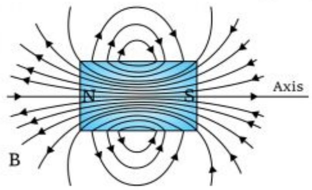
CHAPTER 5
MAGNETISM AND MATTER

BAR MAGNET

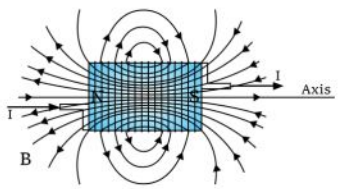
A bar magnet is a permanent magnet with two poles where the attractive property of the magnet is concentrated.

A freely suspended bar magnet aligns approximately in the geographic north-south direction.

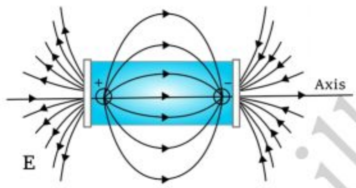
Magnetic field lines of a bar magnet



Magnetic field lines of a current carrying finite solenoid



Electric field lines of an electric dipole



NOTE

- The pattern of the magnetic field lines of a current carrying finite solenoid and a bar magnet is identical.
- **Difference between electric field lines and magnetic field lines**
  Magnetic field lines are continuous closed loops, but electric field lines do not form closed loops.

PROPERTIES OF MAGNETIC FIELD LINES

1. Magnetic field lines are continuous closed loops.
2. The tangent drawn to the MF lines gives the direction of MF at that point.
3. Two MF lines never intersect. If two field lines intersect at a point, it means that there are two different directions for magnetic field at that point. But this is not possible.
4. The number density of field lines gives in a region gives the intensity MF in that region.

BAR MAGNET AS AN EQUIVALENT SOLENOID

The resemblance of MF lines of a bar magnet and a solenoid suggests that a bar magnet can be considered as a large number of circulating current in analogous with a solenoid.

Therefore the **MF at a far point on the axial line of a bar magnet**

$$B_{ax}=\frac{\mu_0}{4\pi}\frac{2m}{x^3}$$

And the **MF at a far point on the equitorial line of a bar magnet**

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

where, 'm' is the **magnetic moment of the bar magnet(**which is equal to the magnetic moment of an equivalent solenoid that produces the same MF)

MAGNETIC DIPOLE MOMENT (m)

Magnetic dipole moment is the product of pole strength and the distance between the poles.

$$m=p\,x\,2l$$

Where, p – Pole strength
2l – Distance b/w the poles

Note: magnetic dipole moment is a vector quantity whose direction is from the south pole to the north pole.

Problem

(a) What happens if a bar magnet is cut into two pieces: (i) transverse to its length
(ii) along its length?

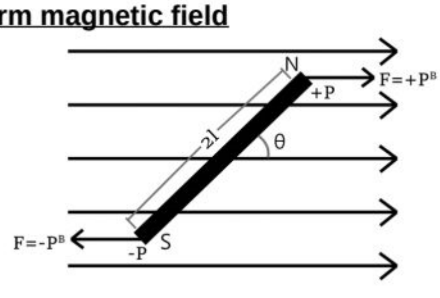
(b)How does the pole strength and the magnetic dipole moment changes if a bar magnet is cut into two pieces:
(i) Longitudinally (ii) Transversally ?

Solution

(a) In either case, one gets two magnets, each with a north and south pole.
(b)(i) Pole strength and magnetic moment become half
(ii) No change in Pole strength and magnetic moment becomes half

MAGNETIC DIPOLE IN A UNIFORM MAGNETIC FIELD

1. Torque acting on a magnetic dipole placed in a uniform magnetic field



Two equal and opposite forces acting at the two ends of the dipole constitutes a torque.

$$\tau=\tau_1+\tau_2$$

=> $\tau=PBl\sin\theta+PBl\sin\theta=PB2l\sin\theta$

=> $\boxed{\tau=mB\sin\theta}$ => $\boxed{\vec{\tau}=\vec{m}\,X\,\vec{B}}$

where, $P2l=m$, the magnetic dipole moment.

Note : Net force acting on the dipole is zero.

