Friday

/06/2024

5. MAGNETISM AND MATTER

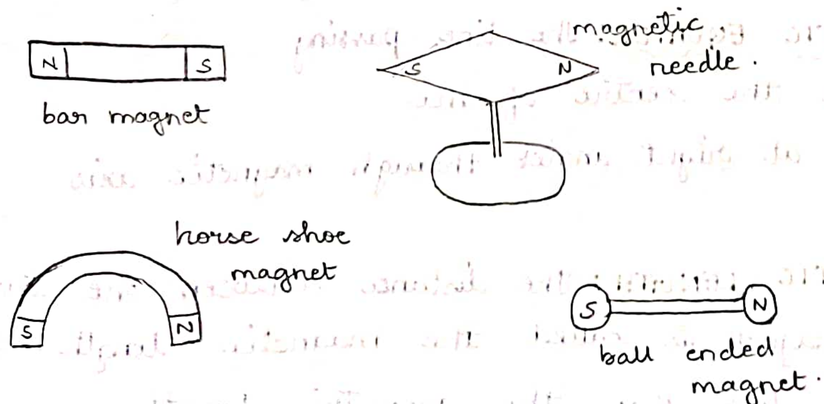
INTRODUCTION:

* A magnet is a material that have both attractive and directive properties.
* As early as the 6th century BC, the Greeks had some knowledge about natural magnets (naturally occuring iron ore called as lodestone (or) magnetite (or) black iron oxide [Fe_3O_4]).
* The world magnetism originates from the place magnetia, a province in the upper part of Greece.
* Later on, the Chinese discovered that thin long pieces of lodestone, if suspended horizontally would naturally orient themselves in geographical North-South direction. By 1000 AD, chinese were using magnetic compass for navigating.
* William Gilbert, in his book, "De Magnate", in 1600 AD suggested that earth itself is a huge magnet.

ARTIFICIAL MAGNETS:

* Generally, natural magnets are not strong enough magnetically and have inconvenient shapes.
* The pieces of iron and other magnetic materials can be made to acquire the properties of natural magnets.
* Such magnets are called artificial magnets.

Ex: Bar magnet, horseshoe magnet, magnetic needle and ball ended magnet.



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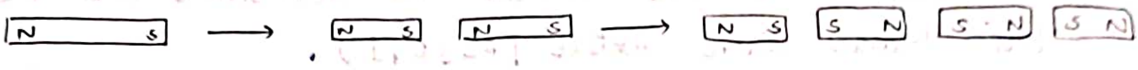
BASIC PROPERTIES OF MAGNETS:

1) Attractive property: Attracts small pieces of Fe, Co, Ni
2) Directive property: A magnet alligns itself in geographic North - South direction.
3) Like poles repel and unlike poles attract.
4) Magnetic poles always exist in pairs:



⇒ Unlike electric charges, magnetic monopoles, does not exist. Every magnet exists as a dipole.

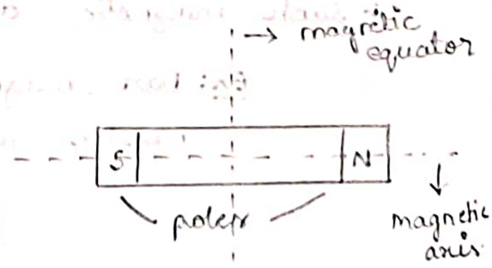
5) Magnetic Induction: A magnet induces magnetism in a magnetic substance placed near it. This phenomenon is called 'magnetic induction.

⇒ When the north pole of a powerful magnet is placed closed to soft iron bar, the closer end becomes south pole. Thus, magnet attracts iron bar. As a result, we can say induction precedes attraction.

TERMS RELATED TO MAGNETISM:

1) MAGNETIC POLES:
* Region of apparently concentrated magnetic strength in a magnet where the magnetic attraction is maximum.

2) MAGNETIC AXIS: The line passing through the poles of ~~the axis~~ the magnet is called the magnetic axis of magnet.



3) MAGNETIC EQUATOR: The line passing through the centre of the magnet at right angles through magnetic axis

4) MAGNETIC LENGTH: The distance between the two poles of a magnet is called the magnetic length. It is slightly less than the geometric length.

