MAGNETISM AND MATTER Ch.5

CBSE Syllabus 2023-24

Chapter–5: Magnetism and Matter

Bar magnet, bar magnet as an equivalent solenoid (qualitative treatment only), magnetic field intensity due to a magnetic dipole (bar magnet) along its axis and perpendicular to its axis (qualitative treatment only), torque on a magnetic dipole (bar magnet) in a uniform magnetic field (qualitative treatment only), magnetic field lines.

Magnetic properties of materials- Para-, dia- and ferro - magnetic substances with examples, Magnetization of materials, effect of temperature on magnetic properties.

* 'Qualitative treatment only' means not going in depth into equations. It is only understanding of working principles.

Ch: 5

Magnetism And Matter

Magnet - A magnet is a material (rock or metal) that has two poles and produces magnetic field.
It attracts small pieces of iron, nickel, cobalt etc.

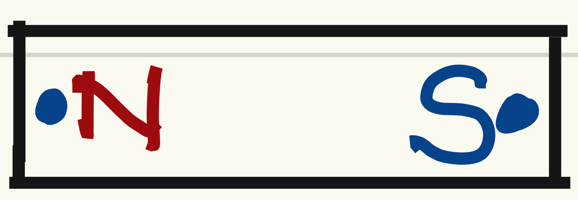
Magnetism - The force exerted by magnets when they attract or repel is called magnetism

* Magnetism caused by the motion of electric charges.

Magnets
- Natural → Permanent
- Artificial → Permanent or temorary

Artificial Magnets: Magnets which are made from iron in different shape and sizes for different uses are called artificial magnets.
* These magnets are magnetised piece of iron steel, cobalt, or nickel.

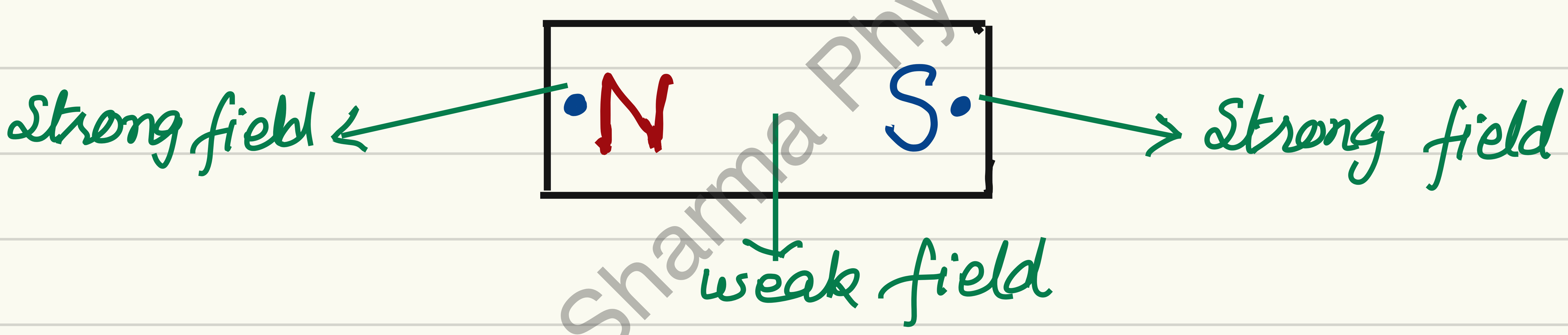
Bar Magnet: A rectangular piece of magnet having north and south pole of equal strength.
* It is also called magnetic dipole.



