Chapter

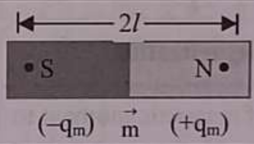
11 Magnetic Materials

Quick Review

➤ **Magnetic dipole moment:**

Magnetic Dipole Moment ⇒ It represents the strength of a magnet.

$$\vec{m} = q_m \left(2\vec{l}\right)$$



Torque acting on a magnetic dipole in a uniform magnetic field

- $\tau = mB \sin\theta$

- The torque tends to align the magnetic dipole moment vector with the magnetic field vector.
- This torque is responsible for various phenomena, like the behavior of compass needles aligning with Earth's magnetic field, the operation of electric motors based on the interaction between a magnetic field and current-carrying wires

Magnetic potential energy in a uniform magnetic field

- $U_m = -mB \cos\theta$

Case 1 $\theta = 0°, U_m = -mB$	• The bar magnet is in stable equilibrium and has minimum potential energy.
Case 2 $\theta = 180°, U_m = mB$	• The bar magnet is in the most unstable state and has maximum potential energy.
Case 3 $\theta = 90°, U_m = 0$	• The bar magnet is perpendicular to the direction of magnetic field and has zero potential energy.

Time period of angular oscillation

- $T = \dfrac{2\pi}{\omega} = 2\pi\sqrt{\dfrac{I}{mB}}$

➢ Types of Magnetic Materials:

Types of Magnetic Materials

Diamagnetic

Substances which when placed in a magnetic field, are feebly magnetised in a direction opposite to that of the magnetising field are called diamagnetic substances.

Paramagnetic

Substances which when placed in a magnetic field are feebly magnetised in the direction of the magnetising field are called paramagnetic substances.

Ferromagnetic

Substances which when placed in a magnetising field are strongly magnetised in the direction of the magnetising field are called ferromagnetic substances.

➢ Properties of Magnetic Material:

Properties

Magnetization

The ratio of magnetic moment to the volume of the material is called magnetization.

Magnetic permeability (μ)

The ratio of the magnitude of total field inside the material to that of intensity of magnetising field is called magnetic permeability.

Magnetic susceptibility (χ)

The ratio of magnitude of intensity of magnetization to that of magnetic intensity is called as magnetic susceptibility.

Magnetic intensity

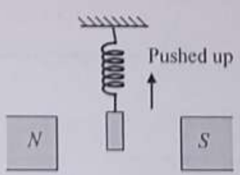
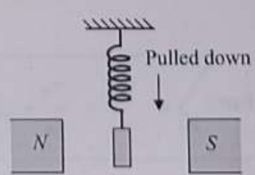
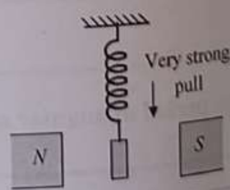
The ratio of the strength of magnetising field to the permeability of free space is called as magnetic intensity.

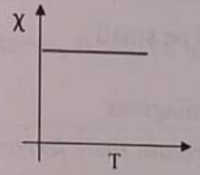
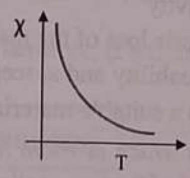
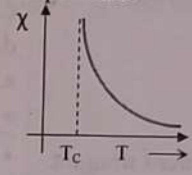
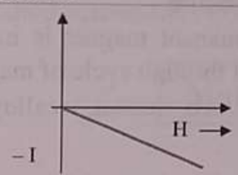
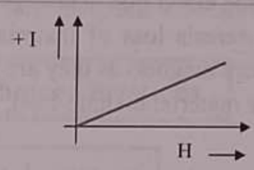
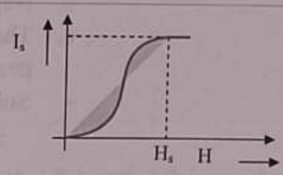
It is a quantity used to describe a magnetic phenomenon in terms of the magnetic field.

Relative permeability (μ_r)

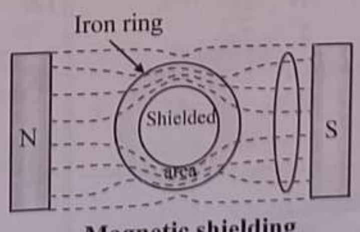
The ratio of magnetic permeability of the material (μ) and magnetic permeability of free space (μ_0) is called relative permeability.

➢ Properties of Dia-, Para- and Ferro-magnetic substances:

Property	Diamagnetic substances	Paramagnetic substances	Ferromagnetic substances
Cause and Explanation of magnetism	Orbital motion of electrons	Spin motion of electrons	Formation of domains
Behaviour in a non-uniform magnetic field	They are repelled in external magnetic field hence move from high to low field region. 	These are feebly attracted in an external magnetic field they move from low to high field region hence slightly attracted. 	They easily move from low to high field region hence strongly attracted. 
State of magnetisation	Feebly magnetised in a opposite direction.	Feebly magnetised in same direction.	Strongly magnetised in same direction.