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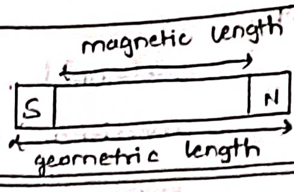
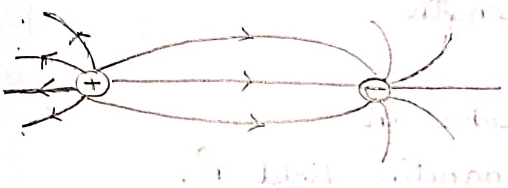
$$\frac{\text{magnetic length}}{\text{geometric length}} = 0.84$$



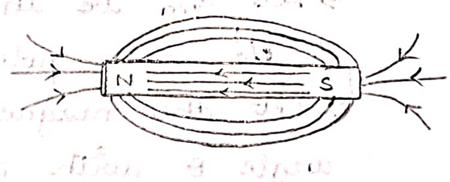
MAGNETIC FIELD LINES:

* Magnetic ~~fiet~~ lines of force are closed curves which start in air from north to south pole and return to north pole through the interior of the magnet.
* The lines of force never cross each other because then there will be two directions of magnetic field at the point of intersection which is not possible.
* They start from and end on the surface of the magnet normally.
* They have tendency to contract lengthwise and expand sidewise. This explains attraction between unlike poles and repulsion between like poles.
* The relative closeness of the lines of force gives a measure of the strength of the magnetic field, which is maximum at the poles.

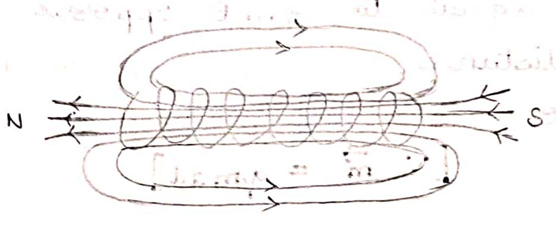
a) Electric dipole:



b) Magnetic dipole: [bar magnet]



c) Solenoid:



BAR MAGNET AS AN EQUIVALENT SOLENOID:

* The resemblence of magnetic field lines for a bar magnet and solenoid suggest that bar magnet may be though of as a large number of circulating current in anology with solenoids.
* Cutting a bar magnet in half is like cutting a

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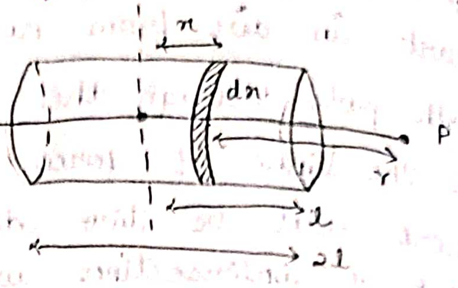
solenoid. We get two smaller solenoids with weaker magnetic properties the field lines remain continuous. To make this anology more firm we calculate the axial field of a finite solenoid as shown in the figure.

* At large distances, this axial field resembles that of a bar magnet. Thus a bar magnet of and a solenoid produce similar magnetic field and produce similar magnetic moment.

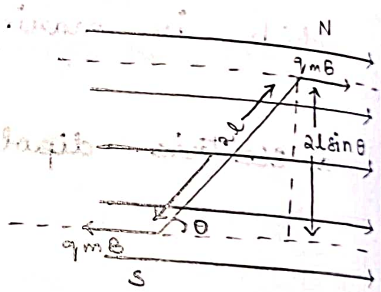


[derivation deleted]

$$\boxed{B_{ar} = \frac{\mu_0}{4\pi}\frac{2m}{r^3}}$$

★ Torque on a magnetic dipole in a magnetic field :

→ Consider a bar magnet NS of length $2l$ placed in a uniform magnetic field $\vec{B}$.



→ Let q_m be the pole strength of its each pole.

→ Let the magnetic axis make an angle θ with the ~~magn~~ magnetic field $\vec{B}$.

→ Force on North Pole is equal to $q_m B$ along $\vec{B}$.

