MAGNETIC PROPERTIES OF MATERIALS- INDUCTION, SUSCEPTIBILITY AND PERMEABILITY

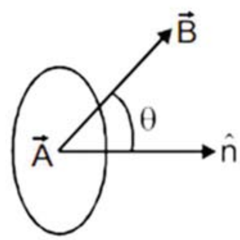
Intensity of Magnetism

$$I = \frac{M}{V} \text{ (Units A/m or oersted)}$$

$$I = \frac{\text{Pole strength}}{\text{area}} \begin{bmatrix} \because M = m \times I \\ \because V = A \times I \end{bmatrix}$$

Magnetic flux

Magnetic flux measures how much magnetic field passes through a certain area. Imagine a shape enclosing an area 'A' with a magnetic field 'B' inside. The magnetic flux through 'A', shown as 'Φ', is calculated using the formula:



$$\Phi = BA\cos(\theta)$$

Here, 'θ' is the angle between the magnetic field 'B' and a line perpendicular to the surface. This line points away from the enclosed surface.
When 'B' is perpendicular to this line ($\theta = 90°$), the magnetic flux through 'A' is zero. This happens because the magnetic field doesn't cross the surface, resulting in no flux.
The weber (Wb) is the unit for magnetic flux.

Key Points:

- The line perpendicular to the surface is crucial for calculating flux.
- For open surfaces, choose one direction for the perpendicular line.
- For closed surfaces, the line points outward from the enclosed area.
- Magnetic flux tells us how many magnetic lines cross a surface.
- Magnetic field lines always form loops, so enclosing them is vital for accurate flux calculations.

Magnetic Induction

$$B = B_0 + \mu_0 I$$

$$B = \mu_0 H + \mu_0 I \quad \begin{bmatrix} B_0 = \text{ applied magnetic field} \\ \mu_0 I = \text{ magnetic fielddue to magnetisation} \end{bmatrix}$$

$$B = \mu_0 (H + I)$$

Magnetic Susceptibility

$$\chi_m = \frac{l}{H} \text{ (no units)}$$

Magnetic Permeability

$$\mu = \frac{B}{H} \Rightarrow B = \mu H$$

From above $B = \mu_0(H + I)$

$$\Rightarrow \mu H = \mu_0(H + I)$$

$$\frac{\mu}{\mu_0} = 1 + \frac{I}{H}$$

$\mu_r = 1 + \chi_m$ where $\mu_r =$ relative permeability.

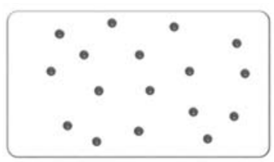
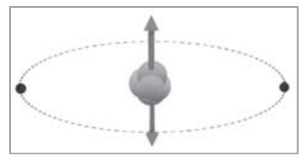
Classification of Magnetic Materials

Based on their behavior there are three types of magnetizing field

1. Diamagnetic
2. Paramagnetic
3. Ferromagnetic

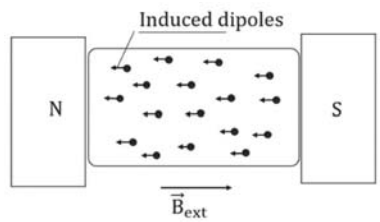
1. Diamagnetic

- Materials have paired electrons in their orbit.
- Resultant magnetic moment becomes ZERO.
- Materials in which individual magnetic moment of each atom or molecule is zero are called Diamagnetic Materials.
- They do not have permanent magnetic dipoles.

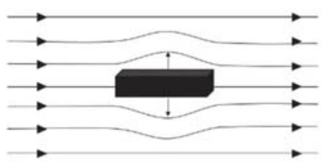
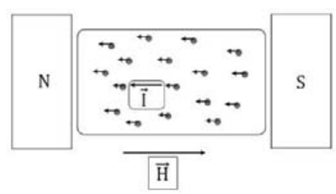
$$\vec{m}_i = 0$$
$$\vec{M}_T = \Sigma\vec{m}_i = 0$$

eg. He, N_2(at STP), NaCl, Water

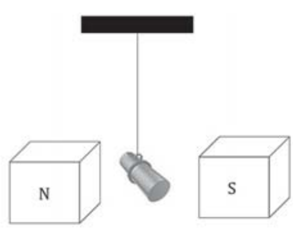


- Dipoles are induced in the material on application of external magnetic field. (Lenz's law)
- A small magnetization occurs opposite to the direction of the external magnetic field.
- Diamagnetic property of a substance is nearly independent of the temperature.
- Induced field $\vec{I}$ is small and opposite to the external field $\vec{H}$

Magnetic Susceptibility: $\vec{I} = \chi\vec{H}$
Relative permeability: $\mu_r = (1 + (\chi)$

- The magnetic field lines are weakly repelled by diamagnetic materials.



