MATS UNIVERSITY

NAAC GRADE A+ ACCREDITED UNIVERSITY

MATS CENTRE FOR OPEN & DISTANCE EDUCATION

Organic Chemistry I

Master of Science
Semester - 1

SELF LEARNING MATERIAL

SELF LEARNING MATERIAL

ORGANIC CHEMISTRY 01

CONTENT

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MODULE INTRODUCTION

Course has five modules. Under this theme we have covered the following topics:

S.No	Module No	Unit No
1	**Module No**	**NATURE OF BONDING IN ORGANIC MOLECULES**
	Unit 1.1	Delocalized chemical bonding
	Unit 1.2	Aromaticity
2	**Module 02**	**STRUCTURE, REACTIVITY AND INTERMEDIATES**
	Unit 2.1	Fundamental Principles of Molecular Structure and Reactivity
	Unit 2.2	Stability of Reaction Intermediates and Their Impact on Reaction Pathways
	Unit 2.3	Effect of Structural features on Charge-Associated Reactivity
3	**Module 03**	**REACTION MECHANISM**
	Unit 3.1	Introduction to Reaction Mechanism Fundamentals
	Unit 3.2	General Statement of the Postulate in Reaction Mechanisms
	Unit 3.3	Strength and Type of Nucleophile
4	**Module 04**	**ALIPHATIC ELECTROPHILIC SUBSTITUTIONS**
	Unit 4.1	Bimolecular mechanism SE1 & SE2
	Unit 4.2	Regeneration of Aromaticity
	Unit 4.3	Quantitative treatment of reactivity in substrates and electrophiles
5	**Module 05**	**STEREOCHEMISTRY**
	Unit 5.1	Isomerism
	Unit 5.2	Priority Rule and nomenclature for Isomers
	Unit 5.3	Optical activity

These themes of the Book discuss about the nature of bonding in organic molecules, focusing on carbon's ability to form four covalent bonds, which shapes molecular structures and determines stability and reactivity and also highlights how molecular structure, driven by functional groups, governs reactivity through concepts explains reaction mechanisms, another chapters detailing step-by-step transformations involving electron movement and bond changes and focusing on stereoisomerism, which significantly impacts molecular reactivity, especially in drug design. We suggest you do all the activities in the CHAPTERs, even those which you find relatively easy. This will reinforce your earlier learning.

MODULE NO 1

NATURE OF BONDING IN ORGANIC MOLECULES

Unit 1.1

Delocalized Chemical Bonding

1.1.1 Definition:

Delocalized chemical bonding occurs when electrons are not confined between two atoms (as in a localized bond), but are spread over three or more atoms. These electrons are shared by all atoms in a molecule or ion, forming a **resonance structure** or **electron cloud**.

1.1.2Key Features:

- Found in molecules with **conjugated π-systems** (alternating single and double bonds).
- Involves **π-electrons** that can move freely across multiple atoms.
- Enhances **stability** of the molecule (resonance stabilization).
- Common in **benzene**, **carboxylate ions**, and **polyatomic ions** like nitrate.

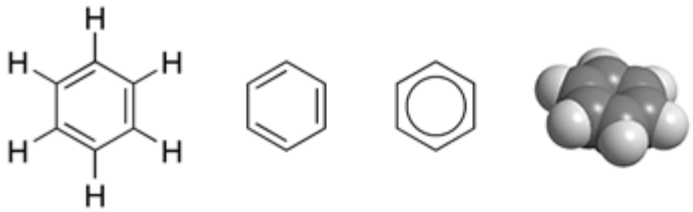


Diagram: Delocalized Bonding in Benzene (C_6H_6)

- All C–C bond lengths are equal.
- The circle represents delocalized π-electrons.

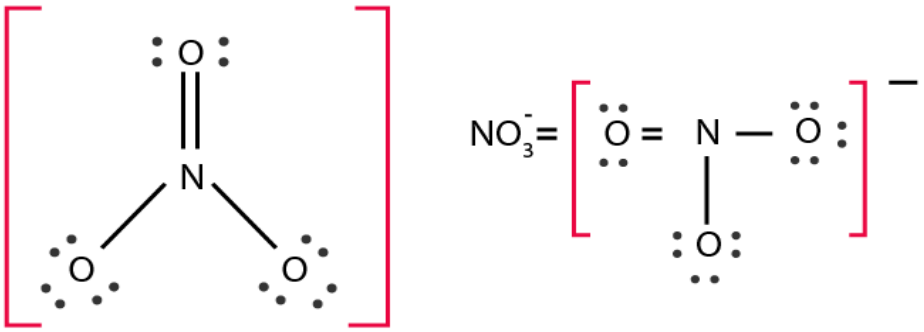
Example: Benzene (C_6H_6)

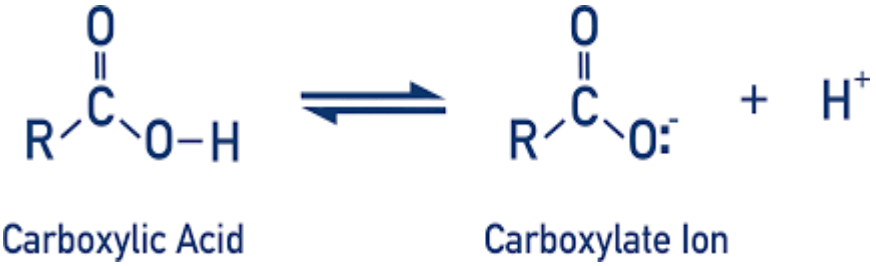
- **Structure:** Alternating single and double bonds.
- **Reality:** All six carbon-carbon bonds are **identical** in length and strength due to **electron delocalization**.

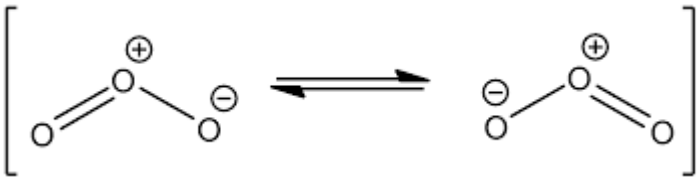
- **Stability:** Benzene is more stable than expected for a compound with three double bonds because of **resonance energy**.

Other Examples:

- **Nitrate ion (NO_3^-)**
- **Carboxylate group (COO^-)**
- **Ozone (O_3)**







Resonated Structure of Ozone

1.1.3 Summary:

Delocalized chemical bonding occurs when electrons, usually π electrons, are spread over three or more atoms instead of being confined between two

atoms. It is represented by resonance structures and gives rise to equal bond lengths, extra stability (resonance energy), and aromaticity in cyclic systems. Examples include benzene, carbonate (CO_3^{2-}), and nitrate (NO_3^-).

Multiple Choice Questions

Q.1.Which of the following best describes delocalized bonding?

a) Electrons confined between two specific atoms

b) Electrons shared equally between only two atoms

c) Electrons spread over three or more atoms

d) Electrons completely transferred to another atom

Answer: c) Electrons spread over three or more atoms

Q.2.The resonance stabilization in benzene is due to:

a) Localized π bonds

b) Delocalized π electrons over six carbon atoms

c) Hydrogen bonding

d) σ bond conjugation

Answer: b) Delocalized π electrons over six carbon atoms

Q.3.Which of the following is an example of delocalized bonding?

a) HF molecule

b) Ethene (C=C)

c) Benzene (C_6H_6)

d) Methane (CH_4)

Answer: c) Benzene (C_6H_6)

Q.4.Delocalized electrons are usually represented using:

a) Lewis dot structure

b) Resonance structures

c) Ionic structures

d) Crystal field theory

Answer: b) Resonance structures

Q.5.Which type of orbitals mainly contribute to delocalized π bonding in aromatic compounds?

a) s-orbitals

b) p-orbitals

c) d-orbitals

d) f-orbitals

Answer: b) p-orbitals

Very Short Questions

1. Define delocalized chemical bonding.
2. Give one example of a compound with delocalized π electrons.
3. What is resonance energy?
4. Why is benzene more stable than expected from localized bonding?
5. Which orbitals overlap to form delocalized π bonds?

Long Questions

1. Discuss the concept of delocalized bonding in benzene. Explain with resonance structures and molecular orbital theory.
2. Explain the delocalized bonding in polyatomic ions such as nitrate (NO_3^-) and carbonate (CO_3^{2-}). Why are their bond lengths equal?
3. Describe the concept of resonance. How does resonance stabilization arise from delocalization of electrons?
4. Explain the differences in stability, bond length, and reactivity between localized double bonds and delocalized π bonds using suitable examples.
5. Discuss delocalized bonding in aromatic systems. Explain Huckel's rule of aromaticity with examples.

Unit 1.2

Aromaticity

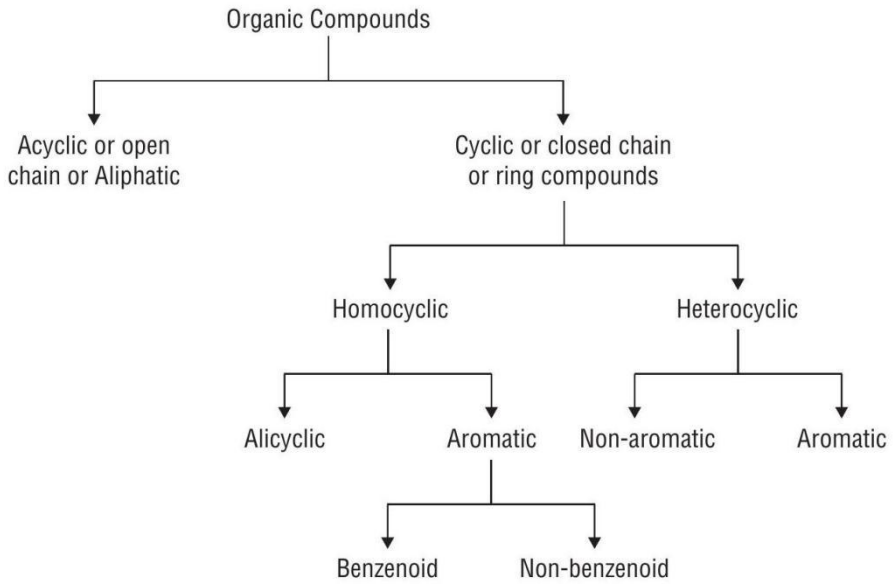
1.2.1Definition:

Aromaticity is a property of certain cyclic molecules with **delocalized π-electrons** that leads to **exceptional stability**. These molecules are called **aromatic compounds**.

1.2.2Conditions for Aromaticity (Hückel's Rule):

A compound is aromatic if it satisfies the following:

1. **Cyclic** – The molecule must form a ring.
2. **Planar** – All atoms in the ring must lie in the same plane.
3. **Conjugated** – Must have alternating single and double bonds (or lone pairs), allowing continuous overlap of p-orbitals.
4. **(4n + 2) π-electrons** – Must have **a specific number of delocalized π-electrons** (where *n* is an integer: 0, 1, 2, …).
   This is known as **Hückel's Rule**.



Example: Benzene (C_6H_6)

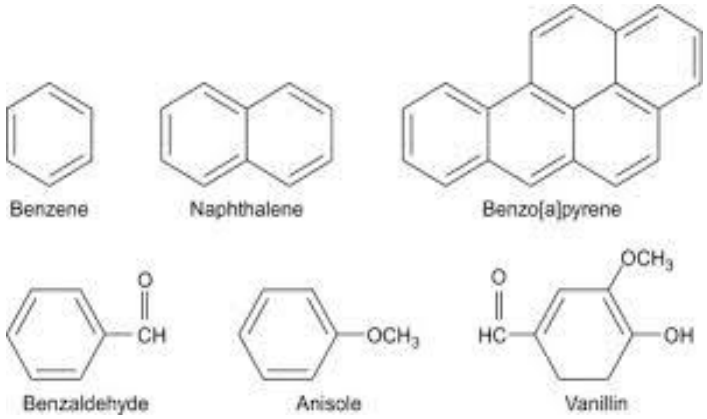
- **Structure:** A 6-membered ring with alternating double bonds.

- **π-Electrons:** 6 (n = 1; 4n+2 = 6)
- **Properties:**
    - All bond lengths are equal.
    - Highly stable.
    - Undergoes substitution rather than addition.

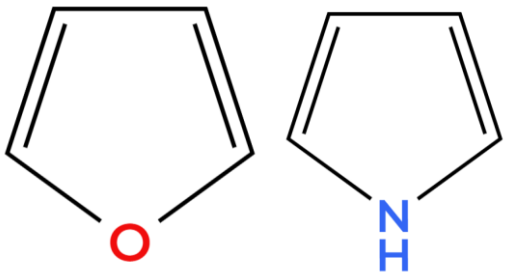
1.2.3Types of Compounds Based on Aromaticity:

1. **Aromatic** – Follows all 4 conditions (e.g., benzene, naphthalene).
2. **Anti-aromatic** – Follows all conditions except it has **4n π-electrons** (e.g., cyclobutadiene).
3. **Non-aromatic** – Does not meet one or more of the required conditions (e.g., cyclohexane).