2. Motion of a dipole in a uniform magnetic field

When a magnetic dipole is released from an angular position, θ in a uniform magnetic field , it executes SHM. Whose period,

$$\boxed{T=2\pi\sqrt{\frac{I}{mB}}}$$

=> $$\boxed{\upsilon=\frac{1}{2\pi}\sqrt{\frac{mB}{I}}}$$

using the above equations , we can find out the magnetic field at a place by $\boxed{B=\frac{4\pi^2 I}{mT^2}}$

3 . Magnetic potential energy

Magnetic potential energy, $U_m=work\ done$

$$\boxed{U_m=-mB\cos\theta=-\vec{m}.\vec{B}}$$

Special cases

Case1 : $\theta=0$, ($\vec{m}$ and $\vec{B}$ are parallel)

$\boxed{U_m=-mB}$ (PE is minimum, this is stable equilibrium)

Case2: $\theta=180$, ($\vec{m}$ and $\vec{B}$ are anti parallel)

$\boxed{U_m=mB}$ (PE is maximum, this is unstable equilibrium)

Problem

A magnetised needle in a uniform magnetic field experiences a torque but no net force. An iron nail near a bar magnet, however, experiences a force of attraction in addition to a torque. Why?

Solution

No force if the field is uniform. The iron nail experiences a non- uniform field due to the bar magnet. There is induced magnetic moment in the nail, therefore, it experiences both force and torque. The net force is attractive because the induced south pole (say) in the nail is closer to the north pole of magnet than induced north pole.

Example 5.2

A short bar magnet placed with its axis at 30° with an external field of 800 G experiences a torque of 0.016 Nm.

(a) What is the magnetic moment of the magnet?

(b) What is the work done in moving it from its most stable to most unstable position?

(c) The bar magnet is replaced by a solenoid of cross-sectional area 2 × 10 $^{-4}$ m ^{2} and 1000 turns, but of the same magnetic moment. Determine the current flowing through the solenoid

Solution

(a) $\tau=mB\sin\theta$ => $m=\frac{\tau}{B\sin\theta}=0.40\,A\,m^2$

(b) $u(180)-u(0)=mB+mB=2mB$

= 2 x 0.40 x 800 x 10^{-4} = 0.064 J

(c) $m=NIA$ => $I=\frac{m}{NA}$ = 2 A

Comparison between Electrostatics and Magnetism

	Electrostatics	magnetism
	$\frac{1}{\varepsilon_0}$	μ_0
Dipole moment	p	m
Axial Field for a short dipole	$\frac{1}{4\pi\varepsilon_0}\frac{2m}{x^3}$	$\frac{\mu_0}{4\pi}\frac{2m}{x^3}$
Equatorial Field for a short dipole	$\frac{-1}{4\pi\varepsilon_0}\frac{m}{x^3}$	$\frac{-\mu_0}{4\pi}\frac{m}{x^3}$
External Field: torque	$\vec{P}\,X\,\vec{E}$	$\vec{m}\,X\,\vec{B}$
External Field: Energy	$-\vec{P}.\vec{E}$	$-\vec{m}.\vec{B}$

GAUSS'S LAW IN MAGNETISM

The law states that "**the net magnetic flux through any closed surface is zero**"

$$\boxed{\phi_B=\oint_S \vec{B}.\vec{ds}=0}$$

Note: The RHS of the above equation is zero as there is no magnetic monopole exist.

MAGNETIC PROPERTIES OF MATERIALS

SOME BASIC DEFINITIONS

Magnetization

- The process of bringing up magnetism in a material is called magnetization

Intensity of magnetization (M)

- It is the net magnetic dipole moment induced per unit volume when the sample is subjected to magnetizing field.
- It is a vector quantity

- $M = \frac{m_{net}}{V}$, In vector form $\vec{M} = \frac{\vec{m}}{V}$

(or) $M = \frac{p2l}{A2l} = \frac{P}{A}$, where P – Pole strength

- Unit: A/m Dimension: $L^{-1}A$
- It depends on the material property

Magnetising field (Or) Magnetic Intensity (H)

- The field which induces magnetism in a material is called magnetizing field and the strength of that field is called magnetic intensity (H)
- The magnetizing field along the axis of a solenoid having n turns per unit length and carrying a current I is given by $H = nI$
- The MF inside a solenoid is given by $B_0 = \mu_0 nI = \mu_0 H$
- H=nI does not depends on the medium (material)inside the solenoid.
- Unit: A/m Dimension: $L^{-1}A$