→ Bar magnet

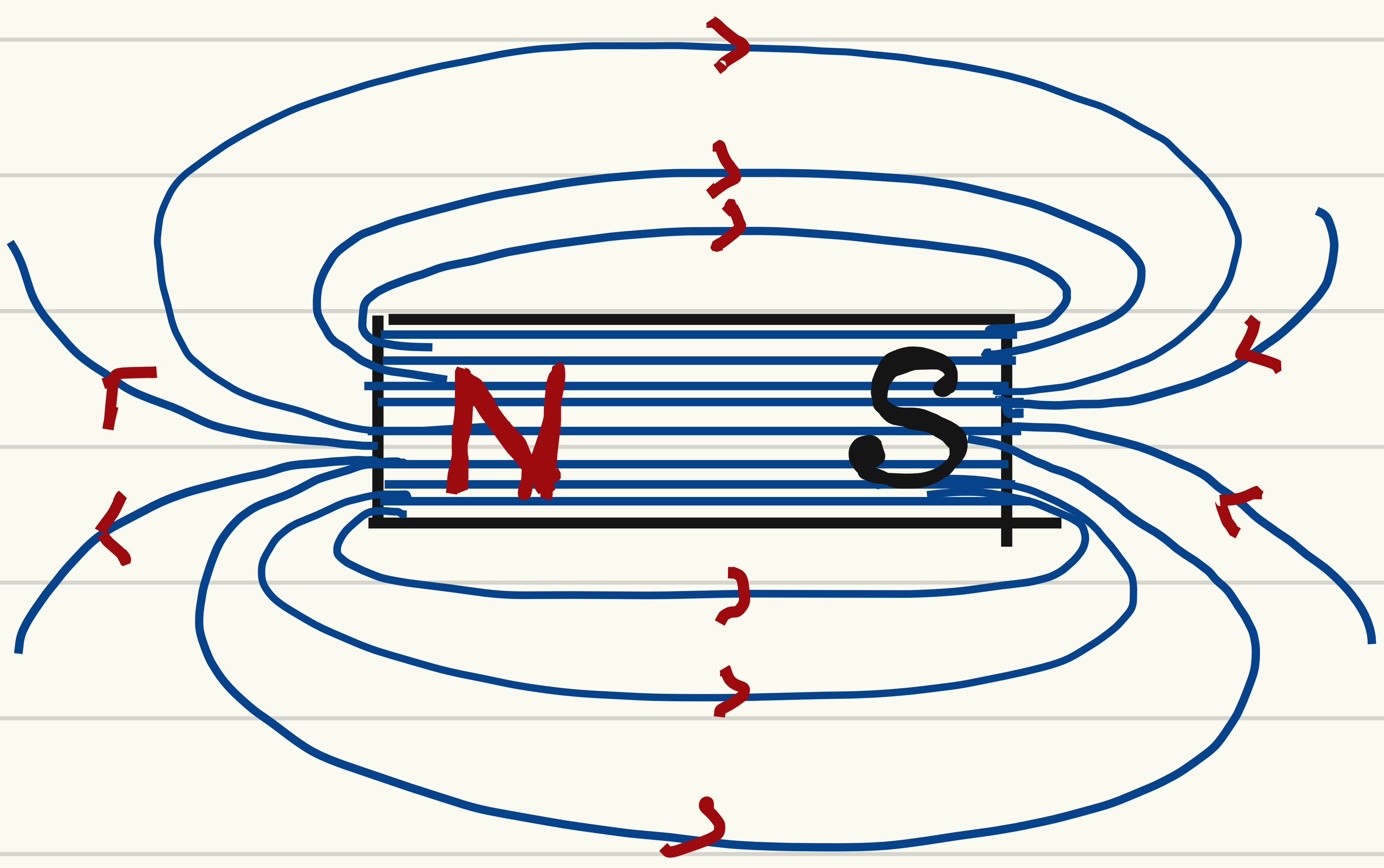
Properties of Bar Magnet:

1. It has two poles - North pole and south pole.
2. It attracts the magnetic materials like iron, cobalt, nickel etc.
3. When a magnet is suspended freely it rests always in north and south direction.
4. Line joining the poles called magnetic axis and a verticle plane passing through this line is called magnetic maridian.
5. Like poles repel and unlike poles attract.
6. Bar magnets are permanent magnets.
7. Magnetic field is maximum at poles and minimum at towards center.



8. Magnetic monopoles do not exist.
9. Magnetic material near a magnet aquires magnetic properties. This is known induced magnetism.

Magnetic Field Lines In A Bar Magnet



"Imaginary lines which sepresent magnetic field are called magnetic field lines or lines of force."

Properties of Magnetic Field lines:

1. The direction of M.F.L is N to S outside the magnet and S to N inside the magnet. Therefore they form closed curve.
2. M.F.L never intersect each other because at the point of intersection there will be two directions of magnetic field which is not possible.
3. They start and end normally.
4. Closer the lines stronger the field, wider the lines weaker the field.

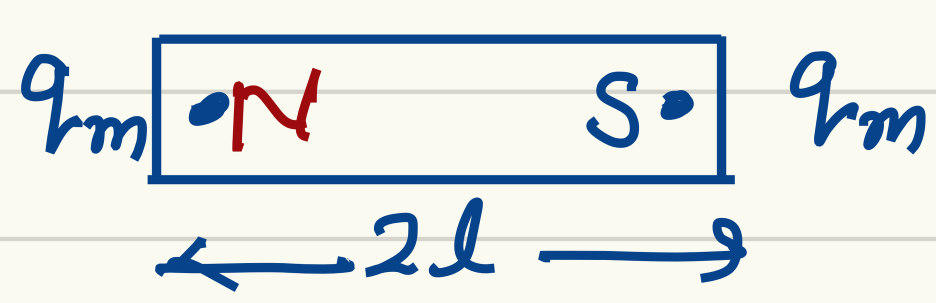
Magnetic Dipole and Magnetic Dipole Moment:

Magnetic Dipole: Two equal and opposite poles separated by a small distance is called magnetic dipole.

Dipole Moment (m): The product of pole strength and magnetic length of a magnetic dipole is called magnetic dipole moment.

$$\boxed{m = q_m \times 2l}$$

$q_m \rightarrow$ pole strength



Magnetic dipole moment is a vector quantity.