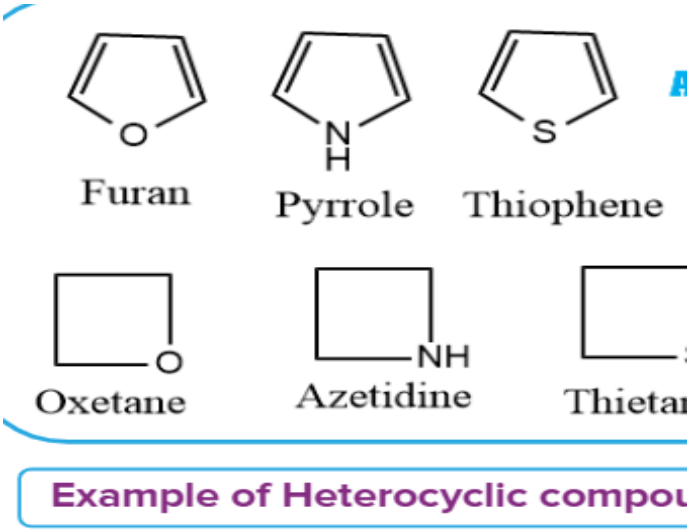
Structure of some aromatic compounds



Structure of some anti aromatic compounds



Structure of some non aromatic compounds



1.2.4 Importance of Aromaticity:

- Affects **chemical reactivity** and **stability**.
- Found in many biologically important molecules like **DNA bases**, **chlorophyll**, and **drugs**.

1.2.5 Summary

Organic molecules are primarily composed of carbon and hydrogen, often with oxygen, nitrogen, sulfur, and halogens. The nature of bonding in these molecules is governed by covalent bonding, where atoms share electrons to achieve stable electronic configurations.

1. Covalent Bonding:
Carbon atoms form four covalent bonds to satisfy the octet rule. These bonds may be:

Single bonds (σ bonds): formed by head-on overlap of orbitals (e.g., C–C, C–H).

Double bonds (σ + π bonds): one sigma and one pi bond (e.g., C=C).

Triple bonds (σ + 2π bonds): one sigma and two pi bonds (e.g., C≡C).

2. Hybridization:
To explain molecular shapes, carbon undergoes hybridization:

sp^3 (tetrahedral, 109.5°): seen in alkanes (e.g., methane).

sp^2 (trigonal planar, 120°): in alkenes (e.g., ethene).

sp (linear, 180°): in alkynes (e.g., ethyne).

3. Bond Polarity and Electronegativity:
Differences in electronegativity between atoms lead to polar covalent bonds (e.g., C–O, C–Cl), influencing physical properties and reactivity.

4. Resonance:
Some molecules are best represented by multiple resonance structures (e.g., benzene), which delocalize electrons across atoms, stabilizing the molecule.

5. Aromaticity:
Aromatic compounds like benzene exhibit delocalized π-electrons in a cyclic, planar structure that obeys Hückel's rule (4n+2 π electrons).

6. Non-covalent Interactions:
Weak interactions like hydrogen bonding, van der Waals forces, and dipole-dipole interactions play crucial roles in molecular structure, solubility, and biological activity.

Multiple-choice questions

1. What type of bond is primarily responsible for holding atoms together in organic molecules?

A. Ionic bond
B. Metallic bond
C. Covalent bond
D. Hydrogen bond

Answer: C. Covalent bond

2. What is the hybridization of carbon in methane (CH_4)?

A. sp
B. sp^2
C. sp^3
D. dsp^2

Answer: C. sp^3

3. In ethyne (C_2H_2), what type of bonds are present between the two carbon atoms?

A. One sigma bond only
B. One sigma and one pi bond
C. One sigma and two pi bonds
D. Three sigma bonds

Answer: C. One sigma and two pi bonds

4. Which of the following best describes the geometry of carbon in ethene (C_2H_4)?

A. Linear
B. Tetrahedral
C. Trigonal planar
D. Octahedral

Answer: C. Trigonal planar

5. Which concept explains the existence of multiple valid Lewis structures for a molecule like benzene?

A. Resonance
B. Isomerism
C. Tautomerism
D. Polymerization

Answer: A. Resonance

6. What rule must be satisfied for a molecule to be considered aromatic?

A. 2n+1 rule
B. Lewis rule
C. VSEPR rule
D. Hückel's rule (4n + 2 π electrons)

Answer: D. Hückel's rule (4n + 2 π electrons)

7. Which type of hybridization involves one s and two p orbitals?

A. sp
B. sp^2
C. sp^3
D. sp^3d

Answer: B. sp^2

8. Which of the following bonds is the strongest in organic compounds?

A. C–C (single bond)
B. C=C (double bond)
C. C≡C (triple bond)
D. C–H bond

Answer: C. C≡C (triple bond)

9. Which of the following is a non-covalent interaction?

A. C–C bond
B. Hydrogen bonding
C. C=O bond
D. C≡C bond

Answer: B. Hydrogen bonding

10. Which molecule contains delocalized π electrons?

A. Ethane
B. Ethene
C. Ethyne
D. Benzene

Answer: D. Benzene

Short questions

1. What is aromaticity in chemistry?
2. State Hückel's rule for aromatic compounds.
3. Is benzene aromatic? Why?
4. What is the hybridization of carbon atoms in aromatic compounds?
5. Give one example of an antiaromatic compound.
6. Why is cyclobutadiene not aromatic?
7. How many π-electrons are present in benzene?
8. What is the difference between aromatic and antiaromatic compounds?
9. Is cyclohexane aromatic? Why or why not?
10. What conditions must a compound meet to be aromatic?

Module 02

STRUCTURE, REACTIVITY AND INTERMEDIATES

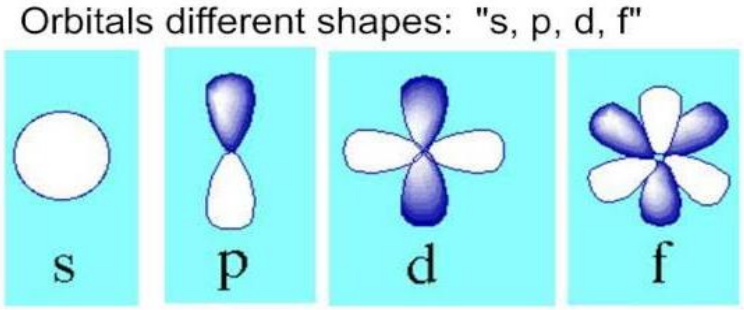
Unit 2.1

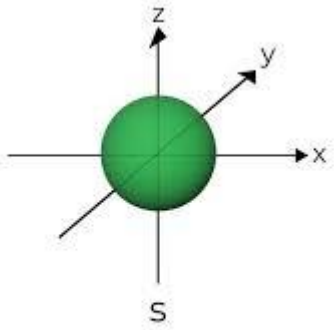
Fundamental Principles of Molecular Structure and Reactivity

2.1.1 Atomic and Molecular Structure

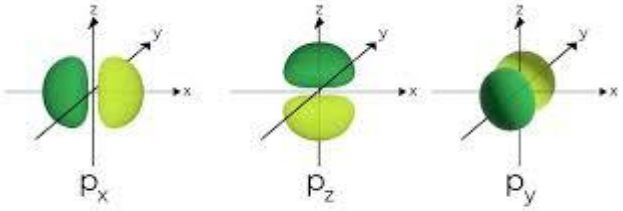
● Atomic Orbitals:

- Atoms have orbitals (s, p, d, f) where electrons reside.
- Chemical bonding involves the interaction of atomic orbitals.

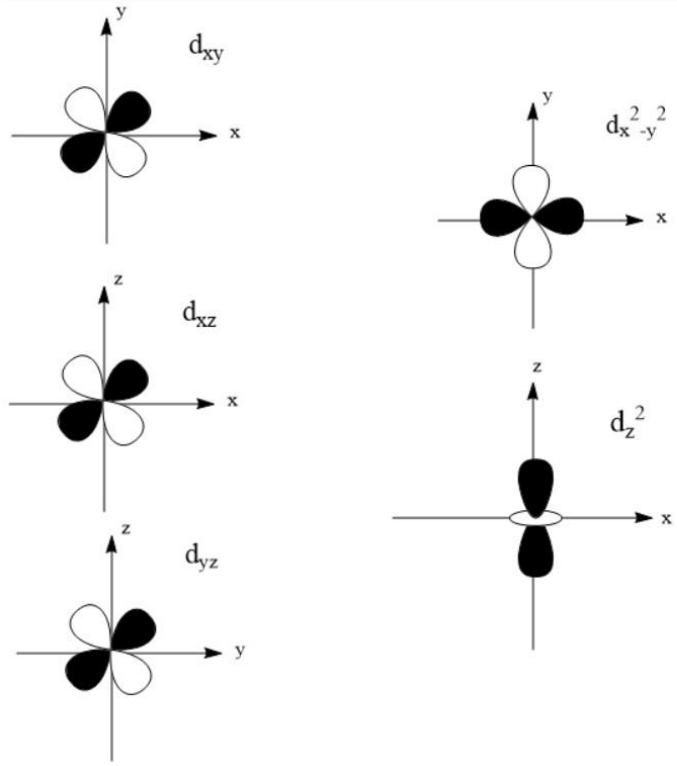




Shape of s-orbital



Shape of p-orbital



Shape of d-orbitals

2.1.2 Reaction Intermediates

2.1.2.1 Definition:

A **reaction intermediate** is a short-lived, unstable species that is formed during a **chemical reaction** but does **not appear in the final products**. It exists **between the steps** of a multi-step reaction mechanism.

2.1.2.2 Characteristics:

- Highly **reactive** and **short-lived**.
- Not isolated easily (but can sometimes be detected).
- Lies in a **valley** between two transition states on the energy profile diagram.
- Essential for understanding **reaction mechanisms**.

2.1.3 Common Types of Intermediates:

1. **Carbocations (R^+):** Positively charged carbon atoms
    - e.g., CH_3^+
2. **Carbanions (R^-):** Negatively charged carbon atoms
    - e.g., CH_3^-

3. **Free Radicals (R•):** Neutral species with an unpaired electron
    - e.g., Cl•
4. **Carbenes (R–C–R') :** Neutral species with two bonds and a lone pair
    - e.g., CH_2
5. **Nitrenes (R–N):** Like carbenes, but with nitrogen

2.1.4 Importance:

- Help explain **how reactions proceed**.
- Useful in predicting **reaction rates**, **products**, and **selectivity**.
- Understanding them aids in designing **better catalysts** and **synthetic pathways**.

2.1.5 SUMMARY: Molecular structure is governed by bonding theories (valence bond, molecular orbital), hybridization, resonance, and intermolecular forces, which together determine geometry, polarity, and stability. Reactivity depends on electronic distribution, functional groups, bond strengths, steric effects, and reaction energetics (thermodynamics and kinetics). These principles explain why molecules adopt certain shapes, how they interact, and how they undergo chemical transformations.

Multiple Choice Questions (with answers)

Q.1.Which theory explains molecular geometry based on electron pair repulsions?

a) Valence Bond Theory

b) VSEPR Theory

c) Crystal Field Theory

d) Molecular Orbital Theory

Answer: b) VSEPR Theory

Q.2.Resonance in molecules leads to:

a) Higher reactivity

b) Equal bond lengths and stabilization

c) Ionic bonding

d) Orbital hybridization

Answer: b) Equal bond lengths and stabilization

Q.3.Which factor primarily governs reaction rate?

a) Thermodynamic stability

b) Kinetic barrier (activation energy)

c) Bond polarity alone

d) Steric hindrance only

Answer: b) Kinetic barrier (activation energy)

Q.4.Hybridization of carbon in methane (CH_4) is:

a) sp

b) sp^2

c) sp^3

d) dsp^2

Answer: c) sp^3

Q.5.Which of the following is NOT an intermolecular force?

a) London dispersion forces

b) Dipole–dipole interactions

c) Covalent bonding

d) Hydrogen bonding

Answer: c) Covalent bonding

Short Questions

Q.1. Define molecular orbital theory and its significance in bonding.

Q.2.What is the difference between thermodynamic and kinetic control of reactions?

Q.3. Explain the concept of bond polarity with an example.

Q.4.Why is resonance important in understanding molecular stability?

Q.5.What role does hybridization play in determining molecular geometry?

Long Questions

Q.1. Discuss the fundamental theories of bonding (VBT, MOT, and VSEPR) and their applications in predicting molecular structure.

Q.2. Explain how electronic, steric, and energetic factors influence chemical reactivity with suitable examples.

Q.3. Describe thermodynamics and kinetics as controlling factors of chemical reactions. Give examples of thermodynamically vs. kinetically controlled reactions.

Q.4. Analyze the role of intermolecular forces in determining physical properties such as boiling point, solubility, and reactivity.

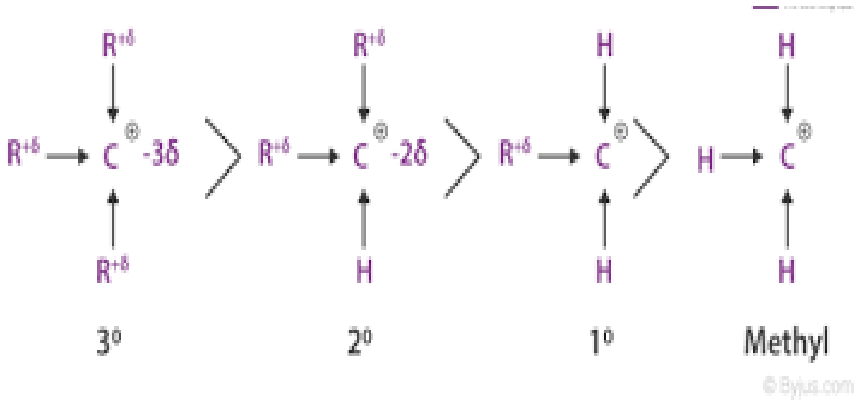
Q.5. Discuss the relationship between molecular structure, resonance, and reactivity in conjugated organic systems.

