

MAGNETISM AND MATTER

Important Points:

1. Magnetic Moment:

It is the product of magnetic length and pole strength $M = 2l m$. A-m²

2. Coulomb's Law:

The force of attraction or repulsion between two magnetic poles is directly proportional to the product of their pole strengths and inversely proportional to the square of the distance between them

them $F = \frac{\mu_0 m_1 m_2}{4\pi d^2}$ in air or vacuum

$$F = \frac{\mu m_1 m_2}{4\pi d^2} \text{ in medium}$$

Where μ_0 = absolute permeability of air or free space

μ = absolute permeability of a medium

3. The magnetic induction due to a pole of pole strength 'm' at a distance 'd' from it is given by

$B = \frac{\mu_0 m}{4\pi d^2}$, where μ_0 is the permeability of free space

4. Magnetic Materials:

A) Intensity of Magnetizing Field (\vec{H}):

The ratio of magnetic induction produced in vacuum (\vec{B}_0) to the magnetic permeability of vacuum is defined as magnetizing field i.e. $\vec{B}_0 = \mu_0 \vec{H}$.

B) Intensity of Magnetisation (I):

When a magnetic material is magnetized by keeping it in a magnetizing field, the induced magnetic moment per unit volume or induced pole strength per unit area of cross section of that

material is known as intensity of magnetization. $I = \frac{M}{V}$ or $I = \frac{m}{A}$ A.m⁻¹

C) Magnetic Susceptibility [χ]:

i) The ratio of magnitude of intensity of magnetization (I) in a material to that of magnetizing field (H) is called magnetic susceptibility of that material.

$$\chi = I / H$$

ii) χ has no units and no dimensions.

iii) For diamagnetic materials χ is low and negative.

iv) For paramagnetic materials χ is low but positive.

v) For Ferro magnetic materials χ is high and positive.

5. Elements of Earth's Magnetic Field:

The magnitude and direction of the magnetic field of the Earth at a place are completely given by certain quantities known as magnetic elements.

1) Magnetic Declination (θ):

It is the angle between geographic and the magnetic meridian planes.

2) Angle of Inclination or Dip (ϕ):

It is the angle between the direction of intensity of total magnetic field of Earth and a horizontal line in the magnetic meridian.

3) Horizontal component of Earth's magnetic field (B_H):

Earth's magnetic field is horizontal only at the magnetic equator. At any other place, the total intensity can be resolved into horizontal component (B_H) and vertical component (B_V).

$$B_H = B \cos \phi \quad \text{and} \quad B_V = B \sin \phi$$

Very Short Answer Questions

1. A Magnetic Dipole placed in a magnetic field experiences a net force. What can you say about the nature of the magnetic field?

A. If a magnetic dipole placed in a magnetic field experiences a net force, the field may be non-uniform.

2. What happens to the compass needles at the Earth's poles?

A. At the Earth's poles the horizontal component of Earth's magnetic field is zero. Hence the compass needles may align in any direction.

3. What do you understand by the 'Magnetization' of a sample?

A. Magnetization is the process of making a sample temporarily or permanently magnetic, when placed in a magnetic field.

Magnetisation (M) of a sample is the net magnetic moment per unit volume $M = \frac{m_{net}}{V}$

4. What is the magnetic moment associated with a solenoid?

A. Magnetic moment associated with a solenoid where $M = niA$

$n \rightarrow$ number of turns per unit length

$A = \pi r^2$ $A \rightarrow$ area of the coil $i \rightarrow$ current in the coil $r \rightarrow$ radius of the solenoid

5. What are the units of magnetic moment, magnetic induction and magnetic field?

A. Magnetic moment - Am^2

Magnetic induction - Tesla

Magnetic field - Tesla

6. Magnetic lines form continuous closed loops .Why?

A. Magnetic monopoles do not exist in nature. Hence the fields lines always begin from one end (pole) have to end at the other (pole).

7. Define magnetic declination?

A. Magnetic Declination:

The angle between the magnetic meridian and geographical meridian measured in the horizontal plane is called magnetic declination.

8. Define magnetic inclination or angle of dip?

A. Magnetic inclination or angle of dip:

The angle made by the resultant magnetic field of the Earth at a place with the horizontal is called magnetic inclination.

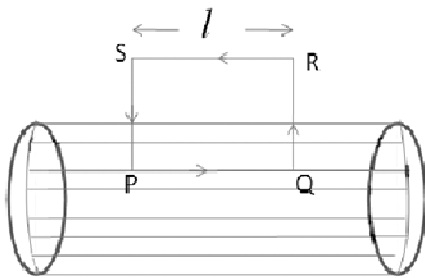
9. Classify the following materials with regard to magnetism: Manganese, Cobalt, Nickel, Bismuth, Oxygen, Copper.