Its dir^n is $S \longrightarrow N$

SI unit Am^2 or JT^{-1}

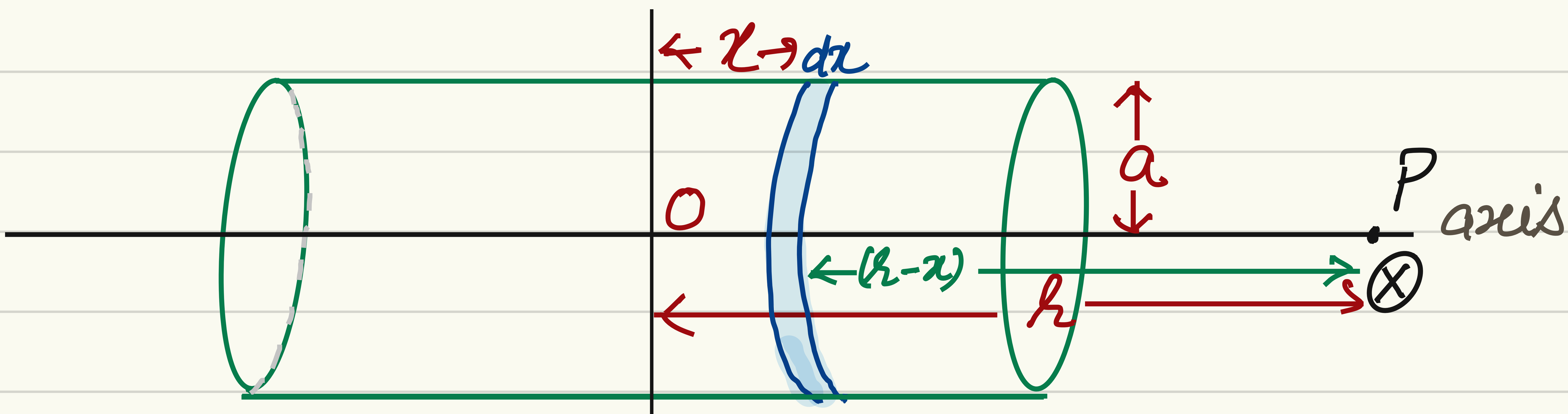
* For current loop magnetic dipole moment

$\vec{m} = I\vec{A} \rightarrow$ Area vector

$I \downarrow$ current

Bar Magnet As An Equivalent Solenoid

Consider a solenoid consists of n turns per unit length. Let its length is $2l$ and radius a.



Finite Solenoid

The magnitude of the field at point P due to the circular element is

$$dB = \frac{\mu_0 n\,dx\, I a^2}{2[(r-x)^2+a^2]^{3/2}}$$

[$\because B = \frac{\mu_0 I a^2}{2(a^2+x^2)^{3/2}}$
here $x \to (r-x)$]

here $n\,dx$ are no. of turns in dx thickness.

Now integrating from $x=-l$ to $x=+l$, then

$$B = \frac{\mu_0 n I a^2}{2}\int_{-l}^{l}\frac{dx}{[(r-x)^2+a^2]^{3/2}}$$

if $r \gg a$ and $r \gg l$ then

$$[(r-x)^2+a^2]^{3/2} \simeq r^3$$

[neglect x and a $\because x \to l$]

and
$$B = \frac{\mu_0 n I a^2}{2r^3}\int_{-l}^{l} dx$$

$$= \frac{\mu_0 n I a^2}{2r^3}[x]_{-l}^{l} = \frac{\mu_0 n I a^2}{2r^3}[2l]$$

but $n(2l)\,I(\pi a^2) = m$,

$$\boxed{B = \frac{\mu_0}{4\pi}\cdot\frac{2m}{r^3}}$$

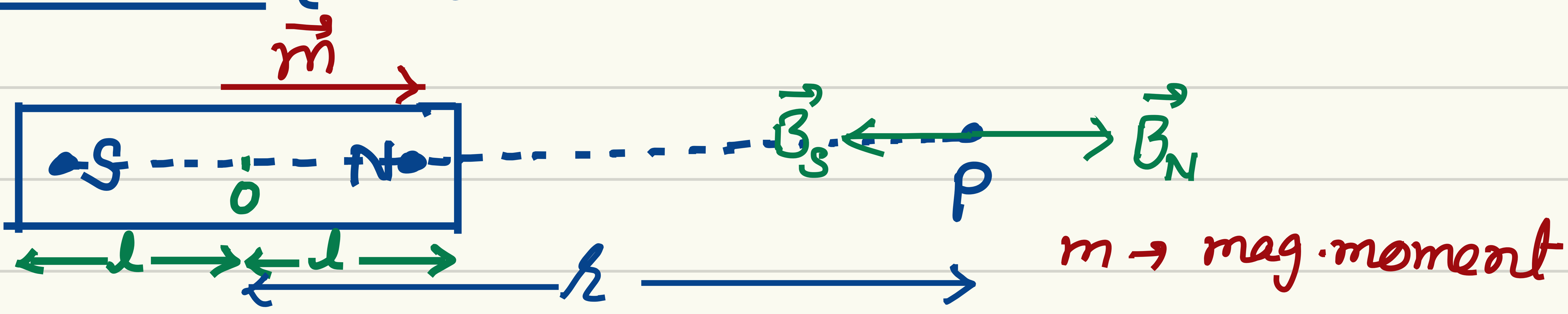
[$\because$ for solenoid $A \to n(2l)(\pi a^2)$
and $m = IA$]

This is also the magnetic field of a bar magnet at a point on its axial line.
Thus a bar magnet and a solenoid produces similar magnetic field.