Unit 2.2

Stability of Reaction Intermediates and Their Impact on Reaction Pathways

2.2.1. Carbocation (R^+)

Structure:



R

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R–C⁺–R ← positively charged carbon (3 bonds, no lone pair)

Example:
In SN1 reaction:

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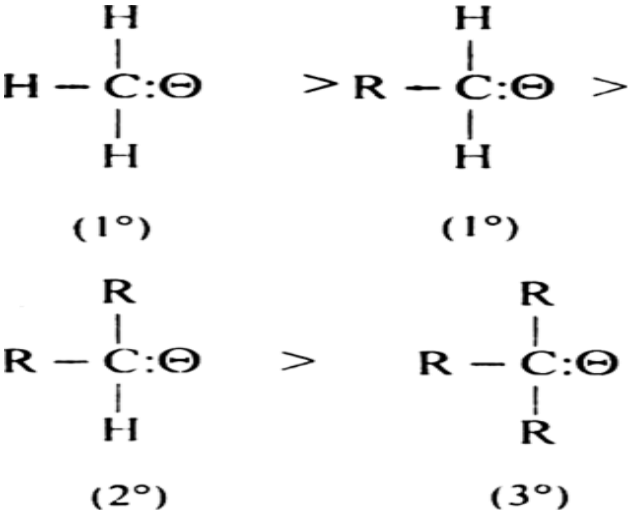
$CH_3–CH_2–Br \rightarrow CH_3–CH_2^+ + Br^-$

The ethyl carbocation ($CH_3–CH_2^+$) is the intermediate.

Stability order:
Tertiary > Secondary > Primary > Methyl
($3° > 2° > 1° > CH_3^+$)

2.2.2. Carbanion (R^-)

Structure:



R

|

R–C:⁻ ← negatively charged carbon with lone pair

Example:
In aldol reaction:

$CH_3–CHO + OH^- \rightarrow CH_2^-–CHO + H_2O$

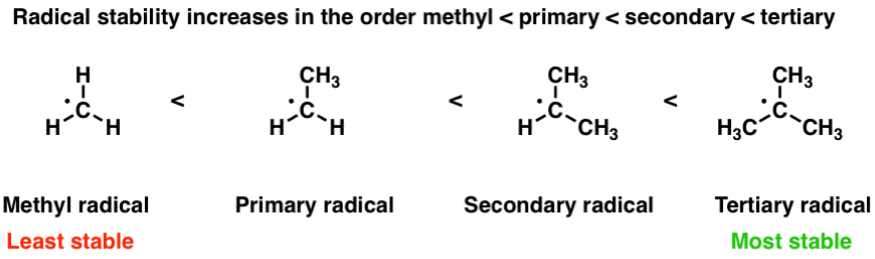
The $CH_2^-–CHO$ is a carbanion intermediate.

Stability order:
Methyl > Primary > Secondary > Tertiary
(Opposite to carbocation due to steric hindrance and electron repulsion)

Carbanion	Carbocation
Carbanions are reaction intermediates that have carbon atoms containing eight electrons and have a negative charge.	Carbocations are reaction intermediates that have carbon atoms containing six electrons and have a positive charge.
It is sp^3 hybridized.	It is sp^2 hybridized.
The geometry of the carbon atom is pyramidal	The geometry of carbon atom is trigonal planar
Shows diamagnetic behaviour due to complete electron pairing.	Shows paramagnetic behaviour due to incomplete electron pairing.
Acts as nucleophile	Acts as electrophile
Stability order: Methyl carbanion > primary carbanion > secondary carbanion > tertiary carbanion	Stability order: Methyl carbocation < primary carbocation < secondary carbocation < tertiary carbocation

2.2. 3. Free Radical (R•)

Structure:



R

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R–C ← neutral carbon with one unpaired electron

Example:
In halogenation of alkanes (initiation step):

nginx

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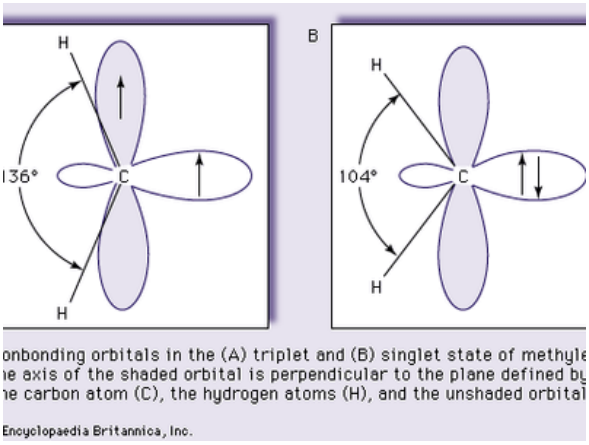
Cl2 → 2Cl•

Chlorine radical (Cl•) initiates chain reactions.

2.2.3.1Stability order:
Tertiary > Secondary > Primary > Methyl
(3° > 2° > 1° > CH3)

2.2.4. Carbene (:C:)

Structure:



onbonding orbitals in the (A) triplet and (B) singlet state of methyle
ie axis of the shaded orbital is perpendicular to the plane defined by
ne carbon atom (C), the hydrogen atoms (H), and the unshaded orbital
Encyclopaedia Britannica, Inc.

:CH2 ← neutral carbon with two bonds and a lone pair

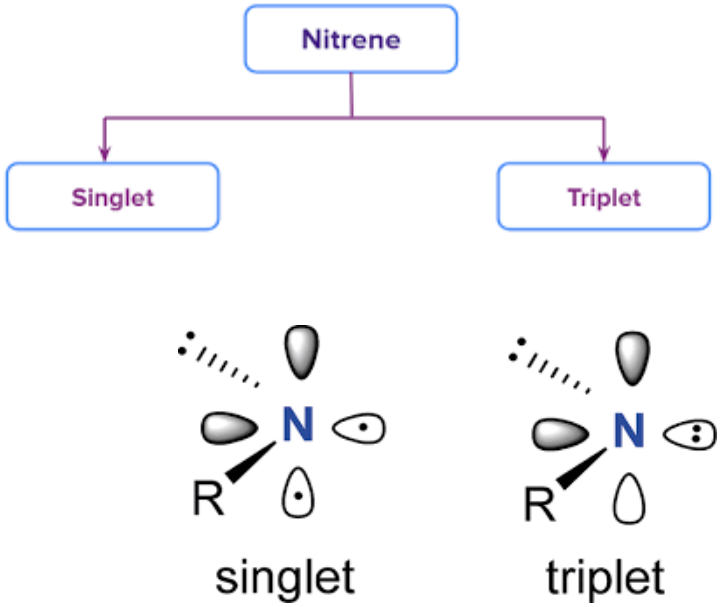
Example:
Generated from diazomethane:

CH2N2 → :CH2 + N2

Carbenes insert into C–H bonds or add to alkenes.

2.2. 5. Nitrene (:N:)

Structure:



:NH ← neutral nitrogen with one lone pair and one unpaired electron

Example:
Formed by loss of N_2 from azide:

$RN_3 \rightarrow :RN + N_2$

Nitrenes are reactive in forming amines and aziridines.

2.2.6 SUMMARY: The stability of reaction intermediates (carbocations, carbanions, free radicals, carbenes, etc.) strongly influences the rate, mechanism, and outcome of chemical reactions. More stable intermediates lower activation energy, favoring faster and selective pathways. Factors such as resonance, hyperconjugation, inductive effects, and aromaticity govern their stability and thereby determine the preferred reaction pathway.

Multiple Choice Questions

Q.1.Which of the following carbocations is the most stable?

a) CH_3^+

b) $CH_3CH_2^+$

c) $(CH_3)_2CH^+$

d) $(CH_3)_3C^+$

Answer: d) $(CH_3)_3C^+$

Q.2.Stability of free radicals follows the order:

a) 1° > 2° > 3°

b) 3° > 2° > 1°

c) 2° > 1° > 3°

d) Allyl > Benzyl > 3°

Answer: b) 3° > 2° > 1°

Q.3.Which factor is most important in stabilizing a carbocation?

a) Inductive effect

b) Hyperconjugation

c) Resonance

d) All of the above

Answer: d) All of the above

Q.4.Which intermediate plays a key role in the **SN1 reaction mechanism**?

a) Carbanion

b) Carbocation

c) Free radical

d) Carbene

Answer: b) Carbocation

Q.5.Carbanion stability decreases with:

a) Increased resonance delocalization

b) Electron-withdrawing groups

c) Electron-donating groups

d) Aromatic stabilization

Answer: c) Electron-donating groups

Short Questions

Q.1 Define a reaction intermediate with an example.

Q.2. Why is a benzyl carbocation more stable than a tertiary carbocation?

Q.3. Explain the order of stability of carbanions.

Q.4. What is the role of resonance in stabilizing free radicals?

Q.5. Differentiate between carbocation and carbanion stability factors.

Long Questions

Q.1 Discuss the various types of reaction intermediates and the factors affecting their stability with suitable examples.

Q.2 Explain how the stability of carbocations influences SN1 and E1 reaction pathways.

Q.3 Compare the stability trends of carbocations, carbanions, and free radicals, highlighting the effects of hyperconjugation, resonance, and inductive effects.

Q.4 Describe the impact of intermediate stability on regioselectivity and stereoselectivity of organic reactions.

Q.5 Using examples, explain how resonance stabilization can direct the course of an organic reaction.

Unit 2.3

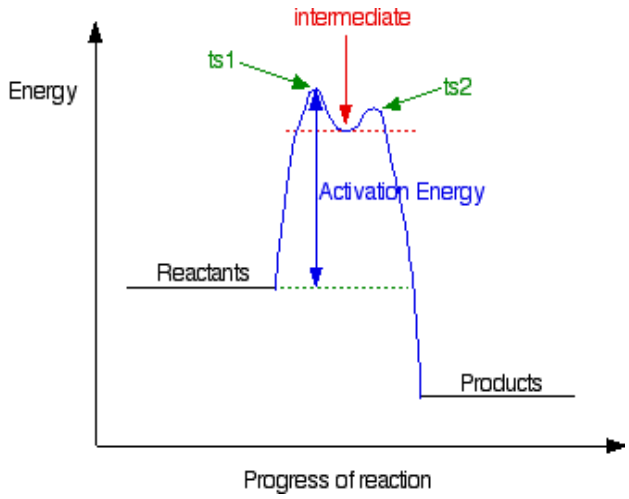
Effect of Structural Features on Charge-Associated Reactivity

Reactants → [Intermediate] → Products

↗ ↘

2.3.1 Transition State Transition State

- Intermediates sit in **valleys** between transition states.



- Hybridization:
  - Mixing of atomic orbitals to form hybrid orbitals (sp, sp^2, sp^3).
  - Determines the geometry of molecules.

2.3.2. Types of Chemical Bonds

- Covalent Bond:
  - Electrons are shared between atoms (e.g., H_2, O_2).
- Ionic Bond:
  - Electrons are transferred from one atom to another (e.g., NaCl).
- Coordinate Bond:
  - A type of covalent bond where both electrons come from one atom.
- Metallic and Hydrogen Bonds:
  - Delocalized electrons in metals.
  - Hydrogen bonds occur between H and electronegative atoms (O, N, F).

2.3.4. Electronic Effects in Reactivity

● Inductive Effect:

- Electron shift through σ-bonds due to electronegativity.

● Resonance Effect:

- Delocalization of π-electrons.

● Hyperconjugation:

- Stabilization through overlap of σ-bonds with p-orbitals.

2.3.5 Summary

1. Structure of Organic Molecules

The **structure** of an organic compound—its atoms' arrangement, functional groups, and bonding—strongly influences how it reacts. Key structural features include:

Hybridization of atoms (sp, sp^2, sp^3)

Functional groups (e.g., alcohols, ketones, amines) that determine chemical properties

Electron distribution (through resonance, inductive effects, or conjugation)

Steric hindrance, where bulky groups affect access to reactive sites

2. Reactivity

Reactivity refers to a molecule's tendency to undergo a chemical change. This is influenced by:

Electronic effects:

Inductive effect: Electron withdrawal or donation through sigma bonds

Resonance effect: Delocalization of electrons across π systems

Stability of intermediates: More stable intermediates result in faster, more favorable reactions

Electrophilicity and nucleophilicity:

Electrophiles: Electron-deficient species that seek electrons (e.g., carbocations, carbonyl groups)

Nucleophiles: Electron-rich species that donate electrons (e.g., amines, alkoxides)

3. Reaction Intermediates

Intermediates are **short-lived, reactive species** formed during the transformation of reactants into products. Common types include:

Carbocations (R^+): Positively charged, electron-deficient carbon species

Carbanions (R^-): Negatively charged carbon species with a lone pair

Free radicals (R•): Neutral species with an unpaired electron

Carbenes (R–C:): Neutral species with two nonbonded electrons on carbon

Nitrenes (R–N:): Similar to carbenes, but centered on nitrogen

Each intermediate has its own geometry, stability, and reactivity:

Carbocation stability increases with resonance and alkyl substitution (3° > 2° > 1°)

Free radical stability follows a similar trend

Carbanion stability is favored by electron-withdrawing groups

4. Structure–Reactivity Relationship

There is a direct correlation between **molecular structure** and **chemical behavior**. Key relationships include:

Resonance → Stabilizes intermediates → Increases reaction rate

Electron-donating groups → Activate aromatic rings (e.g., in electrophilic substitution)

Electron-withdrawing groups → Deactivate rings and stabilize carbanions

Multiple-choice questions

Q.1. Which of the following is the most stable carbocation?