Substance placed inside a Magnetising field (H) OR The value of magnetic induction B	$B < B_0$ (where, B_0 is the magnetic induction in vacuum = $\mu_0 H$)	$B > B_0$	$B >> B_0$
Magnetic susceptibility χ	Low and negative $\lvert\chi\rvert \approx 1$	Low and positive $\chi \approx 1$	Positive and high $\chi \approx 10^2$
Dependence of χ on temperature	Independent of temperature (except *Bi* at low temperature). 	On cooling, these get converted to ferromagnetic materials at Curie temperature. 	These get converted into paramagnetic materials at Curie temperature. 
Relative permeability (μ_r)	$\mu_r < 1$ (as B is less than H.)	$\mu_r > 1$ (as B is slightly greater than H.)	$\mu_r >> 1$, of the order of 10^2
Intensity of magnetisation (I)	I and H are in opposite direction, value can be negative.	I and H are in same direction, value is low (positive).	I is in the direction of H and value is very high (positive).
I-H curves			
Magnetic moment (m)	Very low (≈ 0)	Very low but not zero	Very high
Examples	Cu, Ag, Au, Zn, Bi, Sb, NaCl, H_2O, air, diamond etc.	Al, Mn, Pt, Na, $CuCl_2$, O_2 and crown glass.	Fe, Co, Ni, Cd, Fe_3O_4 etc.

Ferromagnetism

Curie temperature	• Curie's Law: $\frac{I}{H} = \frac{C}{T}$ or $\chi = \frac{C}{T}$ i.e., the magnetic susceptibility of paramagnetic material is inversely proportional to its absolute temperature. • *The minimum temperature at which the domain structure of ferromagnetic substance collapses completely and it is converted into paramagnetic substance is called as Curie temperature.* • Above Curie temperature, ferromagnetic substances lose their magnetic property.
Magnetic Shielding	• When a soft ferromagnetic material is kept in a uniform magnetic field, large number of magnetic lines crowd up inside the material leaving a few outside. • For a closed structure, like an iron ring, kept in magnetic field, very few lines of force pass through the enclosed space. This effect is known as magnetic shielding.  **Magnetic shielding**

Hysteresis	• *The lag of intensity of magnetisation (I) or magnetic induction (B) behind the magnetising field (H) during the process of magnetisation and demagnetisation of a magnetic material is called hysteresis.* • Exhibited only by ferromagnetic substances. • Area of I - H curve over a complete cycle is proportional to the net energy absorbed per unit volume.
Electromagnet	• The properties of the material of electromagnet are as follows: a. Low retentivity b. High value of saturation magnetisation c. Low coercivity d. The hysteresis loss of the material should be small e. High permeability and susceptibility • Soft iron is a suitable material for electromagnets
Permanent magnet	• *Substances which at room temperature retain their ferromagnetic property for a long period of time are called permanent magnets.* • The important requirement of the magnetic material are: a. High retentivity b. High coercivity c. Immunity to loss of magnetisation by alternating fields d. Negligible effect due to change in temperature e. The hysteresis loss of material of permanent magnet is immaterial in case of permanent magnets as they are never put through cycle of magnetisation. • Suitable material include steel, cobalt, alnico, ticonol, vicalloy etc.

Formulae

1. Torque acting on magnetic dipole:
$\tau = m\,B\,\sin\theta$

2. Potential energy of a bar magnet placed in a uniform magnetic field:
$U = -mB\cos\theta$

3. The small work done in rotating a bar magnet by an angle $d\theta$ (dipole moment is $\vec{m}$) will be:
$d\vec{W} = \tau \cdot d\theta$
$$\int_0^w dW = \int_{\theta_1}^{\theta_2} \tau \cdot d\theta \Rightarrow w = \int_{\theta_1}^{\theta_2} (m\,B\sin\theta)\,d\theta$$
$$= mB(\cos\theta_1 - \cos\theta_2)$$

4. Time period of angular oscillations of a bar magnet:
$$T = 2\pi\sqrt{\frac{I}{mB}}$$

5. For a revolving electron:
i. Magnetic moment, $m_{orb} = \frac{evr}{2} = \frac{eL}{2m_e}$
where, L = angular momentum
ii. $I = \frac{e}{T} = ef = \frac{e}{2\pi r/v} = \frac{ev}{2\pi r}$

6. Gyromagnetic ratio: $\frac{m_{orb}}{L} = \frac{e}{2m_e}$

7. Bohr magneton: $\frac{eh}{4\pi m_e}$

8. Magnetic intensity: $H = \frac{B_0}{\mu_0}$

9. Magnetization:
i. $M = \frac{m_{net}}{V}$ ii. $M = \frac{CB_{ext}}{T}$
where, C = Curie constant

10. Magnetic field due to iron core in toroid:
$B = \mu_0(H + M) = B_0 + B_M = \mu_0\mu_r H = \mu H$
where, $B_0 = \mu_0 H$ and $B_M = \mu_0 M$

11. Magnetic susceptibility: $\chi = \frac{M}{H} = \frac{B - B_0}{B_0}$

12. Magnetic permeability: $\mu = \frac{B}{H}$

13. Relation between permeability and susceptibility:
$\mu = \mu_0(1 + \chi)$

14. Relative permeability:
$$\mu_r = \frac{\mu}{\mu_0} = 1 + \chi$$

Shortcuts

1. If a rectangular bar magnet is cut in n equal parts then time period of each part will be $\frac{1}{\sqrt{n}}$ times that of complete magnet $\left(\text{i.e., } T' = \frac{T}{\sqrt{n}}\right)$ while for short magnet $T' = \frac{T}{n}$. If nothing is said then bar magnet is treated as short magnet.
2. If the body is paramagnetic, B will be slightly greater than H. Therefore, μ will be slightly greater than 1.
3. For diamagnetic substance, B will be less than H. Therefore, μ will be less than 1.