→ Force on South Pole is equal to $q_m B$ opposite to $\vec{B}$.

T = Force × ⊥r distance

$= q_mB \cdot 2l\sin\theta$

$= mB\sin\theta$

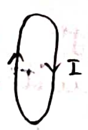
[q_m = pole strength
B = magnetic field]

$$\boxed{T = \vec{m} \times \vec{B}}$$

$[\because \vec{m} = q_m 2l]$

→ The direction of torque is given by right hand screw rule.

Note: 1)



$\vec{m} = NI\vec{A}$ → current loop

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2) 

$\vec{m} = q_m 2\vec{l}$ ⇒ bar magnet

★ Special case :

1) $\theta = 0^\circ$, $\tau = 0$.

⇒ $\vec{m}$ $\parallel^{el}$ $\vec{B}$

2) $\theta = 90^\circ$, $\tau_{max} = mB$

⇒ $\vec{m}$ $\perp^r$ to $\vec{B}$.

3) $\theta = 180^\circ$, $\tau = 0$

⇒ $\vec{m}$ is antiparallel to $\vec{B}$.

★ Potential energy of a magnetic dipole in a magnetic field :

⇒ As shown in the figure, the dipole experiences a torque given by

$$\tau = mB\sin\theta$$

⇒ The work done in turning a small dipole through a small angle θ is

$$dW = \tau d\theta$$

$$W = \int dW = \int_{\theta_1}^{\theta_2} \tau d\theta = mB \int_{\theta_1}^{\theta_2} \sin\theta \, d\theta$$

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

⇒ The work done is stored as P.E of the dipole.

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

⇒ If initial angle $\theta_1 = 90^\circ$ and $\theta_2 = \theta$,

$$U = -mB\cos\theta$$

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

⇒ Special Case :

1) $\theta = 0$ ⇒ m $\parallel^{el}$ to $\vec{B}$

⇒ $U = -mB$ [potential energy is minimum, so the dipole is in stable equillibrium].

2) $\theta = 90^\circ$

⇒ $U = 0$ [this is the position of zero energy.]

3) $\theta = 180^\circ$ ⇒ $\vec{M}$ antiparallel to $\vec{B}$

⇒ $U = MB$ [potential energy is maximum, the dipole is in unstable equillibrium.

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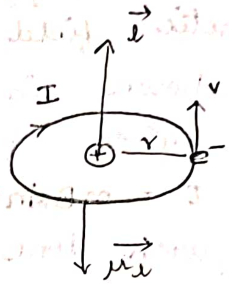
Note: Torque determines equillibrium ($\tau = 0$) and potential energy determines stability of equillibrium.

MAGNETIC DIPOLE MOMENT OF A REVOLVING ELECTRON :

* According to Bohr model of hydrogen like atoms [have only one $e^- \rightarrow H, He^+, Li^{2+}$], negatively charged e^- revolves around the nucleus and is equivalent to a current loop of magnetic moment IA ($= \mu_l$). Let the e^- revolve in anticlockwise direction in an orbit of radius r moving with speed v and time period T.

* The current

$$I = \frac{\text{charge}}{\text{time}} = \frac{e}{T} = \frac{e}{\frac{\text{distance}}{\text{speed}}}$$



$$I = \frac{e}{\frac{2\pi r}{v}}$$

$$\boxed{I = \frac{ev}{2\pi r}}$$

* Area of circular orbit ;

$$A = \pi r^2$$

* Magnetic moment

$$\mu_l = IA = \frac{ev}{2\pi r} \times \pi r^2$$

$$\boxed{\mu_l = \frac{evr}{2}} \quad \text{— ①} \qquad [\mu_l = \text{orbital dipole moment}]$$

* We know that, angular momentum

$$l = m_e v r \quad \text{— ②} \qquad [l = \text{angular momentum}]$$

$$\frac{①}{②} \Rightarrow \frac{\mu_l}{l} = \frac{\frac{evr}{2}}{mvr} = \frac{e}{2m_e}$$

$$\mu_l = \frac{e}{2m_e} l$$

* Vectorically,

$$\boxed{\vec{\mu_l} = \frac{-e}{2m_e} \vec{l}}$$

* The angular momentum is given by the Bohr's

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quantisation condition, that is

$$l = \frac{nh}{2\pi}$$

[n = principal quantum number, h = planck's constant].