The Electrostatic Analog -

	Electrostatics	Magnetism
1.	Electric Field E	• Magnetic Field B
2.	Electric Dipole Moment p	• Mag. Dipole Moment m
3.	Permittivity ϵ_0	• Permeability μ_0
4.	For short dipole electric field on axial line $\vec{E}_{ax} = \frac{1}{4\pi\epsilon_0} \frac{2\vec{p}}{r^3}$	• For short mag. dipole $\vec{B}_{ax} = \frac{\mu_0}{4\pi} \frac{2\vec{m}}{r^3}$
5.	Equatorial field $\vec{E}_{eq} = -\frac{1}{4\pi\epsilon_0} \frac{\vec{p}}{r^3}$	• Equatorial mag. field $\vec{B}_{eq} = -\frac{\mu_0}{4\pi} \frac{\vec{m}}{r^3}$
6.	Torque $\vec{\tau} = \vec{p} \times \vec{E}$	• Torque $\vec{\tau}_m = \vec{m} \times \vec{B}$
7.	Energy $U = -\vec{p} \cdot \vec{E}$	• $U = -\vec{m} \cdot \vec{B}$
8.	Charge q	• Magnetic charge or pole strength q_m
9.	$\int \vec{E} \cdot d\vec{S} = \frac{q_{en}}{\epsilon_0}$	• $\int \vec{B} \cdot d\vec{S} = 0$
10	$\epsilon_0 = 8.85 \times 10^{-12}\ Fm^{-1}$ (F → Farad)	• $\mu_0 = 4\pi \times 10^{-7}\ Hm^{-1}$ (H → Henry)

Magnetic Field of a Bar Magnet at Axial Line: (End-on Position)



$$B_N = \frac{\mu_0}{4\pi} \frac{q_m}{(r-l)^2}, \text{ along } \vec{NP} \qquad \left[\because B = \frac{\mu_0}{4\pi}\frac{q_m}{r^2}\right]$$

and

$$B_S = \frac{\mu_0}{4\pi} \frac{q_m}{(r+l)^2} \quad \text{along } \vec{PS}$$

$$B_{axial} = B_N - B_S$$

$$= \frac{\mu_0}{4\pi} q_m \left[\frac{1}{(r-l)^2} - \frac{1}{(r+l)^2}\right], \text{ along } \vec{NP}$$

$$= \frac{\mu_0}{4\pi} q_m \left[\frac{(r+l)^2 - (r-l)^2}{(r^2-l^2)^2}\right]$$

$$= \frac{\mu_0}{4\pi} q_m \left[\frac{r^2+l^2+2rl - r^2 - l^2 + 2rl}{(r^2-l^2)^2}\right]$$

