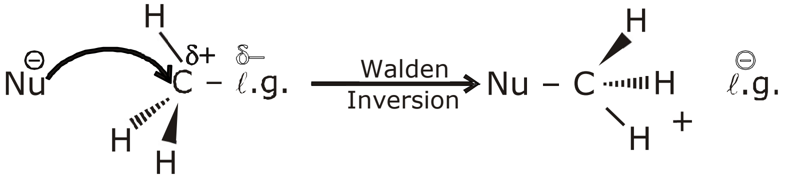
$\Delta G^\ddagger$ → The difference in free energy the reactant and the transition state.

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: – $CH_3 > 1^\circ > 2^\circ >> 3^\circ$ (unreactive)

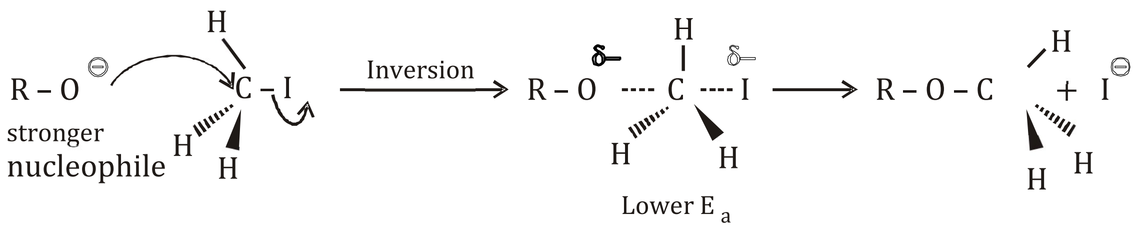
The primary reason for this reactivity order is a steric influence. Extremely large and bulky groups can frequently impede the formation of the necessary transition state. This crowding effect increases the energy of the transition state and decelerates the reaction.

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

Substituent	Compound	Relative rate
Methyl	CH_3X	30
1°	CH_3CH_2X	1
2°	$(CH_3)_2CHX$	0.02
Neopentyl	$(CH_3)_3CCH_2X$	0.00001
3°	$(CH_3)_3CX$	~ 0

(ii) 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., $HO^{\ominus} > H_2O$, $RO^{\ominus} > ROH$.



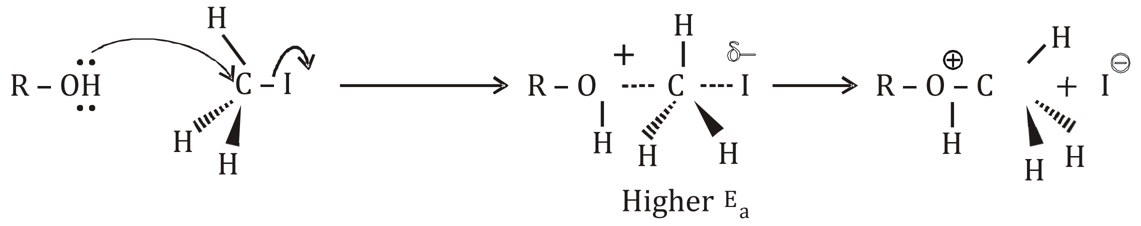
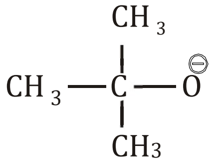


Table:

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

Steric effects on nucleophilicity



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

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

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

ethoxide weaker base, yet stronger nucleophile

(iii) 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.

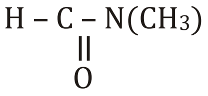
Because small nucleophile is solvated more by the polar protic solvent thus its nucleophilicity decreases and rate of SN^2 decreases.

Relative nucleophilicity in polar protic solvent.

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

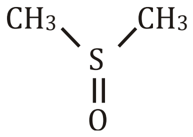
Hence, when the nucleophile is anionic, polar protic solvents are not conducive for S_N^2 reaction rates. In contrast, polar aprotic solvents lack active hydrogen atoms, preventing them from forming hydrogen bonds with nucleophiles. Additionally, polar aprotic solvents have a congested positive center, 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.