Permeability (μ)

- Permeability μ of a medium is the ratio of the magnetic induction (B) to the magnetic intensity (H)
- $\mu_0 = \frac{B_0}{H}$ and $\mu = \frac{B}{H}$

Relative Permeability(μ_r)

- It is the ratio of magnetic induction in a material to the magnetic induction in air $\mu_r = \frac{B}{B_0} = \frac{\mu H}{\mu_0 H} = \frac{\mu}{\mu_0}$

Magnetic Susceptibility (χ_m)

- Magnetisation produced in a material is directly proportional to the magnetic intensity (H).
- $M \alpha H$ (or) $M = \chi_m H$
  Where, χ_m is a constant called susceptibility $\chi_m = \frac{M}{H}$
- It is the ratio of magnetisation to the magnetic intensity.
- It has no unit

Relation between susceptibility (χ_m) and relative permeability(μ_r)

Consider a material (say an iron core) in an air solenoid, then the total magnetic field,

$$B = B_0 + B_m$$

Total MF= External MF + MF due to material

ie, $B = \mu_0 H + \mu_0 M$

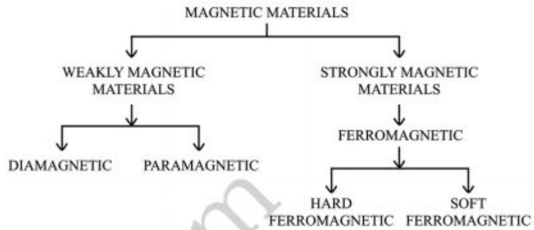
=> $B = \mu_0 H(1 + \frac{M}{H})$

=> $\mu H = \mu_0 H(1 + \frac{M}{H})$

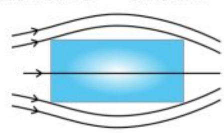
=> $\frac{\mu}{\mu_0} = 1 + \frac{M}{H} = 1 + \chi_m$

=> $\mu_r = 1 + \chi_m$

CLASSIFICATION OF MAGNETIC MATERIALS

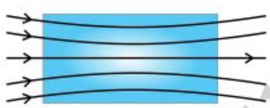


Diamagnetic materials

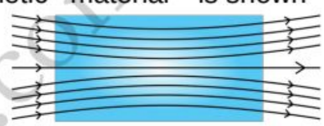
1.	Substances which experience a very weak force of repulsion from a magnet are called diamagnetic substances.
2.	In a non uniform magnetic field , it tend to move from a region of stronger field to a region of weaker field.
3.	Diamagnetism is independent of temperature.
4.	The atoms or molecules of a diamagnetic material do not possess a permanent dipole moment of their own. When an external MF is applied a small dipole moment is developed in it but pointing in the opposite direction of the field.
5.	When freely suspended in a magnetic field it aligns perpendicular to the magnetic field
6.	'M' is small and negative, χ_m is small and negative , μ_r is small and positive $-1 \le \chi_m < 0$ $0 \le \mu_r < 1$ $\mu < \mu_0$ **Note:** A super conductor is a perfect diamagnet whose $\chi_m = -1, \mu_r = 0$
7.	Behaviour of magnetic field lines in a diamagnetic material is shown 
8.	Eg:Bismuth,Gold , Copper, Diamond, Lead,

	Mercury , Silver, Silicon , Nitrogen (at STP)

Paramagnetic materials

1.	Substances which experience a very weak force of attraction from a magnet are called paramagnetic substances.
2.	In a non uniform magnetic field , it tend to move from a region of weaker field to a region of stronger field.
3.	For a paramagnetic material, both χ_m and μ_r depend not only material but also on temperature.
4.	The atoms or molecules of a paramagnetic material possess a permanent dipole moment of their own. When an external MF is applied individual dipole moment aligns in the direction of the field.
5.	When freely suspended in a magnetic field aligns in the direction of the field.
6.	'M' is small and positive, χ_m is small and positive , μ_r is small and positive $\chi_m > 0$ $\mu_r > 1$ $\mu > \mu_0$
7.	Behaviour of magnetic field lines in a paramagnetic material is shown 
8.	Eg: Al, Ca, Cr, W, Li, Mg, Niobium, Platinum, Oxygen (at STP)