$$= \frac{\mu_0}{4\pi} q_m \left[\frac{4rl}{(r^2-l^2)^2}\right]$$

$$= \frac{\mu_0 \cdot 2r}{4\pi} \frac{[2 q_m l]}{(r^2-l^2)^2}$$

$$B_{axial} = \frac{\mu_0}{4\pi} \frac{2mr}{(r^2-l^2)^2}$$

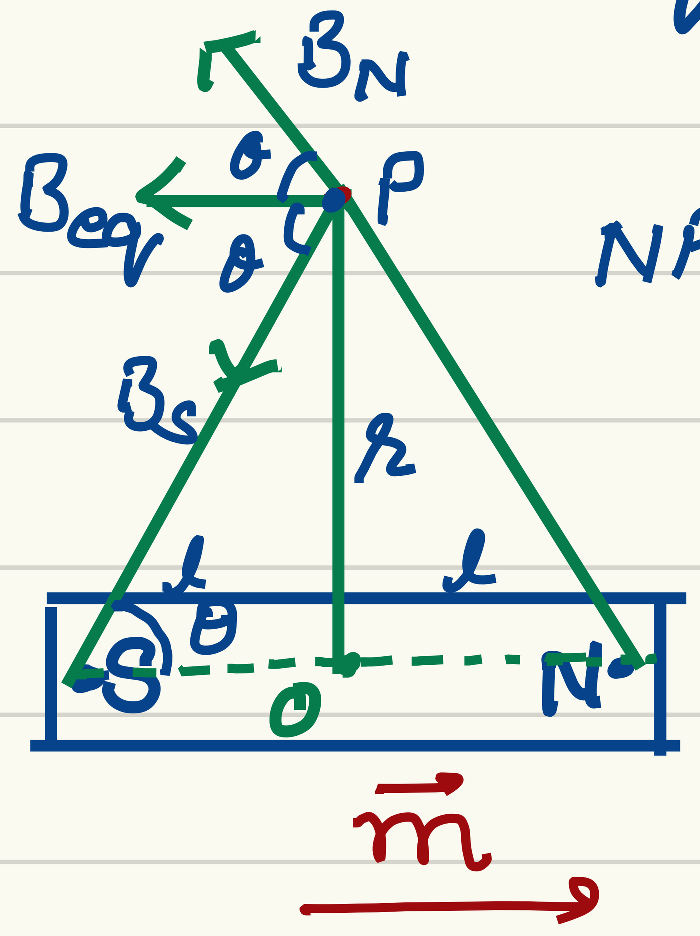
For short dipole $l << r$, then

$$\boxed{B_{axial} = \frac{\mu_0}{4\pi} \cdot \frac{2m}{r^3}}, \text{ along } \vec{NP}$$

Vector form $$\vec{B}_{ax} = \frac{\mu_0}{4\pi} \cdot \frac{2\vec{m}}{r^3}$$

* Dir^n of $\vec{B}_{axial}$ is along the dir^n of $\vec{m}$.

Magnetic field of a Bar Magnet at an Equatorial Point: (Broadside Position)



$NP = PS = \sqrt{r^2+l^2}$

$$B_N = \frac{\mu_0}{4\pi} \frac{q_m}{(r^2+l^2)}, \text{ along } \vec{NP}$$

$$B_S = \frac{\mu_0}{4\pi} \frac{q_m}{(r^2+l^2)}, \text{ along } \vec{PS}$$

$$\cos\theta = \frac{l}{\sqrt{r^2+l^2}}$$

$$B_{equatorial} = 2 B_N \cos\theta$$

$$= 2 \cdot \frac{\mu_0}{4\pi} \cdot \frac{q_m}{(r^2+l^2)} \cdot \frac{l}{\sqrt{r^2+l^2}}$$

$$B_{eq} = \frac{\mu_0}{4\pi} \frac{2 q_m l}{(r^2+l^2)^{3/2}}$$

If $l << r$ (for short dipole), then

$$B_{eq} = \frac{\mu_0}{4\pi} \frac{m}{r^3}$$

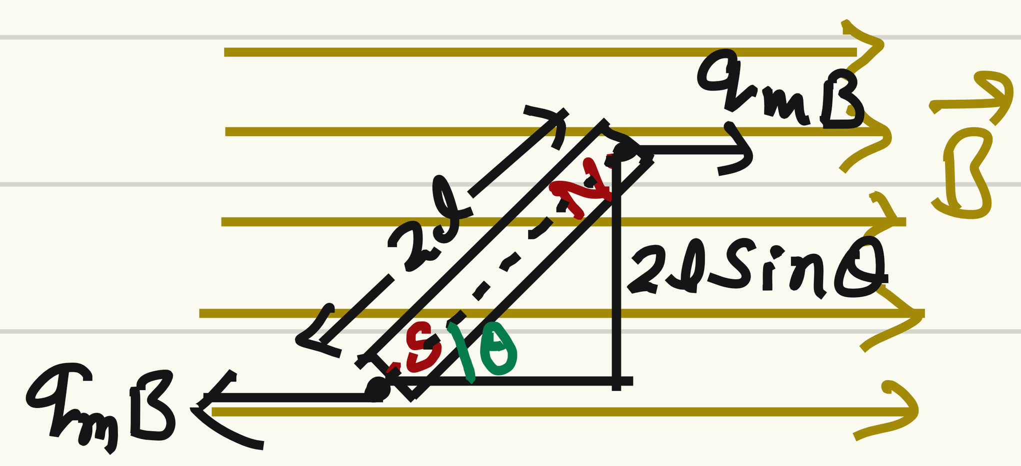
Vector form. $$\vec{B}_{eq} = -\frac{\mu_0}{4\pi} \frac{\vec{m}}{r^3}$$

* Dir^n of $\vec{B}_{eq}$ is antiparallel to $\vec{m}$.

Torque on a Magnetic Dipole in a Uniform Magnetic Field:

Force on N-pole = $q_m B$ along $\vec{B}$

Force on S-pole = $q_m B$ opp. to $\vec{B}$



The forces are equal and opposite so they form a couple. i.e develop a torque.

$$\tau = |force| \times \perp distance$$
$$= q_m B \times 2l \sin\theta$$
$$= (2 q_m l) B \sin\theta$$
$$\boxed{\tau = m B \sin\theta} \quad [m = 2 q_m l]$$

vector form,
$$\boxed{\tau = m \times B}$$

In magnitude $\tau = mB\sin\theta$, τ is restoring torque
θ is angle b/w m and B

In equilibrium, $I\alpha = -mB\sin\theta$ $[\tau = I\alpha$

-ve sign shows opposite dirn of $\tau_{restoring}$ and $\tau_{deflecting}$

For small value of θ, $\sin\theta \simeq \theta$, then

$$I\alpha = -mB\theta$$
or $$\alpha = -\frac{mB}{I}\theta$$
or $$\alpha \propto -\theta$$