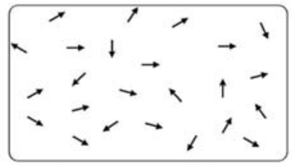
- A diamagnetic rod sets itself perpendicular to the field as field is stronger at poles (align itself along weaker field).

Superconductors

- Diamagnetic materials when cooled to very low temperatures exhibit perfect diamagnetism.
- They also show perfect conductivity and thus called as Superconductors.
- These superconductors expel the pre-established external field.

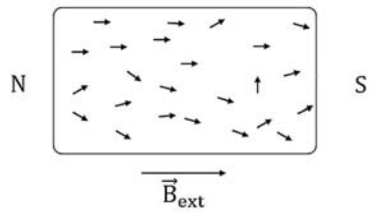
2. **Paramagnetic**

- These substances, when placed in an external magnetic field, acquire a feeble magnetization in the same sense as the applied field .
- In the absence of external field, these dipoles are randomly distributed in volume giving net magnetic moment zero.

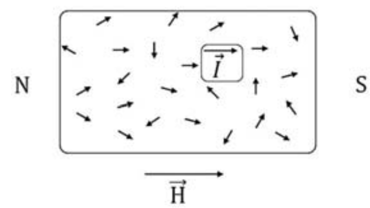


eg. O_2(at STP), Na, FeO, Al

- The dipoles are aligned in the direction of applied external magnetic field.
- This causes weak attraction with the external magnetic field and this phenomenon is called Paramagnetism.



- The alignment is partial.
- The Paramagnetic property of a substance depends on temperature
- Induced field $\vec{I}$ is much larger and along the external field $\vec{H}$.



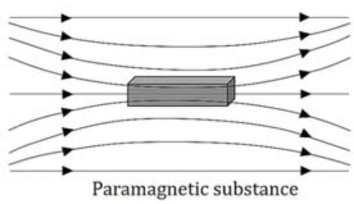
Magnetic Susceptibility:

$$\vec{I} = \chi\vec{H}$$

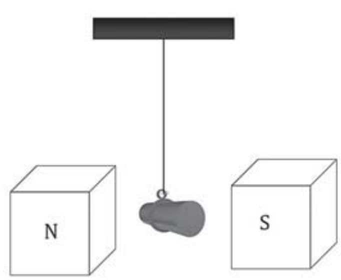
Relative permeability:

$$\mu_r = (1 + \chi)$$

μ_r: Slightly more than one



The magnetic field lines become denser inside paramagnetic materials when placed in external magnetic field.

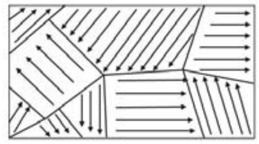


A paramagnetic rod sets itself parallel to the field as the field is stronger at poles.

3. **Ferromagnetic**

- Ferromagnetic substances are those which get strongly magnetized when placed in an external magnetic field.

- The individual atoms (or ions or molecules) in a ferromagnetic material possess a permanent dipole moment.

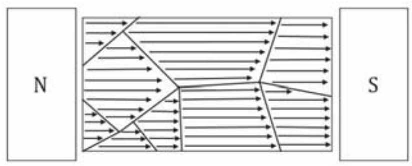


$$\vec{m}_i \neq 0$$

- These individual dipole moments interact with one another in such a way that they spontaneously align themselves in a common direction over a macroscopic volume called domain.
- In the absence of external magnetic field, the domains are randomly oriented giving net magnetic moment zero.
  eg. Fe, Co, Ni and their alloys.

$$\vec{M}_T = \Sigma \vec{m}_i = 0$$

- If the magnetic field is applied, domains orient themselves in the favour of the applied field.