* For n = 1, 2, 3, ...,

$$\boxed{\mu_l = n\left(\frac{eh}{4\pi m_e}\right)}$$

* In the 1st orbit n = 1, the magnetic moment is minimum.

$$\boxed{(\mu_l)_{min} = \frac{eh}{4\pi m_e}}$$

$$= \frac{1.6\times10^{-19} \times 6.626\times10^{-34}}{4\times3.14\times9.1\times10^{-31}}$$

$$\boxed{\mu_l = 9.27\times10^{-24}\ Am^2} \rightarrow \text{Bohr magneton}$$

* Bohr magneton is defined as magnetic moment of e^- due to orbital motion in the 1st orbit of hydrogen atom.

* Besides the orbital angular momentum $\vec{l}$, an e^- has spin angular momentum $\vec{s}$ due to its spinning motion.

* The magnetic moment due to $\vec{s}$ is called spin magnetic moment or intrinsic magnetic moment.

$$\boxed{\vec{\mu_s} = \frac{-e}{m_e}\vec{s}}$$ [μ_s = spin magnetic moment]

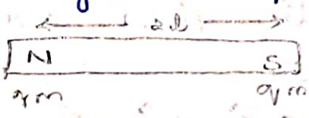
* Total magnetic moment = {orbital magnetic moment} + {spin magnetic moment}

$$\boxed{\vec{\mu} = \vec{\mu_l} + \vec{\mu_s}}$$

Note: 1) q_m represents pole strength of magnetic poles.

2) If equal and opposite magnetic poles are separated by a distance $2l$. Then, the strength of the dipole is measured by the magnetic dipole moment.

$\Rightarrow \vec{m} = q_m 2\vec{l}$



3) Its direction is from south to North.

4) It is a vector quantity and its SI unit is Am^2 (or) JT^{-1}. [joule tesla^{-1}]

COULOMB'S LAW OF MAGNETIC FORCE:

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

q_{m_1} and q_{m_2} are the pole strength of the two magnetic poles which are separated by a small distance r.

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Note: * Magnetic fields are non-conservative as they form closed loop. [for proof → gauss law].

* However, the work done is ~~done~~ zero as the force and velocity are perpendicular to each other.

* On the other hand, electric fields are conservative fields. [W = 0]

* Bar magnet always produces a non-uniform magnetic field.

* Torque, work and energy have same units - J and Nm.

* Magnetic moment is in the direction of axis of magnet.

ANALOGY BETWEEN ELECTRIC AND MAGNETIC DIPOLES:

PHYSICAL QUANTITY	ELECTROSTATICS	MAGNETICS
1) Free space constant	$1/\varepsilon_0$	μ_0
2) Dipole moment	$\vec{p}$	$\vec{\mu}$
3) Equitorial field for a short dipole	$\frac{-\vec{p}}{4\pi\varepsilon_0 r^3}$	$\frac{-\mu_0 \vec{m}}{4\pi r^3}$
4) Axial field for a short dipole	$\frac{2\vec{p}}{4\pi\varepsilon_0 r^3}$	$\frac{\mu_0}{4\pi}\frac{2\vec{m}}{r^3}$
5) External field: Torque	$\vec{p} \times \vec{E}$	$\vec{m} \times \vec{B}$
6) External field: Potential Energy	$-\vec{p}\cdot\vec{E}$	$-\vec{m}\cdot\vec{B}$

GAUSS' LAW IN MAGNETISM:

* In electrostatics, the surface integral of the electrostatic field over a closed surface S is equal to

$$\oint \vec{E}\cdot d\vec{s} = \frac{q}{\varepsilon_0}$$

* Suppose the closed surface encloses an electric dipole

$$\oint \vec{E}_{dipole}\cdot d\vec{s} = 0$$

* Now, magnetic field is produced only by magnetic dipole because isolated magnetic poles do not exist.