A. Methyl carbocation (CH_3^+)
B. Primary carbocation (1°)
C. Secondary carbocation (2°)
D. Tertiary carbocation (3°)

Answer: ☑ D. Tertiary carbocation (3°)

Q.2. Which of the following effects explains the stability of conjugated systems like benzene?

A. Inductive effect
B. Hyperconjugation
C. Resonance effect
D. Steric effect

Answer: ☑ C. Resonance effect

Q.3. Which of the following is a nucleophile?

A. BF_3
B. NO_2^+
C. NH_3
D. H^+

Answer: ☑ C. NH_3
(*It donates a lone pair of electrons*)

Q.4. What is the hybridization of a carbocation carbon center?

A. sp
B. sp^2
C. sp^3
D. dsp^2

Answer: ☑ B. sp^2

Q.5. Which of the following intermediates is characterized by the presence of an unpaired electron?

A. Carbocation
B. Carbanion

C. Carbene
D. Free radical

Answer: ☑ D. Free radical

Q.6. Which intermediate is most likely formed in an SN1 reaction?

A. Free radical
B. Carbanion
C. Carbocation
D. Nitrene

Answer: ☑ C. Carbocation

Q.7. Which of the following stabilizes a carbanion?

A. Electron-donating groups
B. Electron-withdrawing groups
C. Alkyl groups
D. Carbocations nearby

Answer: ☑ B. Electron-withdrawing groups

Q.8. Which of the following correctly lists intermediates in order of increasing stability?

A. Tertiary carbocation < Secondary < Primary
B. Methyl radical < Primary radical < Tertiary radical
C. Primary carbanion > Secondary > Tertiary
D. Carbocation > Carbanion > Free radical

Answer: B. Methyl radical < Primary radical < Tertiary radical

Q.9. The reactivity of a molecule is mainly determined by:

A. Its boiling point
B. Its density
C. Its electronic structure
D. Its color

Answer: C. Its electronic structure

Q.10. Which intermediate is formed during the halogenation of alkanes under UV light?

A. Carbocation
B. Free radical
C. Carbanion
D. Carbene

Answer: B. Free radical

Short questions

1. Explain the stability order of carbocations with examples.
2. Differentiate between carbocation and carbanion in terms of structure and reactivity.
3. What are free radicals? Discuss their generation and stability.
4. How does resonance affect the stability of reaction intermediates? Give examples.
5. Describe the structure and reactivity of a benzylic carbocation. Why is it more stable than a simple alkyl carbocation?

Long Questions

1. What are carbenes? Write their types and give an example of a reaction involving a carbene intermediate.
2. Compare the stability of methyl, primary, secondary, and tertiary free radicals. Explain the reason.
3. What role do inductive and hyperconjugation effects play in stabilizing carbocations?
4. Draw the structure of a nitrene and describe its electronic configuration.
5. Explain the mechanism of a reaction that involves a free radical intermediate, such as halogenation of alkanes.

MODULE NO 3

REACTION MECHANISM

Unit 3.1

Introduction to Reaction Mechanism Fundamentals

3.1.1What is a Reaction Mechanism?

A **reaction mechanism** is a **step-by-step description** of how reactants are converted into products in a chemical reaction. It outlines the **individual elementary steps**, including the breaking and forming of bonds, intermediates, and transition states.

3.1.2 Importance of Studying Reaction Mechanisms

Understanding mechanisms helps to:

- Predict **reaction products**
- Identify **reaction intermediates**
- Determine **reaction rate laws**
- Design better **catalysts and synthetic pathways**

3.1.3 Key Terms in Reaction Mechanisms

1. Elementary Step

A single step in the overall mechanism involving a specific molecular interaction.

2. Reaction Intermediate

A short-lived species formed between steps (e.g., carbocations, radicals).

3. Transition State

The highest energy, unstable state during the reaction (not isolable).

4. Activation Energy (Ea)

The minimum energy required to initiate the reaction.

5. Rate-Determining Step (RDS)

The slowest step in the mechanism that controls the overall reaction rate.

3.1.4Types of Reaction Mechanisms

● Unimolecular (1st order)

- Involves one molecule in the rate-determining step
- Example: **SN1 reaction**

● **Bimolecular (2nd order)**

- Involves two molecules simultaneously in the slow step
- Example: **SN2 reaction**

3.1.5 Representing Mechanisms

- Use **curved arrows (↷)** to show electron movement.
- Arrows start from **electron-rich** regions (lone pair or bond) and go to **electron-poor** areas (atoms or bonds breaking/forming).

Example: SN2 Reaction Mechanism

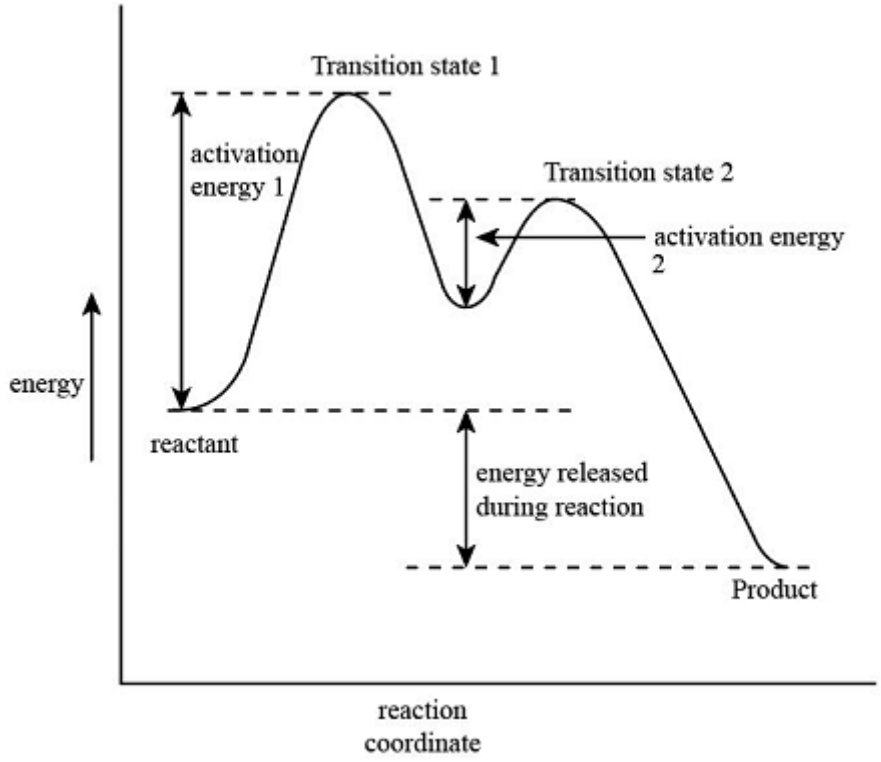
Reaction:

$CH3Br + OH^- \rightarrow CH3OH + Br^-$

Mechanism:

- OH^- attacks the carbon from the opposite side as Br^- leaves (backside attack).
- A **transition state** is formed.
- Br^- leaves and methanol (CH3OH) is formed.

3.1.6 Energy Profile Diagram



Reactants → [Transition State] → Products

- For multi-step reactions, intermediates appear in valleys between peaks (transition states).

3.1.7 Catalysts in Mechanisms

- Catalysts lower the **activation energy**.
- They **do not alter the overall reaction** but **change the pathway**.

3.1.8 Summary

Term	Meaning
Mechanism	Stepwise path of a reaction
Intermediate	Short-lived species formed in-between steps
Transition State	High-energy, unstable configuration during bond rearrangement

Term	Meaning
Rate-Determining Step	Slowest step controlling reaction rate
Curved Arrows	Show electron flow in mechanisms

Multiple Choice Questions

1.The detailed step-by-step description of how a reaction occurs is called:

a) Reaction pathway

b) Reaction mechanism

c) Reaction coordinate

d) Transition state

Answer: b) Reaction mechanism

2.Which of the following represents the highest energy point in a reaction coordinate diagram?

a) Reactants

b) Products

c) Transition state

d) Intermediates

Answer: c) Transition state

3.Which type of arrow is used to represent the movement of an electron pair in a mechanism?

a) Straight arrow

b) Curved arrow

c) Dashed arrow

d) Double-headed straight arrow

Answer: b) Curved arrow

4.In a substitution reaction, SN1 mechanism proceeds via:

a) Carbanion intermediate

b) Carbocation intermediate

c) Free radical intermediate

d) No intermediate

Answer: b) Carbocation intermediate

5.A reaction mechanism helps in understanding:

a) Reaction speed

b) Reaction pathway

c) Stability of intermediates

d) All of the above

Answer: d) All of the above

Short Questions

1. Define reaction mechanism.
2. What is the difference between transition state and intermediate?
3. Why are curved arrows used in writing mechanisms?
4. Differentiate between homolytic and heterolytic bond cleavage.
5. What information can be obtained from a reaction coordinate diagram?

Long Questions

1. Explain the importance of studying reaction mechanisms in organic chemistry with suitable examples.
2. Discuss the types of bond cleavage (homolytic and heterolytic) and their significance in reaction mechanisms.
3. Describe the features of transition state theory and its role in understanding reaction pathways.
4. With examples, explain how electron movement is represented using curved-arrow notation in organic reactions.
5. Discuss the relationship between reaction intermediates, transition states, and activation energy in determining the feasibility of a reaction.

Unit 3.2

General Statement of the Postulate in Reaction Mechanisms

3.2.1 Introduction Understanding how chemical reactions occur at the molecular level is crucial in the study of organic chemistry. Reaction mechanisms provide a detailed step-by-step pathway by which reactants are transformed into products. To interpret these pathways meaningfully, chemists rely on a set of foundational ideas known as *postulates of reaction mechanisms*. These general statements or assumptions help predict, explain, and rationalize the behavior of molecules during chemical reactions. They serve as guiding principles to hypothesize the most probable mechanism for a given reaction.

3.2.2Definition of a Postulate

In the context of chemistry, a **postulate** is an accepted principle or assumption used as a starting point for further reasoning and experiments. Postulates in reaction mechanisms are not proven in the mathematical sense but are supported by experimental observations and logical consistency. They form the theoretical framework upon which detailed mechanisms are constructed and understood.

The **general statement of the postulate in reaction mechanisms** can be summarized as:

"The course of a chemical reaction is governed by the relative energies and structures of the reacting species, and the transformation proceeds through a series of elementary steps involving transition states and reaction intermediates, following the path of lowest possible energy."

3.2.3This statement encapsulates several key ideas:

1. **Energy Considerations**: Reactions occur in such a way that they move toward a more stable (lower energy) state. The transition state—an unstable high-energy configuration between reactants and products—is critical in determining the rate of the reaction.
2. **Elementary Steps**: Complex reactions do not happen in a single leap. Instead, they proceed via a sequence of simpler steps called elementary reactions. Each step involves the making or breaking of specific bonds and follows its own transition state.
3. **Reaction Intermediates**: These are species that are formed in one step and consumed in another. They are usually short-lived and do not appear in the final balanced equation but are essential to understanding the full mechanism.

4. **Transition State Theory**: At each elementary step, the reacting molecules pass through a highly unstable configuration known as the transition state. The structure and energy of this state determine the reaction rate, and the pathway that passes through the lowest energy barrier is the most favorable.
5. **Structure-Reactivity Relationship**: The structure of the molecules involved—such as their geometry, electron distribution, and steric effects—plays a vital role in determining how the reaction proceeds. The reaction mechanism must align with the known behavior of these structures.

Here's a clear explanation of **Hammond's Postulate**:

3.2.4 Hammond's Postulate (General Statement)

Hammond's Postulate states that the structure of the transition state in a reaction step resembles the species (reactants, intermediates, or products) to which it is closer in energy.

In an **exothermic reaction**, the transition state is closer in energy to the **reactants**, so it resembles the reactants.

In an **endothermic reaction**, the transition state is closer in energy to the **products**, so it resembles the products.

3.2.4.1 Significance of Hammond's Postulate

Helps in predicting the nature (structure and stability) of transition states.

Explains why more stable intermediates (e.g., carbocations, radicals) are formed preferentially.

Useful in understanding mechanisms like **SN1, SN2, E1, E2, and electrophilic additions**.

3.2.5 Importance of the Postulate

These general statements help chemists to:

- Predict reaction outcomes.
- Understand reactivity trends.
- Design new reactions with desired products.

- Choose appropriate reaction conditions (e.g., solvent, temperature, catalyst).

They also guide the use of experimental data such as kinetic measurements, isotope effects, and spectroscopic evidence to support or refute proposed mechanisms.

3.2.6 SUMMARY

The general postulate of reaction mechanisms provides a logical and systematic way to understand how and why chemical reactions occur. Though based on assumptions, these postulates are grounded in extensive experimental evidence and have become foundational tools in modern chemistry. By considering the energy landscape, structural changes, and intermediate species involved, chemists can decode the invisible yet intricate choreography of atoms and molecules that drives chemical change.