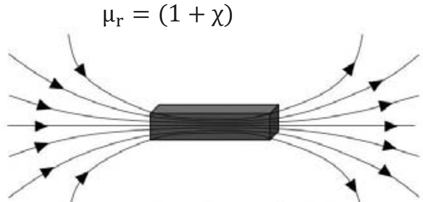


- The ferromagnetic property of a substance depends on temperature.
- Induced field $\vec{I}$ is much larger and along the external field $\vec{H}$.
  Magnetic Susceptibility:

$$\vec{I} = \chi \vec{H}$$

  Relative permeability:

$$\mu_r = (1 + \chi)$$



Ferromagnetic substance

- The magnetic field lines gets greatly enhanced inside ferromagnetic materials when placed in an external magnetic field.

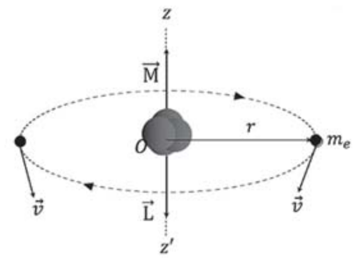
Magnetic Materials

Diamagnetic	Paramagnetic	Ferromagnetic
$-1 \leq \chi \leq 0$	$0 < \chi < k$	$\chi \gg 1$
$0 \leq \mu_r \leq 1$	$0 < \chi < k$	$\chi \gg 1$
$\mu < \mu_0$	$0 < \chi < k$	$\mu \gg \mu_0$

k = Small positive number

Electron theory

Diamagnetism based on Electron theory



Magnetic dipole moment

$$M = \frac{evr}{2}$$

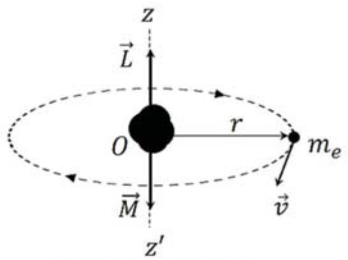
Angular momentum

$$L = m_e vr$$

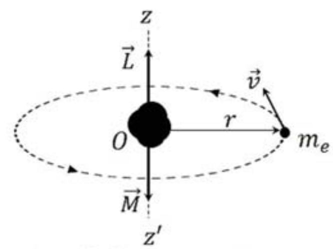
$$\frac{M}{L} = \frac{q}{2m} = \frac{e}{2m}$$

$$\vec{M} = -\frac{e}{2m_g}\vec{L}$$

- Direction of the magnetic dipole moment vector $\vec{M}$ is opposite to the angular momentum vector $\vec{L}$
- All electrons present in diamagnetic material are paired.
- The two electrons in pair have orbital motion in opposite direction and hence possess equal and opposite magnetic moment. So, net magnetic dipole moment is zero



Clockwise rotation



Anti-clockwise rotation

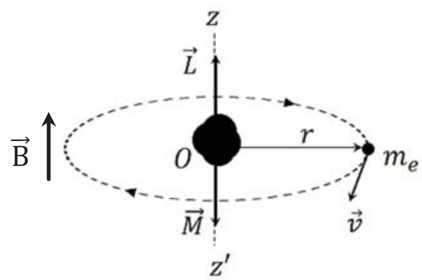
When external magnetic field $\vec{B} = 0$

If electron rotates in anti-clockwise direction:

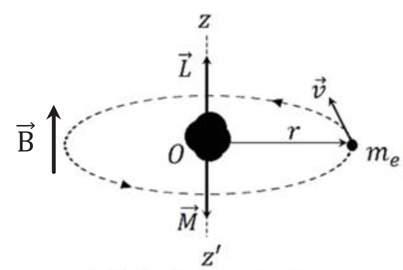
- For this case, the current will be established in clockwise direction and hence, the magnetic moment, $M = \frac{evr}{2}$ will be directed in the downward direction.

If electron rotates in clockwise direction:

- For this case, the current will be established in anti-clockwise direction and hence, the magnetic moment, $M = \frac{evr}{2}$ will be directed in the upward direction.