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* So the above equation for the magnetic field can be written as

$$\oint \vec{B} \cdot d\vec{s} = 0$$

* This is Gauss' Law in magnetism which states that 'the surface integral of magnetic field over a closed surface is always zero'.

* Consequences of Gauss' Law :

⇒ There are no sources or sinks of magnetic field inside a closed surface [isolated magnetic poles (monopoles) do not exist].

⇒ Magnetic poles always exist as unlike pairs of equal strength.

⇒ If a number of ~~closed~~ magnetic lines of force enter a closed surface, then an equal number of lines of force must leave that surface.

EXERCISES [Pg : 152] : [Homework]

5.1] $\tau = mB\sin\theta$

$$m = \frac{\tau}{B\sin 30^\circ} = \frac{4.5 \times 10^{-2}}{0.25 \times 1/2} = 0.36 \text{ Am}^2 \ / \ 0.36 \text{ JT}^{-1}$$

5.2] (a) The ~~mg~~ magnet is in stable equillibrium when its magnet moment is parallel to magnetic field. $[\theta = 0°]$

$$U = -mB = -0.32 \times 0.15 = -0.048$$

$$\boxed{U = -4.8 \times 10^{-2} \text{ J}}$$

(b) The ~~magnet is~~ is in unstable equilibrium when its magnetic ~~moment~~ is antiparallel to magnetic field.

$$U = mB = 0.32 \times 0.15 = 0.048 \quad [\theta = 180°]$$

$$\boxed{U = 4.8 \times 10^{-2} \text{ J}}$$

derivation and formula ⊗

IMPORTANT TERMS USED TO DESCRIBE MAGNETIC PROPERTIES OF MATERIALS :

1) MAGNETISING FIELD : [B_0]

* The magnetic field that exist in vacuum and induces a magnetism in a magnetic material is called magnetising field. ⇒ Unit : Tesla.

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Ex: For a solenoid, $\boxed{B_0 = \mu_0 n I}$

2) MAGNETISING FIELD INTENSITY: [H]

* It is the number of ampere turns flowing round the unit length of a solenoid required to produce the given magnetising field.

$$\boxed{H = nI = \frac{B_0}{\mu_0} = \frac{NI}{l}}$$

Unit: Am^{-1}, $Nm^{-2}T^{-1}$, $Jm^{-1}Wb^{-1}$

* It is a vector quantity.
* It is the ability of the magnetising field to magnetise a material medium.

3) INTENSITY OF MAGNETISATION: [M]

* It is the magnetic moment developed per unit volume of a material when placed in a magnetising field (simply called magnetisation).

① $\boxed{M = \frac{m}{V}}$ [m = magnetic moment, V = volume]

$= \frac{NI_m \cancel{A}}{\cancel{A} l}$ [$n = \frac{N}{l}$]

② $\boxed{M = nI_m}$

Also, $M = \frac{q_m 2l}{A\, 2l}$ [$2l \rightarrow$ magnetic length]

③ $\boxed{M = \frac{q_m}{A}}$

* It can also be defined as the pole strength developed per unit area.
* It's unit is also Am^{-1} [same as H].
* Here, I_m is the net current on the surface and is called magnetisation surface current.
* This current induces magnetic field $\vec{B_m}$.

$\boxed{B_m = \mu_0 n I_m}$

4) MAGNETIC INDUCTION:

* The total magnetic field inside the magnetic material is the sum of external magnetic field and the

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additional magnetic field ~~due~~ produced due to magnetisation and is called magnetic induction $\vec{B}$.

$\Rightarrow \vec{B} = \vec{B_0} + \vec{B_m}$

$\Rightarrow B = \mu_0 n I + \mu_0 n I_m$

$\Rightarrow B = \mu_0 [nI + nI_m]$

$\Rightarrow \boxed{B = \mu_0 [H + M]}$

* Also, $\boxed{H = \frac{B}{\mu_0} - M}$

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5) MAGNETIC PERMEABILITY :

* It is the extent to which a material can be permeated by a magnetic field.
* It is defined as the ratio of its magnetic induction ~~and~~ to the magnetic intensity.

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

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6) RELATIVE PERMEABILITY :

* It is defined as the ratio of permeability of medium to permeability of free space.
* It has no units.