This represents simple harmonic motion (SHM)

$$\omega^2 = \frac{mB}{I} \quad [\because \alpha = \omega^2\theta$$

Time period $T = \frac{2\pi}{\omega} = \frac{2\pi}{\sqrt{mB/I}} \Rightarrow \boxed{T = 2\pi\sqrt{\frac{I}{mB}}}$

or $$\boxed{B = \frac{4\pi^2 \cdot I}{mT^2}}$$

* By $\tau = mB\sin\theta$
 for $\theta = 0°$ or $180°$, $\boxed{\tau = 0}$ → no torque
 for $\theta = 90°$, $\boxed{\tau = mB}$ → Max^m torque

Potential Energy Of A Magnetic Dipole Placed In Uniform Magnetic Field :

Work done in rotating a dipole from angle θ_1 to θ_2 is given by

$$W = \int dW$$

$$= \int_{\theta_1}^{\theta_2} \tau \, d\theta \qquad [\because W = \tau\theta]$$

$$= \int_{\theta_1}^{\theta_2} mB\sin\theta \qquad [\tau = mB\sin\theta]$$

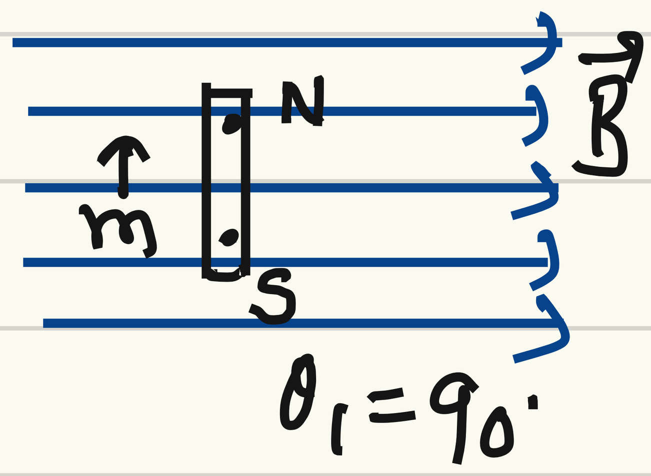
$$= mB\left[-\cos\theta\right]_{\theta_1}^{\theta_2}$$

or $$W = -mB\left[\cos\theta_2 - \cos\theta_1\right]$$

For $\theta_1 = 90^\circ$ and $\theta_2 = \theta$

$$W = -mB\left[\cos\theta - \cos 90^\circ\right]$$

$$\boxed{W = -mB\cos\theta}$$



or $$\boxed{W = -\vec{m}\cdot\vec{B}}$$

This work done is stored in the form of potential energy. So

$$\boxed{U = -mB\cos\theta = -\vec{m}\cdot\vec{B}}$$

<u>Special Cases :-</u>

1. When $\theta = 0$, $U = -mB$ (Min^m energy)

2. When $\theta = 90$ $U = 0$ (zero energy)

3. When $\theta = 180^\circ$, $U = +mB$ (Max^m energy)

* Stable Equalibrium -

When $\theta = 0^\circ$, $U = -mB$ (lowest energy)

(m and B are parallel)

* Unstable Equilibrium –
When $\theta = 180^\circ$, $U = +mB$ (highest energy)
(m and B are antiparallel)

__Coulomb's law__: Magnetic force between two magnetic poles is directly proportional to the product of their pole strength and inversely proportional to the square of the distance between them.

$$F \propto \frac{q_{m_1} q_{m_2}}{r^2}$$

$q_m \rightarrow$ pole strength

or

$$\boxed{F = \frac{\mu_0}{4\pi} \frac{q_{m_1} q_{m_2}}{r^2}}$$

__Gauss's Law in Magnetism__: Surface integral of magnetic field over any closed or open surface is always zero.

$$\oint_s \vec{B} \cdot \vec{ds} = 0$$

* Net magnetic flux through any surface is always zero.

__Current carrying Loop__: A current carrying loop behaves as a magnetic dipole.
Magnetic dipole moment

$$\vec{m} = I\vec{A}$$

For N turns

$$\vec{m} = NI\vec{A}$$

$I \rightarrow$ Current in the loop
$A \rightarrow$ Area of the loop

__Magnetic Moment of An Atom__:
For an orbiting electron in atom

$$I = \frac{q}{t} = \frac{q}{2\pi r/v}$$

or $I = \frac{qv}{2\pi r} = \frac{e(r\omega)}{2\pi r}$ $\left[\begin{matrix} q \to e \\ v = r\omega \end{matrix}\right.$

or $I = \frac{e\omega}{2\pi}$

$\mu_{orb} = IA$ $\left[\begin{matrix} m \to \mu \\ orb \to orbit \end{matrix}\right.$