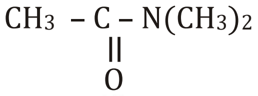
$H-\underset{\underset{O}{\|}}{C}-N(CH_3)$

(DMF)



$\overset{CH_3 \quad CH_3}{\underset{\underset{O}{\|}}{S}}$

(DMSO)



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

(DMA)

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

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

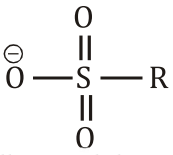
(iv) The characteristics of the leaving group: The most suitable leaving groups are those that transform into the most stable ion once they depart. Since leaving groups generally depart as negative ions, effective stabilization of the negative charge is a key factor. Weaker bases are particularly adept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

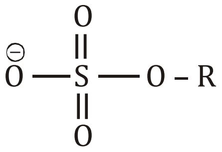
$$I^{\ominus} > Br^{\ominus} > Cl^{\ominus} > F^{\ominus}$$

Other leaving groups are



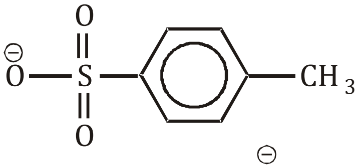
$\overset{\ominus}{O}-\overset{\overset{O}{\|}}{\underset{\underset{O}{\|}}{S}}-R$

Alkane sulphonate ion



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

Alkyl sulphate ion

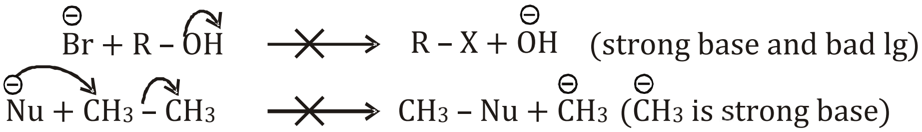


Tosylate ion ($\overset{\ominus}{OTs}$)

$CF_3\overset{\ominus}{SO_3}$

Triftlate ion
(a super leaving group)

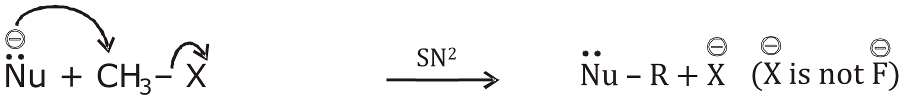
Strongly basic ions rarely act as leaving group →



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

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

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



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

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

Azide

Alkyne

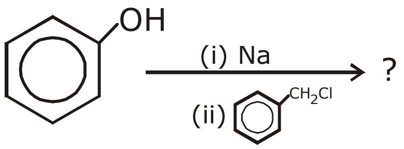
Nitrile

Ester

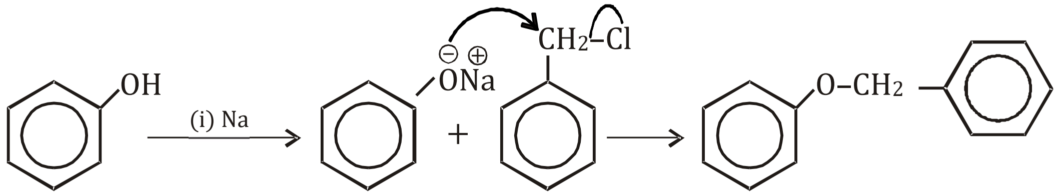
Posphonium salt

Ex. Complete the following reactions with mechanism

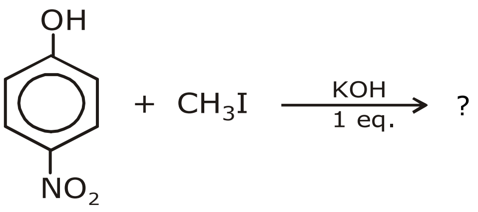
(a)



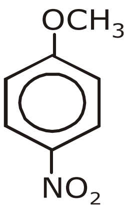
Sol.



(b)

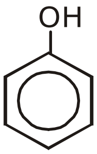


Sol.