MULTIPLE CHOICE QUESTIONS

Q.1.Hammond's Postulate relates:

a) Intermediates and reactants

b) Transition state and energy of species

c) Rate of reaction and equilibrium

d) Catalyst and activation energy

Answer: b) Transition state and energy of species

Q.2.According to Hammond's postulate, in an **endothermic step**, the transition state is closer in energy to:

a) Reactants

b) Products

c) Catalyst

d) Solvent

Answer: b) Products

Q.3.In an **exothermic step**, the transition state resembles:

a) Reactants

b) Products

c) Intermediates

d) Catalyst surface

Answer: a) Reactants

Q.4.The postulate is most useful for predicting:

a) Activation energy

b) Structure of the transition state

c) Enthalpy change of reaction

d) Bond lengths in intermediates

Answer: b) Structure of the transition state

Q.5.Which of the following best represents Hammond's postulate?

a) "Transition states are always identical to intermediates."

b) "Transition state structure is similar to the nearest stable species in energy."

c) "Rate of reaction is independent of transition state."

d) "Transition states have no effect on reaction pathways."

Answer: b) "Transition state structure is similar to the nearest stable species in energy."

Short Questions

Q.1 State the general form of Hammond's postulate.

Q.2.How does Hammond's postulate apply to endothermic reactions?

Q.3.Differentiate between the transition states of exothermic and endothermic reactions.

Q.4. Why is Hammond's postulate important in understanding reaction mechanisms?

Q.5.Give one example of how Hammond's postulate helps explain carbocation stability in SN1 reactions.

Long Questions

1. Explain the **general statement of Hammond's postulate** and discuss its significance in organic reaction mechanisms.
2. Describe the application of Hammond's postulate in **exothermic and endothermic reaction steps** with diagrams.
3. Discuss how Hammond's postulate is useful in predicting the transition state in **SN1 and SN2 mechanisms**.
4. With suitable energy profile diagrams, explain how Hammond's postulate helps in correlating transition states with intermediates or products.
5. Evaluate the limitations of Hammond's postulate in modern physical organic chemistry.

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Unit 3.3

Strength and Type of Nucleophile

3.3.1 Introduction In organic chemistry, the understanding of **nucleophiles** is essential to predict and rationalize many chemical reactions, particularly substitution and addition mechanisms. A **nucleophile** is a chemical species that donates an electron pair to form a chemical bond in reaction with an electrophile. The **strength** and **type** of nucleophile significantly influence the rate and outcome of a reaction. Below is a detailed discussion on these aspects.

3.3.2 Definition of Nucleophile

A **nucleophile** (literally "nucleus-loving") is an atom or molecule that has a pair of electrons available for bonding and seeks a positively charged or electron-deficient center (typically a carbon attached to a leaving group or positively polarized).

Examples:

- Anions: OH^-, CN^-, Cl^-, Br^-
- Neutral molecules with lone pairs: H_2O, NH_3, RNH_2, alcohols

3.3.3 Strength of Nucleophile

The **nucleophilicity** (strength of a nucleophile) refers to the **ability of a species to donate an electron pair** to an electrophile. It is influenced by several factors:

a) Charge

- **Negatively charged** species are generally **stronger nucleophiles** than their neutral counterparts.
    - Example: $OH^- > H_2O$; $RO^- > ROH$

b) Electronegativity

- Less electronegative atoms are better at sharing their lone pairs and are stronger nucleophiles.
    - Example: $NH_3 > H_2O$ (N is less electronegative than O)

c) Solvent Effects

- In **polar protic solvents** (like water or alcohols), nucleophiles are **solvated (hydrogen bonded)**, which reduces their nucleophilicity.

- In **polar aprotic solvents** (like acetone, DMSO), nucleophiles are less solvated, so nucleophilicity increases.

Example in protic solvent:

  - $F^- < Cl^- < Br^- < I^-$

Example in aprotic solvent:

  - $I^- < Br^- < Cl^- < F^-$

d) Size and Polarizability

- Larger atoms or ions with more diffused electron clouds are more polarizable and often act as better nucleophiles, especially in protic solvents.
  - Example: $I^- > Br^- > Cl^- > F^-$

e) Basicity vs. Nucleophilicity

- Although related, **basicity** (ability to accept a proton) and **nucleophilicity** (ability to donate a lone pair to an electrophile) are **not the same**.
  - Example: HO^- is both a strong base and a strong nucleophile, but t-BuO^- is a strong base and a **poor nucleophile** due to steric hindrance.

3.3.4 Types of Nucleophiles

Nucleophiles can be broadly categorized based on their structure, charge, and strength:

a) Neutral Nucleophiles

- Molecules with lone pairs but no formal charge.
- Example: H_2O, NH_3, ROH, RNH_2
- Generally weaker nucleophiles compared to their conjugate bases.

b) Anionic Nucleophiles

- Contain a negative charge; more reactive due to higher electron density.
- Example: OH^-, CN^-, RS^-, N_3^-

c) Hard vs. Soft Nucleophiles

Based on the **HSAB (Hard and Soft Acids and Bases) Theory**:

- **Hard Nucleophiles**: Small, highly charged, not easily polarizable.
  - Examples: F^-, OH^-, NH_2^-

- Prefer to attack hard electrophiles (e.g., carbonyl carbon).

- **Soft Nucleophiles**: Larger, more polarizable, easily distorted electron clouds.
  - Examples: I^-, RS^-, R_3P
  - Prefer soft electrophiles (e.g., alkyl halides).

3.3.5. Examples of Common Nucleophiles and Their Relative Strength

Nucleophile	Relative Strength	Notes
I^-	Strong	Large, polarizable
HS^-	Strong	Soft nucleophile
OH^-	Strong	Also a strong base
NH_3	Moderate	Neutral molecule
H_2O	Weak	Strong solvation in water
ROH	Weak	Neutral, protonated alcohol

3.3.6 Influence on Reaction Mechanism

- **SN1 Reaction**: Nucleophile strength is **less important** because the rate-determining step is the formation of a carbocation intermediate. Even **weak nucleophiles** can participate.
  - Example: H_2O, ROH in hydrolysis or solvolysis.
- **SN2 Reaction**: Nucleophile strength is **very important** as the nucleophile participates in the rate-determining step (one-step concerted mechanism).
  - Strong nucleophiles lead to faster SN2 reactions.

3.3.7 Steric Hindrance and Nucleophilicity

- Bulky nucleophiles (like t-BuO^-) have **reduced nucleophilicity** due to difficulty in approaching the electrophilic carbon.
- These bulky bases may prefer **elimination (E2)** over substitution.

3.3.8 Conclusion

The strength and type of nucleophile play a vital role in determining the **rate, mechanism, and product** of many organic reactions. A deep

understanding of nucleophilicity helps predict whether a substitution reaction will proceed via SN1 or SN2, whether elimination will occur, and what conditions will be most effective. Factors such as charge, size, solvent effects, and polarizability must be carefully considered when evaluating nucleophiles in a given reaction. By mastering these concepts, chemists can better design and control organic synthesis processes.

SUMMARY

A reaction mechanism describes the step-by-step sequence of elementary reactions by which overall chemical change occurs.

It explains how bonds are broken and formed during the transformation from reactants to products.

Each step in the mechanism may involve the formation of short-lived intermediates like carbocations, carbanions, or free radicals.

The highest energy state reached during a reaction step is called the transition state, which is not isolable.

The rate-determining step is the slowest step in the mechanism and controls the overall reaction rate.

Reaction mechanisms can be unimolecular, bimolecular, or rarely termolecular, based on the number of reacting species in an elementary step.

Common types of organic mechanisms include nucleophilic substitution (SN1, SN2), electrophilic substitution, elimination (E1, E2), and addition reactions.

Factors such as the nature of reactants, solvent, temperature, and steric effects influence the pathway and rate of reaction.

Catalysts provide an alternative mechanism with a lower activation energy, speeding up the reaction.

Understanding mechanisms helps chemists predict products, improve yields, and design better synthetic routes.

Multiple Choice Questions

Q.1. What is a reaction mechanism?
A. The final product of a reaction
B. The rate of a reaction
C. The step-by-step pathway from reactants to products

D. The number of molecules involved in a reaction
Answer: C

Q.2. Which of the following species is commonly an intermediate in organic reactions?
A. Water
B. Carbocation
C. Methane
D. Oxygen gas
Answer: B

Q.3. What does the rate-determining step refer to?
A. The last step of the mechanism
B. The fastest step in the mechanism
C. The step that produces the product
D. The slowest step that controls the overall rate
Answer: D

Q.4. In an SN2 mechanism, the reaction occurs in:
A. Two steps with carbocation formation
B. One concerted step with backside attack
C. A free radical chain process
D. An elimination pathway
Answer: B

Q.5. A transition state is:
A. An isolated intermediate
B. A reactant molecule
C. A high-energy unstable structure between reactant and product
D. A type of catalyst
Answer: C

Q.6. Which of the following reactions involves a nucleophile attacking an electrophile?
A. Electrophilic substitution
B. Nucleophilic substitution
C. Elimination
D. Free radical substitution
Answer: B

Q.7. Which factor increases the rate of an SN1 reaction?
A. Strong nucleophile
B. Polar protic solvent
C. Primary alkyl halide
D. Low temperature
Answer: B

Q.8. In an E2 reaction mechanism, how many steps are involved?
A. One
B. Two
C. Three
D. Depends on the substrate
Answer: A

Q.9. Which of the following is *not* a type of reaction intermediate?
A. Free radical
B. Transition state
C. Carbocation
D. Carbanion
Answer: B

Q.10. Catalysts speed up reactions by:
A. Increasing the temperature
B. Increasing the activation energy
C. Decreasing the activation energy by providing an alternate pathway
D. Decreasing the number of molecules
Answer: C

V**ery short questions on Reaction Mechanism**:

1. What is a reaction mechanism?
2. Define transition state.
3. What is an intermediate in a reaction?
4. Name one reaction that proceeds via a carbocation intermediate.
5. What does SN1 stand for?
6. Which is faster: SN1 or SN2 for methyl halides?
7. What is the rate-determining step?
8. Name a reaction that involves a free radical intermediate.
9. What is the difference between concerted and stepwise mechanisms?
10. Give one example of an elimination reaction.

Q.1 Long questions on nucleophiles

Q.2 Define nucleophile. How do nucleophiles differ from electrophiles? Give examples.

Q.3 Compare the nucleophilicity of water, hydroxide ion, and ammonia. Explain the trend.

Q.4 How does solvent affect nucleophilicity? Explain with examples using protic and aprotic solvents.

Q.5 Explain how nucleophilicity is different from basicity with suitable examples.

Q.6 Arrange the following nucleophiles in order of increasing strength and justify your answer: Cl^-, OH^-, H_2O, NH_3.

Q.7 Describe the role of nucleophiles in SN1 and SN2 reactions. How does their strength affect the rate of each type of reaction?

Q. 8What factors influence the strength of a nucleophile?

Include atomic size, charge, electronegativity, and solvent effects.

Q.9 Give an example of a nucleophilic substitution reaction and write its mechanism.

Q.10 Is fluoride ion (F^-) a good nucleophile? Justify your answer with respect to solvent type.

Q.11 Explain why iodide (I^-) is a better nucleophile than fluoride (F^-) in protic solvents.

Module 04

ALIPHATIC ELECTROPHILIC SUBSTITUTIONS

Unit 4.1

Bimolecular Mechanism SE1 & SE2

4.1.1 Bimolecular mechanism SE1 & SE2

In organic chemistry, electrophilic substitution reactions are fundamental, especially in aromatic chemistry. However, electrophilic substitutions can also occur on aliphatic substrates, though less commonly. Among these, two types of bimolecular electrophilic substitution mechanisms are recognized — SE1 (Substitution Electrophilic Unimolecular) and SE2 (Substitution Electrophilic Bimolecular). These mechanisms are particularly significant in specialized areas like organometallic chemistry and reactions involving highly activated substrates.

4.1.2 SE1 Mechanism (Substitution Electrophilic Unimolecular)

The unimolecular electrophilic substitution (SE1) reactions may simply be defined as the chemical change in which a stronger electrophile displaces a weaker one in an aliphatic substrate via the formation of a carbanion. This mechanism is quite analogous with the SN1 route excepting the nature of intermediate.

4.1.2.1Definition:

The SE1 mechanism is a two-step electrophilic substitution process involving an initial slow, rate-determining formation of a carbocation intermediate, followed by fast electrophilic attack.

Mechanism Steps:

1. Ionization (Rate-Determining Step)
   The leaving group departs, forming a carbocation intermediate.
   $\rightarrow R–X \rightarrow R^+ + X^-$
2. Attack by Electrophile
   The electrophile (E^+) attacks the carbocation to give the substituted product.
   $\rightarrow R^+ + E^+ \rightarrow R–E$

4.1.2.2 Features:

- Follows first-order kinetics: Rate = k[R–X]
- Carbocation stability is crucial; works best with tertiary carbons or benzylic systems.
- Similar to the SN1 mechanism in nucleophilic substitution.

Example:

Reaction of tertiary alkyl halides with electrophilic reagents in the presence of Lewis acids.

4.1.3SE2 Mechanism (Substitution Electrophilic Bimolecular)

Definition:

The SE2 mechanism is a single-step, concerted reaction where the electrophile attacks the substrate while the leaving group departs simultaneously.

4.1.3.1Mechanism:

- The bond to the electrophile forms as the bond to the leaving group breaks.
- Both events happen simultaneously in a single transition state.

Subtypes:

- SE2 (frontside attack) – Electrophile attacks from the same side as the leaving group.
- SE2' (backside or allylic attack) – Electrophile attacks at an allylic position, displacing a leaving group via a π-complex intermediate.