Ferromagnetic materials

1.	Substances which experience a very strong force of attraction from a magnet are called ferromagnetic substances.
2.	In a non uniform magnetic field , it tend to move from a region of weaker field to a region of stronger field.
3.	On rising the temperature, ferromagnetic behaviour decreases and above a certain temperature(Curiepoint,T_C)the ferromagnetic behaviour vanish and the substance attain paramagnetic behaviour. The susceptibility above the curie temperature, T_C (ie, in paramagnetic phase) is given by $\chi = \frac{C}{T - T_C}$ for $T > T_C$
4.	Individual atoms have permanent magnetic dipole moments just like in paramagnetic material. But the neighbouring atoms interact with one another and align themselves along a common direction spontaneously. This alignment extends over small regions called domains. There is no bulk magnetisation, since the domains are randomly aligned . In an external magnetic field domains align in the direction of the field.
5.	When freely suspended in a magnetic field aligns in the direction of the field.
6.	'M' is large and positive, χ_m is large and positive , μ_r is large and positive $\chi_m \gg 1$ $\mu_r \gg 1$ $\mu \gg \mu_0$
7.	Behaviour of magnetic field lines in a paramagnetic material is shown 
8.	Eg : Steel, Alnico, soft iron, nickel, cobalt

Problem

What happens if an iron bar magnet is melted? Does it retain it's magnetism?

Solution

Melting point of iron is greater than it's Curie temperature. So iron bar does not retain it's magnetism.

An iron rod of susceptibility 599 is subjected to a magnetising field of 1200 Am^{-1}. The permeability of the material of the rod is :

($\mu_0 = 4\pi \times 10^{-7} T\,m\,A^{-1}$)

(A) $\mu_0 = 2.4\pi \times 10^{-7} T\,m\,A^{-1}$

(B) $\mu_0 = 2.4\pi \times 10^{-4} T\,m\,A^{-1}$

(C) $\mu_0 = 8.0 \times 10^{-5} T\,m\,A^{-1}$

(D) $\mu_0 = 2.4\pi \times 10^{-5} T\,m\,A^{-1}$

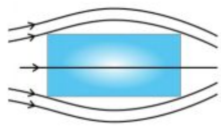
Solution

$\mu_r = 1 + \chi_m = 1 + 599 = 600\, T\,m\,A^{-1}$

$\mu = \mu_0 \mu_r = 4\pi \times 10^{-7} x\, 600 = 2.4\pi \times 10^{-4} T\,m\,A^{-1}$

Ans : (B)

PREVIOUS QUESTIONS

1.	A magnetised needle in uniform magnetic field experiences a torque but no net force. An iron nail near a bar magnet, however, experiences a force of attraction in addition to a torque. Why ?	2
2.a)	The figure below shows a bar of --------------------material placed in an external magnetic field 	1
b)	Give any two properties of this material	2
3.	The expression $\sum \bar{B}.\bar{ds}=0$ is (i) Gauss Law in Electrostatics (ii) Gauss Law in Magnetism (iii) Ampere's circuital law (iv) Lenz's law	1
4.	An air cored solenoid has 1000 turns per metre and carries a current of 2A. Calculate the magnetic intensity (H).	2
5.	The behaviour of magnetic filed lines near two magnetic substances P and Q are shown below. 	
a)	From the figure identify paramagnetic substance.	1
b)	Susceptibility of substance P is .... (positive/negative)	1
6.	Which of the following is not a ferromagnetic material ? (a) Cobalt (b) Iron (c) Nickel (d) Bismuth	1
7.	The temperature at which a ferromagnetic material become paramagnetic is .... (a) Cut off temperature (b) Absolute temperature (c) Curie temperature (d) Fermi Energy	
8.	Define magnetisation. Give its dimension.	2
9.	Differentiate between paramagnetic, diamagnetic and ferromagnetic substances.	3
10.	State Gauss's law in magnetism.	2
11.	Compare dia, para and ferromagnetic substances with suitable examples.	3
12.	Relative permeability of a material $\mu_r<1$, identify the magnetic material. Write the relation between relative permeability and magnetic susceptibility.	2
13.a)	State Gauss's law in magnetism.	1
b)	A short bar magnet placed with its axis at 30^0 with a uniform external magnetic field of 0.3T experiences a torque of magnitude equal to $5x10^{-2}$ J. What is the magnitude of the magnetic moment of the magnet ?	2