$= I(\pi r^2)$

$= \frac{e\omega}{2\pi} \pi r^2$

$$\boxed{\mu_{orb} = \frac{1}{2} e\omega r^2}$$

Angular momentum L of the electron

$L = mvr$

$= m(r\omega)r$

$L = mr^2\omega$

or $\omega r^2 = \frac{L}{m}$

then $\mu_{orb} = \frac{1}{2} e\left(\frac{L}{m}\right)$

or $\mu_{orb} = \frac{e}{2m} . L$

vector form

$$\boxed{\vec{\mu}_{orb} = -\frac{e}{2m} . \vec{L}}$$

-ve sign shows that μ and L are opposite.

put $L = \frac{nh}{2\pi}$ [Acc. to Bohr's model]
[h → Plank constant]

we get $\mu_{orb} = \frac{e}{2m}\left(\frac{nh}{2\pi}\right)$

$$\boxed{\mu_{orb} = \frac{neh}{4\pi m}}$$

Various Term Related to Magnetism

1. **Magnetic Flux (ϕ_m)** Number of magnetic field lines passing through any surface is called magnetic flux linked with that surface.

$$\phi_m = \vec{B}\cdot\vec{A} = BA\cos\theta$$

where B = Mag. field intensity or magnetic induction.

SI unit - Weber or Tm^2

2. **Magnetic Permeability (μ)**: It is the ability of a material to permit the passes of magnetic lines of force through it.

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

B → Mag. induction
H → Mag. intensity

$$\vec{B} = \mu\vec{H}$$

SI unit of μ → TmA^{-1}

3. **Relative Permeability (μ_r)**: The ratio of flux density (mag. induction) inside the material to the flux density in the vacuum.

$$\mu_r = \frac{B}{B_0} = \frac{\mu H}{\mu_0 H} = \frac{\mu}{\mu_0} = \mu_r$$

It is unitless.

4. **Magnetisation (M)** Magnetisation of a sample is equal to its magnetic moment per unit volume.

$$\vec{M} = \frac{\vec{m}_{net}}{V}$$

(circulating electron has a magnetic moment. For bulk these moments give a net non-zero magnetic moment m_{net}.)

$\vec{M}$ is a vector with dim^n $L^{-1}A$ and SI unit Am^{-1}.

* If a solenoid of mag. field $B_0 (= \mu_0 n I)$ inside it, filled with non-zero magnetisation material then net mag. field inside the solenoid $B > B_0$

$$\vec{B} = \vec{B_0} + \vec{B}_m$$

$$\vec{B}_m = \mu_0 \vec{M}$$

$B_m \rightarrow$ field by material

<u>Magnetic Intensity (H)</u>: It is the ratio of magnetising field B_0 to the permeability of free space μ_0.

$$\vec{H} = \frac{\vec{B_0}}{\mu_0} \quad \text{or} \quad \vec{B_0} = \mu_0 \vec{H}$$

also

$$\vec{H} = \frac{\vec{B}}{\mu_0} - \vec{M}, \quad B = B_0 + B_m$$

$M \rightarrow$ Magnetisation

$$\text{or} \quad \vec{B} = \mu_0(\vec{H} + \vec{M})$$

H is a vector.
H has same dim^n and unit as M.
i.e Dim^n - $L^{-1}A$, SI unit Am^{-1}

<u>Magnetic Susceptibility (χ)</u> → Chi (kai)

It is the property which shows how easily a substance can be magnetised.
It is defined as the ratio of magnetisation M and to the magnetic intensity H.

$$\chi = \frac{M}{H}$$

It is dimensionless and unitless. It is scalar.

* It is a measure of how a material respond to a external mag. field.
* It is small and +ve for → Paramagnetic materials.

* It is small and −ve for → Diamagnetic materials. (M and H are in opposite dir^n)

Relation b/w μ and χ

We have

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

put $M = \chi H$, then

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

$$\boxed{B = \mu_0 H (1 + \chi)} \quad \text{——} \; (1)$$

here, $\mu_0 H = B_0$

so $B = B_0 (1+\chi)$

or $\frac{B}{B_0} = 1 + \chi$

or $\mu_r = 1 + \chi$ $\quad [\because \mu_r = \frac{B}{B_0}]$

from eq^n (1)

$B = \mu_0 H \mu_r$ $\quad [\because 1+\chi = \mu_r]$

or $B = \mu_0 \mu_r H$

or $\boxed{B = \mu H}$

From $\mu_r = 1+\chi$ we can write

$$\boxed{\mu_r = \mu_0 \mu = 1 + \chi}$$

μ, μ_r and χ are interrelated and μ_0 is independent.

Magnetic Properties of Materials:

In terms of susceptibility χ: A material is diamagnetic if χ is −ve, para- if χ is +ve and small, and ferro- if χ is large and +ve.

Diamagnetic	Paramagnetic	Ferromagnetic
• $-1 \leq \chi < 0$	$0 < \chi < \varepsilon$	$\chi >> 1$
• $\mu < \mu_0$	$\mu > \mu_0$	$\mu >> \mu_0$

χ → Susceptibility
μ → Permeability of the substance
μ_0 → Permeability of free space or vacuum

Diamagnetism is universal

But only noticiable in materials do not have unpaired electrons

↓↓↓↓↓↓↓↓ electron spins

m is very small

Diamagnetism: Diamagnetic substances have tendency to move from stronger to weaker mag field. All electrons are paired.
A magnet would repel a diamagnetic substance.
e.g. bismuth, copper, lead, silicon, Nitrogen (at STP), water and sodium chloride.
* Most exotic diamagnetic materials are → Superconductors
This phenomenon of perfect diamagnetism is called Meissner effect. ($\chi = -1$)

* Superconducting magnets are used for running magnetically levitated super fast trains.