4.1.3.2 Features:

- Follows second-order kinetics: Rate = k[substrate][electrophile]
- No carbocation intermediate.
- Stereochemistry may be affected depending on frontside or backside attack.
- Analogous to SN2 mechanism.

Example:

Reaction of organometallic compounds such as trialkylaluminums or organosilicon compounds with electrophiles like halogens or acids.

- Comparison Between SE1 and SE2

Feature	SE1	SE2
Mechanism Type	Stepwise (2-step)	Concerted (1-step)
Intermediate	Carbocation	None

Feature	SE1	SE2
Kinetics	First-order	Second-order
Dependence	Substrate only	Substrate and electrophile
Stereochemistry	May rearrange (via carbocation)	Depends on approach (inversion/retention)
Analogy	Similar to SN1	Similar to SN2

4.1.4Applications and Importance

- SE1 and SE2 mechanisms are rare compared to SN reactions but important in organometallic and advanced organic reactions, particularly where the carbon center is highly activated or stabilized.
- Understanding these mechanisms aids in predicting reaction outcomes in complex synthetic routes and helps in designing novel electrophilic substitution reactions beyond aromatic systems.

4.1.5 Summary

Though less common in classical organic chemistry, the SE1 and SE2 mechanisms offer important insights into the behavior of electrophilic substitution reactions, especially for non-aromatic systems. Recognizing the conditions that favor each—such as the stability of intermediates and the nature of electrophiles and substrates—enhances our ability to understand and manipulate chemical reactivity in advanced synthesis.

Multiple Choice Questions

Q.1.In a **bimolecular electrophilic substitution (SE2)** reaction, the rate depends on:

a) Only the concentration of the electrophile

b) Only the concentration of the substrate

c) Both the substrate and electrophile concentrations

d) Neither, it is a constant rate

Answer: c

Q.2.Which of the following best describes the **rate-determining step** in an SE1 reaction?

a) Simultaneous bond breaking and forming

b) Formation of a carbocation-like intermediate

c) Direct attack of the electrophile without intermediate

d) Radical formation

Answer: b

Q.3.The **stability of carbocation intermediates** is crucial in:

a) SE1

b) SE2

c) Both SE1 and SE2

d) Neither

Answer: a

Q.4.Which type of substitution is most likely in a **highly polar protic solvent**?

a) SE1

b) SE2

c) Both equally

d) None

Answer: a

Q.5.Which feature differentiates **SE1** from **SE2**?

a) Presence of a carbocation intermediate

b) Unimolecular rate-determining step

c) Concerted mechanism in one step

d) Both a and b

Answer: d

Short Answer Questions

Q.1. Define SE1 and SE2 mechanisms and mention the key difference between them.

Q.2. What role does solvent polarity play in determining whether SE1 or SE2 predominates?

Q.3.How does substrate structure influence the preference for SE1 or SE2 pathways?

Q.4.Explain why tertiary carbons favor SE1 mechanisms over SE2.

Q.5 Give one example of a reaction proceeding via SE2 and briefly describe the steps.

Long Answer Questions

1. **Compare and contrast SE1 and SE2 mechanisms** in terms of reaction kinetics, intermediates, stereochemistry, solvent effects, and substrate preference. Provide diagrams to illustrate each pathway.
2. Discuss in detail the **factors affecting the rate** of SE2 reactions. How do nucleophilic strength, leaving group ability, and steric hindrance contribute to the mechanism?
3. Explain the **energetics** of SE1 and SE2 reactions with the help of potential energy diagrams. Include a discussion on activation energy and transition states.
4. Describe how **isotopic labeling** or **kinetic studies** can be used to differentiate between SE1 and SE2 pathways experimentally.
5. Provide a **case study** of a reaction that can proceed via either SE1 or SE2 under different conditions. Discuss how changing temperature, solvent, or substrate structure can shift the mechanism.

Unit 4.2

Regeneration of Aromaticity

4.2.1 Definition

Regeneration of aromaticity refers to the restoration of the aromatic π-electron system after it is temporarily disrupted during an electrophilic aromatic substitution (EAS) reaction. Aromatic compounds are highly stable due to their delocalized π-electrons, and any reaction that disturbs this system must ultimately re-establish aromaticity to regain stability.

4.2.2 Importance of Aromaticity

- Aromatic compounds (like benzene) are more stable than expected due to delocalization of π-electrons in a conjugated ring system.
- Disruption of aromaticity causes loss of stability, so reactions are often driven by the need to restore this stability.
- Regeneration of aromaticity is usually the final step in electrophilic aromatic substitution mechanisms.

4.2.3 General Process in Electrophilic Aromatic Substitution (EAS)

Step 1: Formation of Arenium Ion (σ-Complex)

- The aromatic compound (like benzene) reacts with an electrophile (E^+), breaking the aromatic system and forming a carbocation intermediate known as the arenium ion.

Example:

$C_6H_6+E+\rightarrow[C_6H_6E]+C_6H_6 + E+ \rightarrow C_6H_6E]+C_6H_6+E+\rightarrow[C_6H_6E]+$

Step 2: Regeneration of Aromaticity

- A proton (H^+) is removed (typically by a base), restoring the planar, fully conjugated π-system.

Example:

[C6H6E]+→C6H5E+H+[C_6H_6E] + → C_6H_5E + H +[C6H6 E]+→C6H5E+H+

This step re-establishes aromaticity and completes the substitution reaction.

4.2.4 Mechanism Illustration (e.g., Nitration of Benzene)

1. Generation of Electrophile:

HNO3+H2SO4→NO2++H2OHNO_3 + H_2SO_4 → NO_2^+ + H_2OHNO3+H2SO4→NO2++H2O

2. Attack on Benzene Ring:

C6H6+NO2+→[C6H6NO2]+C_6H_6 + NO_2^+ → [C_6H_6NO_2]^+C6H6+NO2+→[C6H6NO2]+

3. Loss of H^+ (Regeneration of Aromaticity):

[C6H6NO2]+→C6H5NO2+H+[C_6H_6NO_2]^+ → C_6H_5NO_2 + H^+[C6H6NO2]+→C6H5NO2+H+

4.2.5 Role of Base in Regeneration

- A base (often the conjugate base of the acid used to generate the electrophile) abstracts the proton from the intermediate.
- Common bases: HSO_4^-, $AlCl_4^-$, etc.

4.2.6 Energy Considerations

- The formation of the non-aromatic intermediate is energetically unfavorable.
- Aromatic stabilization is regained upon loss of H^+, making the overall reaction favorable.
- The regeneration of aromaticity provides the thermodynamic driving force for the EAS reaction.

4.2.7 Other Reactions Involving Regeneration of Aromaticity

- Friedel–Crafts Alkylation/Acylation
- Sulfonation
- Halogenation
- Diazonium Coupling Reactions

In each case, the aromatic ring must temporarily lose its aromatic character and then regenerate it through deprotonation.

4.2.8 **SUMMARY**

Regeneration of aromaticity is a crucial final step in electrophilic aromatic substitution reactions. It ensures the restoration of the stable aromatic system, making the reaction both chemically favorable and thermodynamically driven. This step not only completes the mechanism but also emphasizes the central role of aromatic stability in guiding organic reactions involving benzene and other aromatic

Multiple Choice Questions

Q.1.In Electrophilic Aromatic Substitution, **regeneration of aromaticity** usually occurs by:

a) Loss of a proton (H^+) from the arenium ion

b) Addition of another electrophile

c) Rearrangement of the carbocation intermediate

d) Radical substitution

Answer: a

Q.2.The intermediate formed **before regeneration of aromaticity** is called:

a) Carbene

b) Aryl radical

c) Arenium ion (sigma complex)

d) Enolate ion

Answer: c

Q.3.The driving force for the regeneration of aromaticity is:

a) Formation of an sp^3 hybridized carbon

b) Recovery of delocalized π-electron stability

c) Removal of electron density from the ring

d) Loss of nucleophilic strength

Answer: b

Q.4.In nitration of benzene, the species that abstracts the proton to regenerate aromaticity is usually:

a) NO_2^+

b) H_2O

c) HSO_4^-

d) HNO_3

Answer: c

Q.5.During halogenation of benzene, which statement is correct about regeneration of aromaticity?

a) The aromatic ring becomes permanently non-aromatic.

b) The Lewis acid catalyst (e.g., $FeBr_3$) helps remove H^+ to restore aromaticity.

c) The leaving group is a halide ion (X^-).

d) No intermediate is formed before aromaticity returns.

Answer: b

Very Short Questions:

1. What is meant by regeneration of aromaticity?
2. In which type of reactions does aromaticity get temporarily lost and then restored?
3. Name one reaction where aromaticity is regained in the final step.
4. What is the role of a base in restoring aromaticity in electrophilic substitution?
5. Does aromaticity increase or decrease the stability of a compound?

Long Questions:

Q.1 With the help of a mechanism, explain the process of electrophilic aromatic substitution and show how aromaticity is temporarily lost and then regenerated.

Q.2 Discuss the energetic importance of regenerating aromaticity in reactions involving aromatic compounds.

Q.3 Describe the role of resonance and delocalization in stabilizing the regenerated aromatic system.

Q.4 Explain the concept of arenium ion and how it leads to the final restoration of aromaticity.

Q.5 Compare the stability of the intermediate arenium ion with the aromatic starting compound and explain how this difference influences the reaction pathway.

Unit 4.3

Quantitative Treatment of Reactivity in Substrates and Electrophiles

4.3.1 Introduction

In organic chemistry, understanding **why certain reactions occur faster or more efficiently than others** is critical. This can be explained by analyzing the **reactivity of substrates and electrophiles**. A **quantitative treatment** involves using **measurable parameters** such as reaction rates, equilibrium constants, and electronic properties to **numerically assess and compare** reactivity. This approach helps predict reaction outcomes and design better synthetic strategies.

4.3.2 Key Concepts in Quantitative Reactivity

1. Reaction Rate (k)

- The **rate constant (k)** gives a measure of how quickly a reaction proceeds.
- For example, in a reaction:

Rate=k[Substrate][Electrophile]\text{Rate} = k[\text{Substrate}][\text{Electrophile}]Rate=k[Substrate][Electrophile]

- A higher value of **k** indicates greater reactivity.

2. Free Energy Change (ΔG‡)

- The **activation energy barrier** (ΔG‡) must be overcome for a reaction to occur.
- The lower the ΔG‡, the faster the reaction.
- Related by the **Arrhenius equation** :

Logarithmic Form

Taking natural log on both sides:

$$\ln k = \ln A - \frac{E_a}{R} \cdot \frac{1}{T}$$

This is of the form:

$$y = mx + c$$

- Plot of $\ln k$ vs. $1/T$ gives a **straight line**
  - **Slope** = $-E_a/R$
  - **Intercept** = $\ln A$

4.3.3 Quantitative Factors Affecting Substrate Reactivity

a) Electronic Effects

- **Electron-donating groups (EDGs)** increase reactivity by stabilizing carbocations (in SN1) or increasing electron density (in EAS).
- **Electron-withdrawing groups (EWGs)** reduce nucleophilicity or destabilize intermediates.

b) Steric Hindrance

- Bulky groups around the reactive site can **reduce reactivity** by blocking the approach of electrophiles.

c) Resonance and Inductive Effects

- **Resonance** can stabilize reactive intermediates (e.g., arenium ions).
- **Inductive effects** shift electron density through σ-bonds and can either stabilize or destabilize transition states.

d) Solvent Effects

- Polar solvents stabilize charged intermediates and transition states, affecting rate constants.

4.3.4 Quantitative Factors Affecting Electrophile Reactivity

a) Electrophilicity Index (ω)

- A **quantitative descriptor** in density functional theory (DFT) defined as:

ω=μ22η\omega = \frac{\mu^2}{2\eta}ω=2ημ2

where μ = chemical potential, η = chemical hardness.

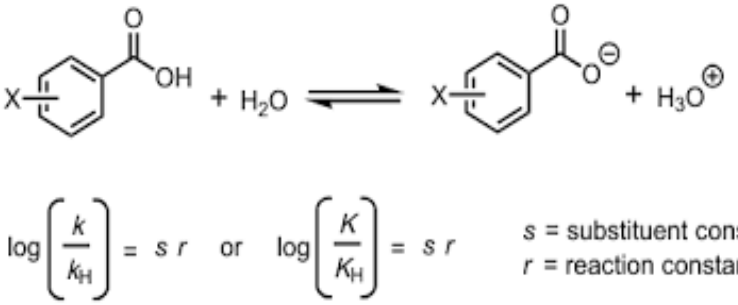
- Higher ω means stronger electrophile.

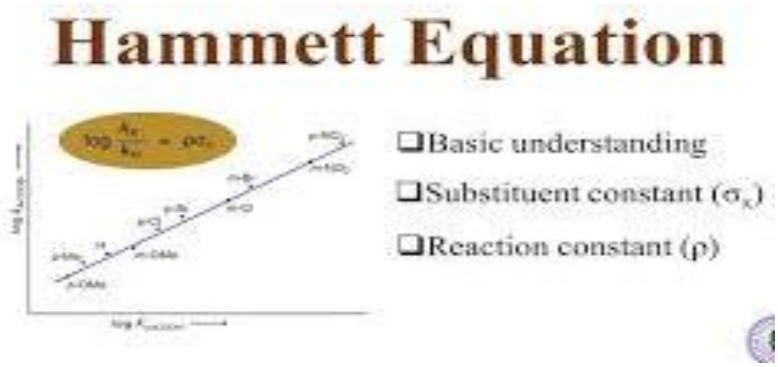
b) Frontier Molecular Orbital (FMO) Theory

- Electrophiles interact with the **HOMO of nucleophiles**.
- Lower LUMO energy = more reactive electrophile.

c) Hammett Equation

- Used to **quantify electronic effects** of substituents on reactivity.