$\boxed{\mu_r = \frac{\mu}{\mu_0}}$

* For i) vacuum $\Rightarrow \mu_r = 1$
  ii) air $\Rightarrow \mu_r = 1.0000004$
  iii) iron $\Rightarrow \mu_r =$ exceeds 1000 [ferromagnetic]

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7) MAGNETIC SUSCEPTIBILITY :

* It is the ability to take up magnetisation.
* It is defined as the ratio of intensity of magnetisation to the magnetising field intensity.

$\boxed{\chi_m = \frac{M}{H}}$

* It has no units.

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RELATION BETWEEN RELATIVE PERMEABILITY AND MAGNETIC SUSCEPTIBILITY :

$\Rightarrow [B = \mu_0 (H + M)] \div H$

$\Rightarrow \frac{B}{H} = \mu_0 \left(\frac{H+M}{H}\right)$

$\Rightarrow \mu = \mu_0 \left(1 + \frac{M}{H}\right)$

$\Rightarrow \boxed{\mu = \mu_0 (1 + X_m)}$

$\Rightarrow \frac{\mu}{\mu_0} = (1 + X_m)$

$\Rightarrow \boxed{\mu_r = 1 + X_m}$

Using ,

* $\mu = \frac{B}{H}$
* $X = \frac{M}{H}$

DIAMAGNETISM :

* The e^- possess orbital magnetic moment but if they are in pairs they cancel the magnetic moment of each other. and the net magnetic moment of atom becomes zero.
* When ~~are~~ they are placed in external field , the electrons having orbital magnetic moment in same direction slow down and those in the opposite direction speed up in accordance with Lenz's law.
* Thus the substance develops a net magnetic moment in opposite direction to apply field and results in repulsion.
* Therefore, diamagnetic substance have tendency to move from strong to weak field.

Ex: Bi, Cu, Pb, Si, N at STP , H_2O , NaCl

perfect diamagnet

diamagnet

* In superconductors, perfect conductivity and perfect diamagnetism is seen.
* The phenomenon of perfect diamagnetism in superconductors is called the Meissner Effect.

These superconductors are used for magnetically levitated super fast train.

* For, superconductors, $\boxed{\chi_m = -1}$.

$$\mu_r = 1 + \chi_m = 1 - 1$$

$$\boxed{\mu_r = 0}$$

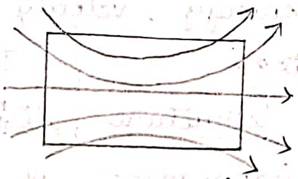
* The range of χ_m for diamagnets is 0 to (−1).

PARAMAGNETISM:

* The individual atoms posses a permanant magnetic dipole of their own but due to ceaseless random thermal motion of the atoms, the net magnetic moment of a material is zero.
* In the presence of external field which is strong enough and at low temperatures the individual atomic dipole moment can be made to align in same direction as external field.
* They have tendency to move from weak to strong field (weakly attracted by a magnet).

Ex: Al, Na, Ca, O_2 at STP, $CuCl_2$.

* χ_m and μ_r depend not only on material but also on the sample temperature.
* The magnetisation increases until it reaches saturation value at which all the dipoles are perfectly aligned with the field.



paramagnet

FERROMAGNETISM:

* The individual atoms in a ferromagnetic material possess a dipole moment as in paramagnetic material.
* However, they interact in such a way that they spontaneously align in a common direction over a microscopic volume called domains.
* Typical domain size is 1 mm and has 10^{11} atoms.
* When external field is applied, the domains orient themselves in the direction of B_0 and grow in size to form a single giant domain.

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* Thus, in ferromagnetic materials, field lines are highly concentrated and move from weak to strong field.
* When we remove the external field, in some ferromagnetic materials, the magnetisation persists. Such materials are called hard ferromagnets.

Ex: Alnico [alloy of Al, Ni, Co, Cu], lodestone

* These are used to make permanant magnets and magnetic needle for compass.
* On the other hand when magnetic field is removed, the magnetisation disappears in some materials and are called soft ferromagnets.

Ex: Soft iron

* They are used as electromagnets.
* There are a number of elements which are ferromagnets.