Clockwise rotation



Anti-clockwise rotation

- Electrostatic force on the electron due to the nucleus:

$$F_{el} = \frac{k(Ze)e}{r^2} = \frac{k(Ze^2)}{r^2}$$

- To balance this force, required centrifugal force:

$$F_{centrifugal} = \frac{mv^2}{r}$$

When external magnetic field $\vec{B} \neq 0$ and directed in the upward direction:

- The magnetic force on the electron due to the magnetic field: $F_M = evB$ towards the centre of the orbit.

If electron rotates in anti-clockwise direction:

Electrostatic force on the electron

$$F_{el} = \frac{k(Ze)e}{r^2} = \frac{k(Ze^2)}{r^2}$$

The net force on the electron

$$F_{net} = \frac{k(Ze^2)}{r^2} + evB$$

- To balance the net force, the velocity of the electron should increase from its own velocity when no magnetic field was there.
- As the velocity of the electron increases, its present magnetic moment (M_1) also increases i.e., $M_1 > M$ and direction is '⊗'

When external magnetic field $\vec{B} \neq 0$ and directed in the upward direction (⊙):
If electron rotates in clockwise direction:
Balancing the force on the electron, we get

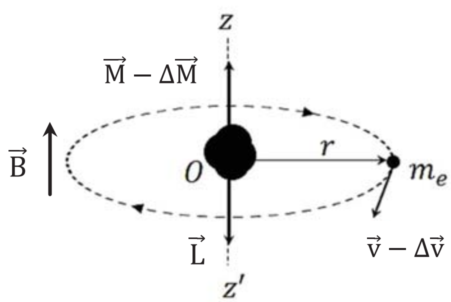
$$\frac{k(Ze^2)}{r^2} = evB + \frac{mv^2}{r}$$

- In this case, to balance the net force, the velocity of the electron should decrease from its own velocity when no magnetic field was there.
- As the velocity of the electron decreases, its present magnetic moment (M_2) also decreases i.e., $M_2 < M$ and direction is '⊙'.
- Thus, net magnetic moment (After application of magnetic field) is: $(M_1 - M_2)$ ⊗
- Whereas, the net magnetic moment (Before application of magnetic field) is: $(M\otimes - M\odot) = 0$

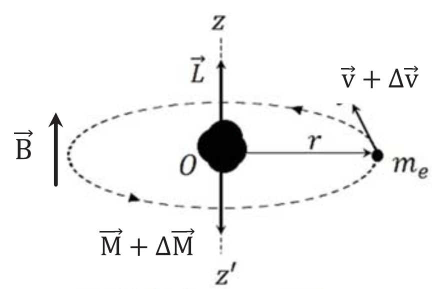
When external magnetic field $\vec{B} \neq 0$
- Magnetic Lorentz force acts on the electron

$$\vec{F} = -e(\vec{v} \times \vec{B})$$

- The magnetic dipole moments of the two electrons in a pair become unequal
- The pair of electrons possesses a net magnetic dipole moment $2\Delta\vec{M}$ in a direction opposite to the direction of external magnetic field.



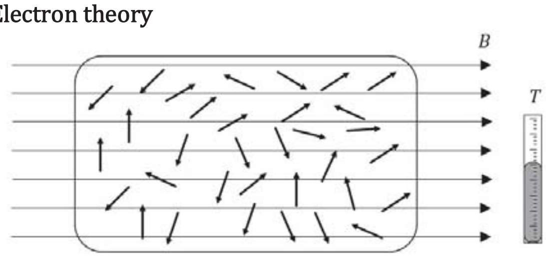
Clockwise rotation

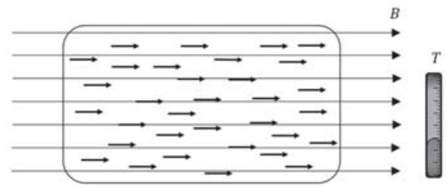


Anti-clockwise rotation

- Thus, the diamagnetic material gets feebly magnetised along a direction opposite to that of the applied field.

Paramagnetism based on Electron theory





- At a higher temperature, if external magnetic field B is applied, dipoles try to align themselves along the direction of the magnetic field but thermal agitation prevents the alignment.
- At a given temperature, Maximum Alignment occurs at certain value of applied magnetic field (B_0).
- At a lower temperature and high external field , all the magnetic dipoles align themselves along the direction of B.