- 

log⁡(kk0)=ρσ\log\left(\frac{k}{k_0}\right) = \rho \sigmalog(k0k)=ρσ

where:

  - kkk = rate constant for substituted compound
  - k0k_0k0 = rate constant for unsubstituted compound
  - σ\sigmaσ = substituent constant
  - ρ\rhoρ = reaction constant

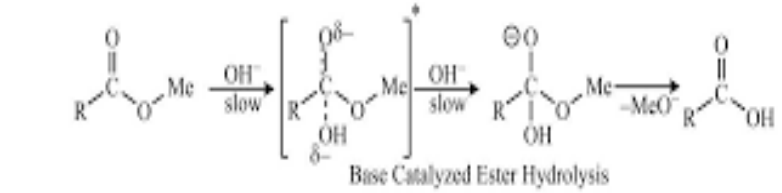
- Positive ρ → sensitive to electron withdrawal; negative ρ → sensitive to electron donation.

4.3.5 Linear Free Energy Relationships (LFERs)

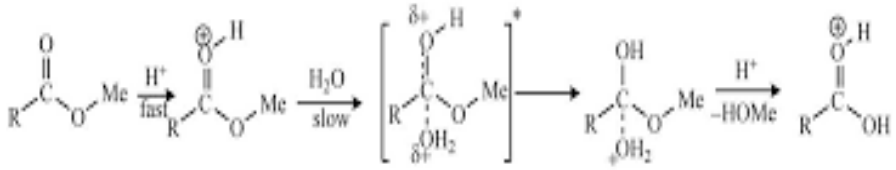
These relate **reaction rates** or **equilibrium constants** to **structure-based parameters**.

Examples:

- **Hammett equation** – for aromatic systems.
- **Taft equation** – for aliphatic reactions.

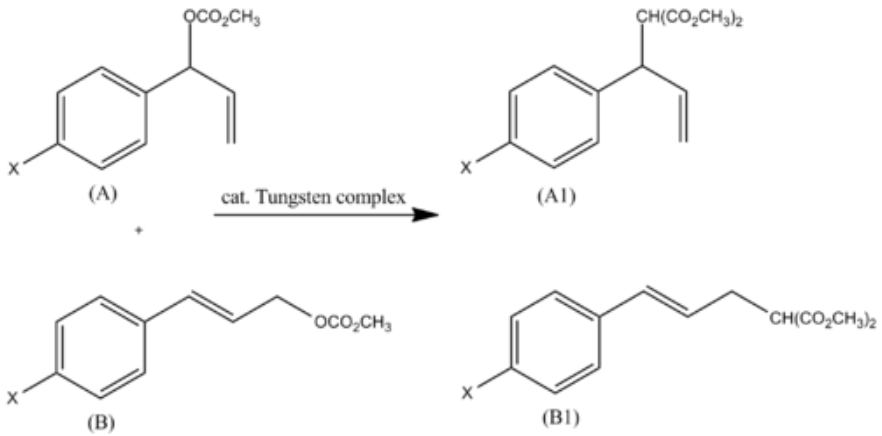


Base Catalyzed Ester Hydrolysis



Acid Catalyzed Ester Hydrolysis

- **Swain–Lupton equation** – combines field and resonance effects.



4.3.6 Kinetic Isotope Effects (KIE)

- Changing an atom to a heavier isotope (e.g., H → D) can affect reaction rate.
- Used to study **reaction mechanism and transition state structure**.

4.3.7 Applications of Quantitative Treatment

- Predicting **which electrophile or substrate** will react faster.
- Comparing reactivity across a **series of compounds**.
- Optimizing reaction conditions (solvent, temperature, substituents).

- Designing **selective synthetic routes**.
- Understanding **reaction mechanisms quantitatively**.

4.3.8 SUMMARY

Aliphatic electrophilic substitution is a type of reaction where an electrophile replaces a hydrogen atom in an aliphatic (non-aromatic) compound.

These reactions are less common than nucleophilic or free radical substitutions in aliphatic systems.

The substrate in such reactions is usually rich in electrons, allowing it to interact with an incoming electrophile.

Common electrophiles include halogens (e.g., Cl^+, Br^+), nitronium ion (NO_2^+), or sulfonium ion.

The reaction generally proceeds via a two-step mechanism: formation of a carbocation intermediate followed by deprotonation.

Stability of the intermediate carbocation plays a crucial role in determining the feasibility and rate of the reaction.

Examples of aliphatic electrophilic substitution include the Hell-Volhard-Zelinsky reaction and reactions involving α-halogenation of carboxylic acids.

These reactions often require acidic conditions or specific catalysts to generate the electrophile.

Aliphatic electrophilic substitution is important in organic synthesis, especially in modifying α-positions of carbonyl compounds.

The reaction pathway is influenced by the nature of the substituent, solvent, and the stability of any intermediate species formed.

Multiple Choice Questions

Q.1. Aliphatic electrophilic substitution involves the replacement of:
A. A hydrogen atom by a nucleophile
B. A hydrogen atom by a free radical
C. A hydrogen atom by an electrophile

D. An alkyl group by a nucleophile
Answer: C

Q.2. Which of the following is a classic example of an aliphatic electrophilic substitution reaction?
A. Friedel–Crafts alkylation
B. Hell–Volhard–Zelinsky reaction
C. Nitration of benzene
D. Wurtz reaction
Answer: B

Q.3. In the Hell–Volhard–Zelinsky reaction, the substitution occurs at:
A. β-carbon of carboxylic acid
B. α-carbon of carboxylic acid
C. Carbonyl carbon
D. Carboxylate group
Answer: B

Q.4. Which of the following is typically required to generate the electrophile in aliphatic electrophilic substitution?
A. Strong acid or halogen carrier
B. Basic catalyst
C. Ultraviolet light
D. None of the above
Answer: A

Q.5. The stability of which intermediate is crucial in aliphatic electrophilic substitution?
A. Free radical
B. Carbanion
C. Carbocation
D. Transition state only
Answer: C

Q.6. Aliphatic electrophilic substitutions are generally favored in compounds that have:
A. Electron-withdrawing groups
B. Aromatic rings
C. Electron-donating groups near the reactive site
D. No functional groups
Answer: C

Q.7. Which of the following is *not* an electrophile used in aliphatic electrophilic substitution?
A. Cl^+
B. NO_2^+
C. OH^-

D. Br^+
Answer: C

Q.8. What type of compound is most reactive toward aliphatic electrophilic substitution at the α-position?
A. Alkanes
B. Alcohols
C. Carbonyl-containing compounds
D. Aromatics
Answer: C

Q.9. The mechanism of aliphatic electrophilic substitution typically involves:
A. A radical intermediate
B. Nucleophilic attack followed by elimination
C. Carbocation formation followed by loss of proton
D. Direct displacement without any intermediate
Answer: C

Q.10. Electrophilic substitution at aliphatic positions is least likely to occur in:
A. Aldehydes
B. Ketones
C. Alkanes
D. α-Haloacids
Answer: C

Short questions on Aliphatic Electrophilic Substitution reactions:

1. What is aliphatic electrophilic substitution?
2. Give one example of an aliphatic electrophilic substitution reaction.
3. Name the key reactive intermediate in aliphatic electrophilic substitution.
4. Which type of compounds commonly undergo aliphatic electrophilic substitution?
5. What is the role of the electrophile in this reaction?
6. Is carbocation formation involved in aliphatic electrophilic substitution?
7. Name one reagent used in aliphatic electrophilic substitution.
8. Does this reaction usually require acidic or basic conditions?
9. How does the presence of electron-withdrawing groups affect the reaction?

10. What is the difference between aliphatic and aromatic electrophilic substitution?

Long Questions

1. Describe in detail the mechanism of aliphatic electrophilic substitution (SE) reactions. Differentiate between SE1 and SE2 mechanisms with suitable examples.
2. Discuss the various factors affecting the rate and outcome of aliphatic electrophilic substitution reactions. Explain the role of substrate structure, leaving group, solvent, and electrophile strength.
3. With suitable examples, explain the halogenation, nitrosation, and diazonium coupling as aliphatic electrophilic substitution reactions. Provide detailed reaction mechanisms.
4. Explain the occurrence of rearrangements in aliphatic electrophilic substitution reactions. Why are rearrangements common in SE1 reactions? Illustrate with examples.
5. Compare aliphatic electrophilic substitution with aromatic electrophilic substitution. Discuss the similarities and differences in mechanisms, intermediates, and factors affecting reactivity.

MODULE NO 5

STEREOCHEMISTRY

Unit 5.1

Isomerism

5.1.1 Introduction

Isomerism is the phenomenon where two or more compounds have the same molecular formula but different structural arrangements or spatial orientations.

These compounds are called **isomers**.

Isomerism is one of the most important concepts in organic chemistry as it explains why compounds with the same formula can have very different properties.

5.2.2. Classification of Isomerism

Isomerism is broadly classified into:

Structural (Constitutional) Isomerism

Stereoisomerism

5.1.3. Structural Isomerism

Structural isomers differ in the way atoms are connected. They have the same molecular formula but different structures.

Chain Isomerism: Difference in the carbon chain (straight chain vs. branched).
Example: *n-butane (C_4H_{10})* and *isobutane (2-methylpropane)*.

Position Isomerism: Same carbon skeleton, same functional group, but located at different positions.
Example: *1-propanol* and *2-propanol*.

Functional Group Isomerism: Compounds with the same formula but different functional groups.
Example: C_2H_6O → *ethanol (–OH)* and *dimethyl ether (–O–)*.

Metamerism: Isomers differ due to unequal distribution of alkyl groups around a polyvalent atom (like O, N, S).
Example: *ethyl methyl ether* ($C_2H_5–O–CH_3$) and *diethyl ether* ($C_2H_5–O–C_2H_5$).

Tautomerism: A special case of dynamic isomerism where two structures exist in equilibrium, usually involving migration of a proton.
Example: Keto–enol tautomerism ($CH_3–CO–CH_2–$ ↔ $CH_2=C(OH)–CH_3$).

5.1.4. Stereoisomerism

Stereoisomers have the same structural formula but differ in spatial arrangement of atoms.

Types:**Geometrical Isomerism (Cis–Trans or E–Z)**

Optical Isomerism (Enantiomers and Diastereomers)

5.1.5. Geometrical Isomerism

Found in alkenes and cyclic compounds due to restricted rotation.

Cis-isomer: similar groups on the same side.

Trans-isomer: similar groups on opposite sides.

Example: *Cis-2-butene* and *Trans-2-butene*.

E–Z Notation: Based on Cahn–Ingold–Prelog priority rules.

Properties:

Cis and trans isomers differ in polarity, dipole moment, and boiling/melting points.

5.1.6. Optical Isomerism

Occurs when compounds can rotate plane-polarized light.

Compounds containing an **asymmetric carbon atom (chiral center)** show optical activity.

Key Terms:

Enantiomers: Non-superimposable mirror images (rotate light in opposite directions).

Diastereomers: Not mirror images, have different physical properties.

Racemates: Equimolar mixture of enantiomers, optically inactive.

Resolution: Separation of enantiomers.

Example: *Lactic acid* exists as two enantiomers: L(+) and D(–).

5.1.7. Conformational Isomerism

Different spatial arrangements of atoms due to rotation around a single bond.

Example: *Ethane* conformers – staggered (stable) and eclipsed (unstable).

In *cyclohexane*: chair, boat, and twist-boat conformations.

5.1.8. Structural vs. Stereoisomerism

Structural isomers differ in connectivity, stereoisomers differ in spatial orientation.

Structural isomerism affects molecular structure more drastically than stereoisomerism.

5.1.9. Importance of Isomerism

Explains diversity of organic compounds.

Pharmaceutical significance: some isomers are active drugs, while others can be inactive or toxic.
Example: *Thalidomide enantiomers*.

Used in material science, biochemistry, and industry.

5.1.10. Examples and Applications

Isomers of C_4H_{10}: *n-butane* and *isobutane*.

Isomers of C_4H_8: *1-butene, 2-butene (cis & trans), cyclobutane, methylcyclopropane*.

Biological Importance: Glucose has different isomers (α and β anomers).

Drug Industry: Isomer-specific drug action (ibuprofen, thalidomide).

5.1.11. Summary

Isomerism is the phenomenon where compounds have the same molecular formula but different arrangements of atoms.

It is broadly classified into **Structural isomerism** and **Stereoisomerism**.

Structural isomers differ in bonding sequence (chain, position, functional group, tautomerism, etc.).

Stereoisomers have the same connectivity but differ in spatial arrangement (geometrical and optical isomerism).

Isomerism explains why compounds with the same formula can have different physical and chemical properties.