Ex: Fe, Co, Ni, Ga

* The relative magnetic permeability (μ_r) is greater than 1000.

Note: • The ferromagnetic property depends on temperature.

• At high enough temperature (curie temperature), a ferromagnet turns gradually to a paramagnet as the temperature increases (heat energy is converted to kinetic energy, velocity increases and the domains disintegrates).

• The domains structure disintegrates with temperature and the disappearance of magnetisation with temperature is gradual.

EXERCISES [Pg:152]:

5.3] $N = 800$, $A = 2.5 \times 10^{-4}\ m^2$, $I = 3A$

Magnetic moment $(m) = NIA$

$= 800 \times 2.5 \times 10^{-4} \times 3$

$$\boxed{m = 0.6\ Am^2 \text{ or } JT^{-1}}$$

The magnetic of a solenoid has the same pattern as that of a bar magnet. It acts along the axis of the solenoid. Its direction is determined by the sense of flow of current.

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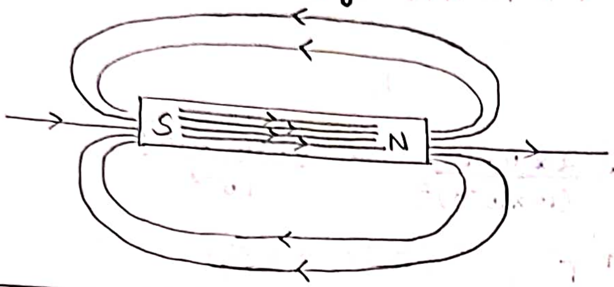
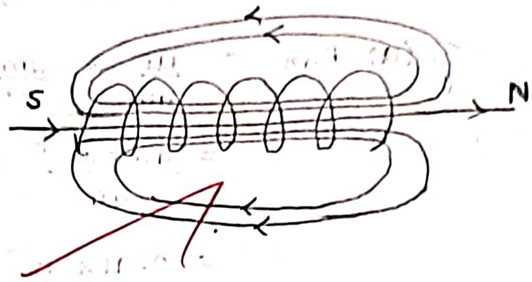
Bar magnet   Solenoid





5.5] $m = 1.5\ JT^{-1}$, $B = 0.22\ T$, $\theta_1 = 0°$

(a) i) Normal to the field $\rightarrow \theta_2 = 90°$

Work done is stored as PE.

$W = U = -mB(\cos\theta_2 - \cos\theta_1) = -mB(0-1)$

$= mB = 1.5 \times 0.22$

$\boxed{W = 0.33\ J}$

ii) Opposite to the field $\rightarrow \theta_2 = 180°$

$W = -mB(\cos\theta_2 - \cos\theta_1) = -mB(-1-1)$

$= 2mB = 2 \times (0.33)$

$\boxed{W = 0.66\ J}$

(b) i) $\tau_{max} = mB\sin 90° = mB$

$\boxed{\tau_{max} = 0.33\ J}$

ii) $\tau = mB\sin 180°$

$\boxed{\tau = 0\ J}$

5.4] $B = 0.25\ T$, $\theta = 30°$, $m = 0.6\ JT^{-1}$ [From 5.3]

$\tau = mB\sin 30° = 0.6 \times 0.25 \times \frac{1}{2} = 0.075\ Nm$

$\boxed{\tau = 7.5 \times 10^{-2}\ Nm}$

5.6] a) $m = NIA = 2000 \times 4 \times 1.6 \times 10^{-4}$

$= 128 \times 10^{-2}$

$\boxed{m = 1.28\ A\ m^2}$

b) $B = 7.5 \times 10^{-2}\ T$, $\theta = 30°$

$\tau = mB\sin 30° = 128 \times 10^{-2} \times 10^{-2} \times 7.5 \times \frac{1}{2}$

$= 480 \times 10^{-4}$

$\boxed{\tau = 0.048\ Nm}$

$\Rightarrow$ Force is zero in uniform field.

