Lecture Notes: Electric Dipole

1. Definition and Examples of Dipoles

Definition:

- An **electric dipole** consists of **two equal and opposite charges** ($+q$ and $-q$) separated by a small distance $2a$.
- The **dipole moment** ($\mathbf{p}$) is a vector quantity defined as:

$$\mathbf{p} = q \cdot (2a)$$

  - **Direction:** From **negative to positive charge**.

Examples of Electric Dipoles:

1. **Water Molecule (H_2O)** – The oxygen atom has a slight negative charge, while the hydrogen atoms have a slight positive charge.
2. **Ammonia Molecule (NH_3)** – Due to the asymmetry in charge distribution.
3. **Polar Molecules** – HCl, CO, etc., exhibit a dipole moment.
4. **Artificial Dipoles** – A pair of oppositely charged metal spheres in a physics experiment.

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2. Electric Field Due to a Dipole

A. Electric Field on the Axial Line (End-On Position)

- The **axial line** is the line passing through both charges of the dipole.
- The net electric field at a point on the axial line (distance r from the center) is:

$$E_{\text{axial}} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{2p}{r^3}$$

  Where:
  - ε_0 = Permittivity of free space.
  - $p = q \cdot 2a$ = Dipole moment.
  - r = Distance from the center of the dipole.
- **Direction:** Along the dipole axis (outward for $+q$ and inward for $-q$).

B. Electric Field on the Equatorial Line (Broadside-On Position)

- The **equatorial line** is the perpendicular bisector of the dipole.
- The net electric field at a point on the equatorial line (distance r from the center) is:

$$E_{\text{equatorial}} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{p}{r^3}$$

- **Direction:** Opposite to the dipole moment ($-\mathbf{p}$).

🔹 **Key Observation:** The field along the axial line is **twice** the field along the equatorial line.

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3. Torque on a Dipole in a Uniform Electric Field

- When a dipole is placed in a uniform electric field E at an angle θ, it experiences a **torque (τ)** given by:

$$\tau = pE\sin\theta$$

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Where:

  - p = Dipole moment.
  - E = External electric field.
  - θ = Angle between $\mathbf{p}$ and $\mathbf{E}$.
- **Effect of Torque:**
  - The torque **rotates** the dipole to align it with the field direction.
  - If the dipole is already aligned with the field ($\theta = 0^\circ$ or 180°), the torque is **zero**.

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4. Potential Energy of a Dipole in an Electric Field

- The **potential energy (U)** of an electric dipole in a uniform electric field is:

$$U = -pE\cos\theta$$

  - U is **minimum** when $\theta = 0^\circ$ (aligned with E).
  - U is **maximum** when $\theta = 180^\circ$ (opposite to E).
- The work required to rotate the dipole is stored as **potential energy**.

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5. Summary of Key Formulas

Concept	Formula	Direction
Dipole Moment	$p = q(2a)$	From $-q$ to $+q$
Electric Field on Axial Line	$E_{\text{axial}} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{2p}{r^3}$	Along the dipole axis
Electric Field on Equatorial Line	$E_{\text{equatorial}} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{p}{r^3}$	Opposite to dipole moment
Torque on Dipole	$\tau = pE\sin\theta$	Rotates dipole towards alignment
Potential Energy	$U = -pE\cos\theta$	Minimum at $\theta = 0^\circ$

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6. Applications of Electric Dipoles

1. **Water as a Polar Molecule** – Helps in dissolving salts and ionic substances.
2. **Microwave Ovens** – Water molecules rotate in an electric field, generating heat.
3. **Electrostatics in Chemistry** – Dipole interactions in molecular structures.
4. **Sensors and Detectors** – Dipole-based materials detect electric fields.