Multiple Choice Questions

Q1. Compounds having the same molecular formula but different structural arrangements are called:

a) Isotopes

b) Isomers

c) Allotropes

d) Polymers

Answer: b) Isomers

Q2. Which of the following is an example of *functional group isomerism*?

a) Ethanol and Dimethyl ether

b) Butane and Isobutane

c) Maleic acid and Fumaric acid

d) Cis-2-butene and Trans-2-butene

Answer: a) Ethanol and Dimethyl ether

Q3. Which type of isomerism is shown by glucose and fructose?

a) Chain isomerism

b) Position isomerism

c) Functional group isomerism

d) Optical isomerism

Answer: c) Functional group isomerism

Q4. Geometrical isomerism is possible in:

a) CH_4

b) C_2H_2

c) $C_2H_4Cl_2$ (in cis/trans form)

d) C_2H_6

Answer: c) $C_2H_4Cl_2$

Q5. Optical isomerism arises due to:

a) Restricted rotation around double bond

b) Presence of conjugation

c) Presence of a chiral carbon atom

d) Position of substituents

Answer: c) Presence of a chiral carbon atom

Short Questions

1. Define isomerism and give two examples.
2. Differentiate between structural isomerism and stereoisomerism.
3. What are cis–trans isomers? Give an example.
4. Explain chain isomerism with an example.
5. What is meant by enantiomers?

Long Questions

1. Discuss different types of **structural isomerism** with suitable examples.
2. Explain **geometrical isomerism** with reference to cis–trans isomers in alkenes.
3. Describe **optical isomerism** with the help of a diagram showing chirality and enantiomers.
4. Write a detailed note on **tautomerism** with keto–enol examples.
5. Compare **structural isomers and stereoisomers** in detail with at least two examples each.

Unit 5.2

Priority Rule and nomenclature for Isomers

5.2.1. Introduction

Isomers are compounds that have the same molecular formula but different structural arrangements or spatial orientation of atoms.
Nomenclature of isomers requires **clear priority rules** so that the correct systematic name can be given according to **IUPAC conventions**.

5.2.2. Types of Isomerism

Structural Isomerism (Constitutional isomerism)

– Atoms connected differently.

Chain isomerism

Position isomerism

Functional group isomerism

Metamerism

Tautomerism

Stereoisomerism

– Same connectivity, different spatial arrangement.

Geometrical isomerism (cis/trans or E/Z)

Optical isomerism (R/S configuration, enantiomers, diastereomers)

5.2.3. General Priority Rules (IUPAC)

5.2.3.1. Cahn–Ingold–Prelog (CIP) Rules

These rules are used for assigning priority in stereoisomerism (R/S and E/Z).

Atomic number: Higher atomic number = higher priority. (I > Br > Cl > F > O > N > C > H)

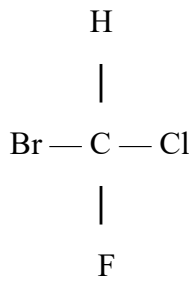
First point of difference: If directly attached atoms are same, compare the next set of atoms until a difference is found.

Multiple bonds: Treat multiple bonds as if the atom is duplicated or triplicated.

Example: C=O is treated as C bonded to two O atoms.

Isotopes: Higher mass number gets higher priority.

Diagram: CIP Priority Rule (Atomic Number Rule)
Example: CHBrClF



Priority order: Br (Z=35) > Cl (Z=17) > F (Z=9) > H (Z=1)

5.2.4. Priority in Geometrical Isomerism

Cis/Trans (for simple cases with identical substituents).

E/Z system (CIP rule applied when substituents differ):

Compare groups attached to each C of the double bond.

If higher-priority groups are on the **same side**, it is **Z** (zusammen = together).

If higher-priority groups are on the **opposite side**, it is **E** (entgegen = opposite).

5.2.5. Priority in Optical Isomerism

Assign R/S configuration using CIP rules:

Assign priorities to substituents (1 = highest, 4 = lowest).

Place lowest priority (usually H) behind the plane.

Trace path from 1 → 2 → 3.

Clockwise = **R** (rectus).

Counterclockwise = **S** (sinister).

5.2.6. Nomenclature of Structural Isomers

Chain isomers: Named by identifying the longest carbon chain (e.g., pentane vs. 2-methylbutane).

Position isomers: Named by numbering to give functional group/branch the lowest locant (e.g., 1-propanol vs. 2-propanol).

Functional isomers: Named according to different functional groups (e.g., ethanol vs. dimethyl ether).

5.2.7. Nomenclature of Stereoisomers

Geometrical Isomers: Prefix **cis/trans** or **E/Z** before the name.

Example: cis-2-butene or (E)-2-butene.

Optical Isomers: Prefix **R/S** configuration before the name.

Example: (R)-lactic acid vs. (S)-lactic acid.

Diastereomers: Use a combination of E/Z and R/S descriptors if multiple stereocenters exist.

5.2.8. Special Priority Rules

Functional Group Priority for Parent Chain Selection (highest to lowest, some common ones):

Carboxylic acids (–COOH)

Sulfonic acids ($–SO_3H$)

Esters (–COOR)

Acid halides (–COCl)

Amides ($–CONH_2$)

Nitriles (–CN)

Aldehydes (–CHO)

Ketones (–CO–)

Alcohols (–OH)

Amines ($–NH_2$)

Alkenes (C=C)

Alkynes (C≡C)

Alkanes (C–C)

Halides (–X)

(Highest priority group decides suffix; others are prefixes.)

5.2.9. SUMMARY

The Cahn–Ingold–Prelog (CIP) priority rules are applied to systematically name stereoisomers and distinguish between their configurations such as R/S (optical isomers) and E/Z (geometrical isomers). According to these rules, the priority of substituents is first determined by the atomic number of the atom directly attached to the chiral center or double bond; the higher the atomic number, the higher the priority. If two substituents have the same atom, then the next atoms along the chain are compared until a difference is found. In cases of multiple bonds, the bonded atom is considered duplicated or triplicated for priority assignment. By following these rules, chemists can provide a clear, unambiguous nomenclature for isomers, avoiding confusion in structural representation.

Multiple Choice Questions

Q1. Compounds having the same molecular formula but different structural arrangements are called:

a) Isotopes

b) Isomers

c) Allotropes

d) Polymers

Answer: b) Isomers

Q2. Which of the following is an example of *functional group isomerism*?

a) Ethanol and Dimethyl ether

b) Butane and Isobutane

c) Maleic acid and Fumaric acid

d) Cis-2-butene and Trans-2-butene

Answer: a) Ethanol and Dimethyl ether

Q3. Which type of isomerism is shown by glucose and fructose?

a) Chain isomerism

b) Position isomerism

c) Functional group isomerism

d) Optical isomerism

Answer: c) Functional group isomerism

Q4. Geometrical isomerism is possible in:

a) CH_4

b) C_2H_2

c) $C_2H_4Cl_2$ (in cis/trans form)

d) C_2H_6

Answer: c) $C_2H_4Cl_2$

Q5. Optical isomerism arises due to:

a) Restricted rotation around double bond

b) Presence of conjugation

c) Presence of a chiral carbon atom

d) Position of substituents

Answer: c) Presence of a chiral carbon atom

Short Questions

1. Define isomerism and give two examples.
2. Differentiate between structural isomerism and stereoisomerism.
3. What are cis–trans isomers? Give an example.
4. Explain chain isomerism with an example.
5. What is meant by enantiomers?

Long Questions

1. Discuss different types of **structural isomerism** with suitable examples.
2. Explain **geometrical isomerism** with reference to cis–trans isomers in alkenes.
3. Describe **optical isomerism** with the help of a diagram showing chirality and enantiomers.
4. Write a detailed note on **tautomerism** with keto–enol examples.

5. Compare **structural isomers and stereoisomers** in detail with at least two examples each.

Unit 5.3

Optical activity

Optical Activity

1. Introduction

Optical activity is a property of certain substances that enables them to rotate the plane of polarized light. This property arises due to the presence of **chiral molecules** that lack elements of symmetry (such as a plane of symmetry or center of symmetry).

Substances that rotate plane-polarized light are called **optically active substances**.

This phenomenon was first observed by Jean-Baptiste Biot (1815) and studied systematically by Louis Pasteur (1848) in tartaric acid.

2. Basic Concepts

2.1 Polarized Light

Ordinary light vibrates in all directions perpendicular to the direction of propagation.

When passed through a **Nicol prism** or polarizer, only one vibration plane is transmitted → **plane polarized light**.

2.2 Optical Rotation

When plane-polarized light passes through a chiral substance:

If it rotates the plane **to the right (clockwise)** → the substance is **dextrorotatory (+)**.

If it rotates the plane **to the left (anticlockwise)** → the substance is **laevorotatory (–)**.

3. Chirality and Optical Activity

Chirality: A molecule is chiral if it cannot be superimposed on its mirror image.

Chiral center: An sp^3 carbon atom bonded to four different groups.

Chiral molecules → optically active (usually).

Achiral molecules → optically inactive.

Example:

Lactic acid has one chiral carbon → exists in two enantiomeric forms:

(+)-lactic acid (dextrorotatory)

(–)-lactic acid (laevorotatory)

4. Enantiomers and Diastereomers

4.1 Enantiomers

Non-superimposable mirror images.

Same physical properties (mp, bp, density, solubility) but **opposite optical rotation**.

Rotate light by equal magnitude but opposite direction.

4.2 Diastereomers

Stereoisomers that are not mirror images.

Differ in physical and chemical properties.

May or may not show optical activity.

5. Measurement of Optical Activity

5.1 Polarimeter

An instrument used to measure angle of rotation (α).

Main parts:

Light source (monochromatic sodium D-line, λ = 589 nm).

Polarizer (Nicol prism).

Sample tube containing optically active substance.

Analyzer (second Nicol prism to measure rotation).

5.2 Observations

Angle of rotation α measured.

Sign of rotation determined: (+) or (–).

6. Specific Rotation

Optical activity depends on concentration, path length, temperature, and wavelength. To standardize:

$$[\alpha]_{\lambda}^{T} = \frac{\alpha}{l \cdot c}$$

Where:

- $[\alpha]_{\lambda}^{T}$ = Specific rotation at temperature T and wavelength λ
- α = observed angle of rotation (degrees)
- l = path length of tube (dm)
- c = concentration of solution (g/mL or g/100 mL depending on system)

Example:

If α = +5°, l = 1 dm, c = 0.1 g/mL →

$[\alpha] = \frac{5}{1 \times 0.1} = +50^{\circ}$

7. Factors Affecting Optical Activity

Wavelength of light – rotation varies with wavelength (Optical Rotatory Dispersion, ORD).

Temperature – higher temperature usually decreases optical rotation.

Solvent – different solvents change molecular interactions.

Concentration and Path length – directly proportional to observed rotation.

Molecular structure – number of chiral centers and substituents affect optical behavior.

8. Types of Optically Active Substances

Chiral molecules: Molecules with at least one asymmetric carbon.

Atropisomers: Optical activity due to restricted rotation (e.g., substituted biphenyls).

Helical structures: DNA, proteins show optical activity.

Inorganic complexes: e.g., $[Co(en)_3]^{3+}$.

9. Special Optical Phenomena

Racemization: Conversion of an optically active compound into an equimolar mixture of enantiomers (racemic mixture, optically inactive).

Resolution: Separation of racemic mixture into pure enantiomers.

Meso compounds: Optically inactive despite having chiral centers due to internal plane of symmetry.

Optical Rotatory Dispersion (ORD): Variation of rotation with wavelength.

Circular Dichroism (CD): Differential absorption of left vs. right circularly polarized light.

10. Applications of Optical Activity

Determination of purity of chiral compounds.

Quality control in pharmaceuticals (many drugs are active only in one enantiomeric form).

Studying structure of biomolecules (proteins, nucleic acids).

Determining sugar concentrations (polarimetry in food industry).

Research in stereochemistry and asymmetric synthesis.

11. Summary

Optical activity is the ability of a substance to rotate the plane of polarized light when passed through its solution.

It arises due to the presence of a **chiral center** (usually a carbon atom attached to four different groups).

Substances that rotate light to the **right (clockwise)** are called **dextrorotatory (+)**, while those rotating it to the **left (anticlockwise)** are **levorotatory (–)**.

The rotation is measured using a **polarimeter**.

Compounds that exist as **non-superimposable mirror images** are called **enantiomers**, and they show equal but opposite optical rotations.

Multiple Choice Questions (with answers)

Q1. Optical activity is due to:

a) Presence of conjugated double bond

b) Presence of chiral center

c) Resonance stabilization

d) Hydrogen bonding

Answer: b) Presence of chiral center

Q2. A compound that rotates plane-polarized light to the right (clockwise) is called:

a) Levorotatory (–)

b) Dextrorotatory (+)

c) Mesomeric

d) Geometrical isomer

Answer: b) Dextrorotatory (+)

Q3. Which instrument is used to measure optical rotation?

a) Spectrophotometer

b) Polarimeter

c) Refractometer

d) Chromatograph

Answer: b) Polarimeter

Q.4. Enantiomers have:

a) Identical physical and chemical properties in achiral environment

b) Different boiling points

c) Different molecular formula

d) Different functional groups

Answer: a) Identical physical and chemical properties in achiral environment

Q.5. A mixture containing equal amounts of two enantiomers is:

a) Racemic mixture (optically inactive)

b) Dextrorotatory

c) Levorotatory

d) Geometrical isomer

Answer: a) Racemic mixture (optically inactive)

Short Questions

1. Define optical activity.
2. What is meant by dextrorotation and levorotation?

3. Name the instrument used to measure optical rotation.
4. What is a racemic mixture?
5. Differentiate between enantiomers and diastereomers.

Long Questions

1. Explain the concept of chirality and its role in optical activity with suitable examples.
2. Discuss the principle and working of a **polarimeter**.
3. Describe enantiomers and racemic mixtures in detail with examples.
4. Explain the difference between optical activity and geometrical isomerism.
5. Write a detailed note on **applications of optical activity** in chemistry and biology.

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