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5.7] $m = 0.48\ JT^{-1}$, $r = 10 \times 10^{-2}\,m$

(a) $$B_{ax} = \frac{\mu_0}{4\pi} \times \frac{2m}{r^3}$$

$$= \frac{4\pi \times 10^{-7}}{4\pi} \times \frac{2 \times 0.48}{(10 \times 10^{-2})^3} = \frac{0.96 \times 10^{-7}}{10^{-3}}$$

$$= 0.96 \times 10^{-4}\ T \qquad [10^{-4} T = 1\ G]$$

$$\boxed{B_{ax} = 0.96\ G}$$

(b) $$B_{eq} = \frac{B_{ax}}{2} = \frac{0.96 \times 10^{-4}}{2}$$

$$= 0.48 \times 10^{-4}\ T$$

$$\boxed{B_{eq} = 0.48\ G}$$

Note: * Magnetic force is always perpendicular to magnetic field (and velocity). Hence, magnetic field lines do not represent lines of force.

* If Gauss law existed for magnetic field, it will be

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 q_m \quad \left[\text{Comparing to } \oint \vec{E} \cdot d\vec{s} = \frac{q}{\varepsilon_0}\right]$$

Actual law : $\oint \vec{B} \cdot d\vec{s} = 0$

* Even if the charge of a material is zero, it might have magnetic moment.

Ex: paramagnets

S.No	PROPERTY	DIAMAGNETIC SUBSTANCE	PARAMAGNETIC SUBSTANCE	FERROMAGNETIC SUBSTANCE
1.	Effect of magnets	They are feebly repelled by magnets.	They are feebly attracted by magnets.	They are strongly attracted by magnets.
2.	In external magnetic field	Acquire feeble magnetisation in the opposite direction of the magnetising field.	Acquire feeble magnetisation in the direction of the magnetic field.	Acquire strong magnetisation in the direction of the magnetising field.
3.	In a non-uniform magnetic field	Tend to move slowly from stronger to weaker parts of the field.	Tend to move slowly from weaker to stronger parts of the field.	Tend to move quickly from weaker to stronger parts of the field.
4.	In a uniform magnetic field	A freely suspended diamagnetic rod aligns itself perpendicular to the field.	A freely suspended paramagnetic rod aligns itself parallel to the field.	A freely suspended ferromagnetic rod aligns itself parallel to the field.
5.	Susceptibility Value (χ_m)	small and negative. $-1 \leq \chi_m < 0$	small and positive. $0 < \chi_m < \varepsilon$, where ε is a small number.	very large and positive. $\chi_m > 1000$
6.	Relative permeability Value (μ_r)	slightly less than 1. $0 \leq \mu_r < 1$	slightly greater than 1. $1 < \mu_r < \varepsilon + 1$	of the order of 1000 $\mu_r > 1000$
7.	Permeability Value (μ)	$\mu < \mu_0$	$\mu > \mu_0$	$\mu \gg \mu_0$

S.No	PROPERTY	DIAMAGNETIC SUBSTANCE	PARAMAGNETIC SUBSTANCE	FERROMAGNETIC SUBSTANCE
8.	Effect of temperature	Susceptibility is independent of temperature.	Susceptibility greater than 1. Varies inversely as temperature. $\chi_m \propto \frac{1}{T}$	Susceptibility decreases with temperature in a complex manner. $\chi_m \propto \frac{1}{T-T_c}$ $(T > T_c)$
9.	Removal of magnetising field	Magnetisation lasts as long as the magnetising field is applied.	As soon as the magnetising field is removed, magnetisation is lost.	Magnetisation is retained even after the magnetising field is removed.
10.	Variation of M with H	M changes linearly with H.	M changes linearly with H and attains saturation at low temperature and in very strong fields.	M changes with H non-linearly and ultimately attains saturation.
11.	Hysteresis effect	B-vector shows no hysteresis.	B-vector shows no hysteresis.	B-vector shows hysteresis.
12.	Physical state of the material	solid, liquid or gas.	solid, liquid or gas.	normally solids only.
13.	Examples	Bi, Cu, Pb, Si, N_2 (at STP), H_2O, NaCl.	Al, Na, Ca, O_2 (at STP), $CuCl_2$	Fe, Ni, Co, Gd, Fe_2O_3, Alnico