(p-Nitro anisole)

(C)

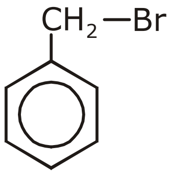


$+ Ph-CH_2Cl \xrightarrow[\overset{\ominus\oplus}{CH_3CH_2OK}\ \text{excess}]{CH_3CH_2OH}$

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

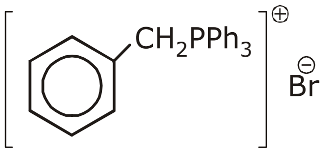
(d) $CH_3 - C \equiv CH \xrightarrow{Na} X \xrightarrow{CH_3 - CH_2 - I} Y$

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

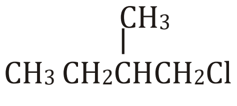
Ans. C

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

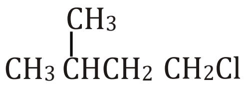
(A) – OH (B) – F (C) – $OCOCF_3$ (D) $OCOCH_3$

Ans. C

Ex. Correct decreasing order of reactivity towards S_N2 reaction

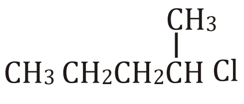
(I)


$CH_3CH_2\overset{CH_3}{\overset{|}{C}}HCH_2Cl$

(II)


$CH_3\overset{CH_3}{\overset{|}{C}}HCH_2CH_2Cl$

(III) $CH_3CH_2CH_2CH_2Cl$

(IV)


$CH_3CH_2CH_2\overset{CH_3}{\overset{|}{C}}H\,Cl$

(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)

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

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_N1

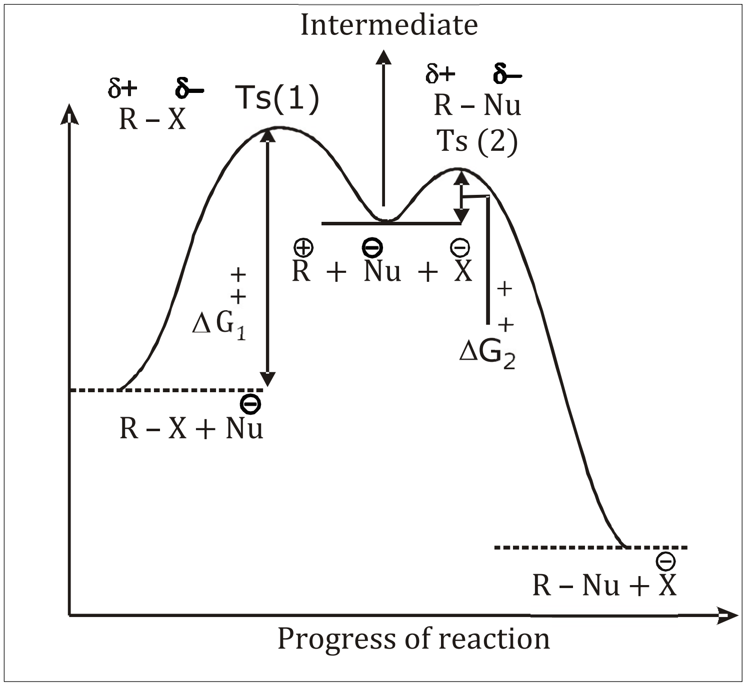


Figure: free energy diagram for the SN^1 reaction.

5 Factor's affecting the rates of S_N1

(i) The structure of the substrate

In the S_N1 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_N1 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.

$$S_N1 \text{ reactivity: } 3^\circ > 2^\circ > 1^\circ > CH_3 - X$$

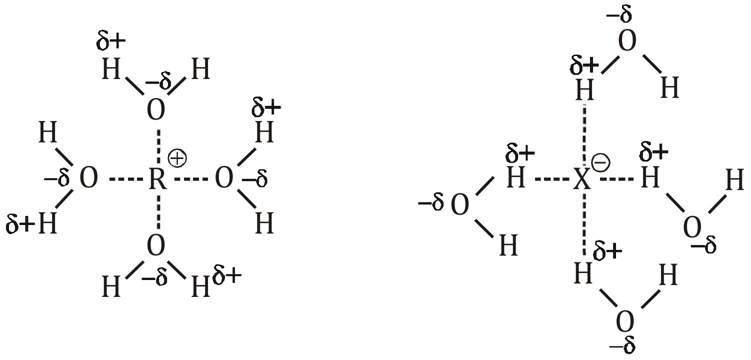
(ii) Concentration and reactivity of the nucleophile

The rate of S_N1 reactions remains unaltered by both the concentration and the characteristics of the nucleophile.

(iii) Effect of the solvent ↣ 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_N1 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.

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



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_N1 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_N1 reactions

In the S_N1 mechanism, the carbocation intermediate possesses S_N2 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_N1) →