Due to unpaired electrons aligning with the field

↑↓↑↑↓↑

m is small, oriented parallel to the mag. field.

Paramagnetism: Paramagnetic substances are weakly magnetised in an external magnetic field.
They have tendency to move weak to strong magnetic field. i.e weakly attracted by a magnet.
* In the presence of strong enough external magnetic field the atoms or ions or molecules have a net magnetic dipole moment and shows paramagnetism.
e.g. Aluminium, sodium, calcium, oxygen (at STP)

and copper chloride.

Curie's Law: The magnetisation of paramagnetic material is inversely proportional to the absolute temperature T.

$$M = \frac{C B_0}{T} \qquad C \rightarrow \text{Curie's constant}$$

$$\chi H = \frac{C \mu_0 H}{T} \qquad \left[\because M = \chi H \text{ and } B_0 = \mu_0 H\right.$$

$$\boxed{\chi = \frac{C \mu_0}{T}}$$

This is known as curie's law.

Curie Temperature: Curie temperature is the temperature above which ferromagnetic material becomes paramagnetic material.

Ferromagnetism: Ferromagnetic substances are strongly magnetised by external magnetic field.

They have strong tendency to move weak to strong magnetic field.

They get strongly attracted to a magnet.

e.g. Alnico (alloy → Al + Ni + Co), Aluminium nickel, cobalt, copper and gadolinium.

↓ soft ferromagnetic

Contains multiple unpaired electrons

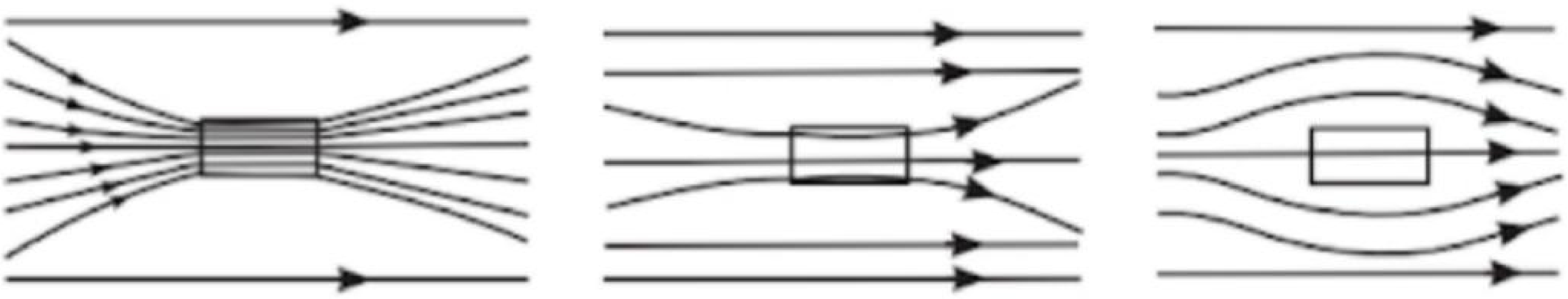
↑↑↑↑↑↑

Below T_c spins are aligned parallel in magnetic domain

The susceptibility above curie temperature is described by

$$\boxed{\chi = \frac{C}{T - T_c}} \qquad T > T_c$$

The density of field lines is very high inside ferromagnetic material. Density of lines is slightly higher (than outside density) inside the paramagnetic material. The density of field lines inside a diamagnetic material is slightly less than the external density.



S. N	Properties	Diamagnetic	Paramagnetic	Ferromagnetic
1	Definition	It is a material in which there is no permanent magnetic moment.	It has permanent magnetic moment.	It has enormous (more) permanent magnetic moment.
2	Spin or magnetic moment or dipole alignment.	No spin alignment.	Random alignment	Parallel and orderly alignment.
3	Behavior	Repulsion of magnetic lines of force from the centre of the material.	Attraction of magnetic lines towards the centre.	Heavy attraction of lines of force towards the centre.
4	Magnetized direction	Opposite to the External magnetic field.	Same direction as the External magnetic field.	Same direction as the External magnetic field.
5	Permeability	It is very less	It is high	It is very high
6	Relativity permeability	$\mu_r < 1$	$\mu_r > 1$	$\mu_r >> 1$
7	Susceptibility	Negative	Low positive	High positive
8	Magnetic phase transition	At 0 K, diamagnetic material is Superconductor. When we increase its temperature it becomes a normal conductor.	When temperature is less than the curie temp, it is converted in to Diamagnetic.	When temperature of the material is greater than it Curie temperature it is converted into Paramagnet.