A. Manganese - Para Bismuth - Dia
Cobalt - Ferro Oxygen - Para
Nickel - Ferro Copper - Dia

Short Answer Questions

1. Derive an expression for the axial field of a solenoid of radius ‘r’, containing ‘n’ turns per unit length and carrying current ‘i’?

A. Consider a solenoid of radius ‘r’, containing ‘n’ turns per unit length and carrying current ‘i’. To calculate the magnetic field at a point P inside the solenoid, let us draw a rectangle PQRS as shown in figure.



The line PQ is parallel to the solenoid axis and hence parallel to the magnetic field \vec{B} inside the solenoid. Thus, $\oint_P \vec{B} \cdot d\vec{l}$, on the remaining three sides, $\vec{B} \cdot d\vec{l}$ is zero everywhere as \vec{B} is either zero (or) perpendicular to $d\vec{l}$. Thus, the circulation of \vec{B} along PQRS is $\oint \vec{B} \cdot d\vec{l} = Bl$, let n be the number of turns per unit length along the length of the solenoid. A total of ‘nl’ turns cross the rectangle PQRS. Each turn carries a current i. So the net current crossing PQRS = nli. using Ampere’s law $\oint \vec{B} \cdot d\vec{l} = \mu_0 nli$

$$Bl = \mu_0 nli$$

$$B = \mu_0 ni \quad n \rightarrow \text{no of turns per unit length}$$

2. The force between two magnet poles separated by a distance ‘d’ in air is ‘F’. At what distance between them does the force become doubled?

A. $F_1 = F; d_1 = d; F_2 = 2F; d_2 = ?$

Using inverse square law, $\frac{F_1}{F_2} = \left(\frac{d_2}{d_1}\right)^2 \Rightarrow \frac{F}{2F} = \frac{d_2^2}{d_1^2}$

$$\therefore d_2 = \frac{d}{\sqrt{2}}$$

3. Compare the properties of Para, Dia and Ferromagnetic substances?

A.

Para Magnetic	Dia Magnetic	Ferro Magnetic
1. They are feebly attracted by magnets.	1. They are feebly repelled by magnets.	1. They are strongly attracted by magnets.
2. Magnetized feebly in the direction of magnetizing field.	2. When subjected to the magnetizing, they are magnetized in opposite direction to the magnetizing field.	2. Magnetized strongly in direction of magnetizing field.
3. They move from weaker to stronger part of the magnetic field.	3. They move from stronger part to the weaker part of the magnetic field.	3. They move from weaker to stronger part of the magnetic field.
4. Magnetic permeability is greater than 1 and positive.	4. Magnetic permeability is less than 1 and positive.	4. Magnetic permeability is much greater than 1 and positive.
5. χ is small and positive.	5. χ is small and negative.	5. χ is high and positive.

4. Explain the elements of the Earth's magnetic field and draw a sketch showing the relationship between the vertical component, horizontal component and angle of dip.

A. The magnetic field of Earth, at a place can be completely characterised by three parameters given as-

- 1) Magnetic declination
- 2) Magnetic dip (or) inclination
- 3) Horizontal component of Earth's magnetic field.

1) Magnetic Declination:

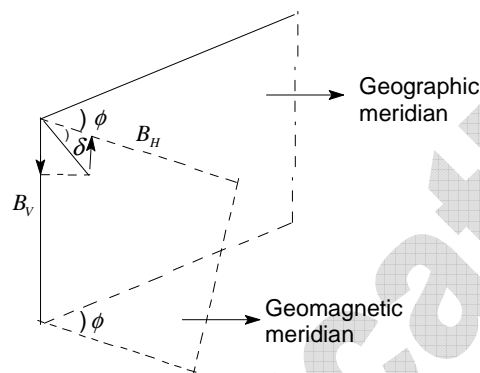
(a) It is defined as the angle between the magnetic meridian and geographical meridian measured in the horizontal plane.

- (b) The magnetic meridian at a place is vertical plane passing through the Earth's magnetic poles.
- (c) The geographical meridian at a place is vertical plane passing through the Earth's geographical poles.
- (d) The angle of declination (ϕ) varies from place to place on the Earth's surface

2) Magnetic Dip

It is defined as the angle made by the resultant magnetic field of the Earth at a place with the horizontal.

When a magnetic needle is so mounted that it is free to rotate in a vertical plane, it is called dip needle the angle (δ) between the needle and the horizontal is angle of dip at that place.



3) Horizontal component of Earth's Magnetic Field (B_H):

It is the component of Earth's total magnetic field along horizontal direction in the magnetic meridian. It is denoted by B_H

From the figure, we can find $B_H = R \cos \delta$ and $B_V = R \sin \delta$ where B_H & B_V are horizontal and vertical component of Earth's magnetic field.

Now we can write $R = \sqrt{B_H^2 + B_V^2}$ and $\tan \delta = \frac{B_V}{B_H}$

5. Define Retentivity and coercivity. Draw the hysteresis curve for soft iron and steel. What do you infer from these curves?

A. Retentivity:

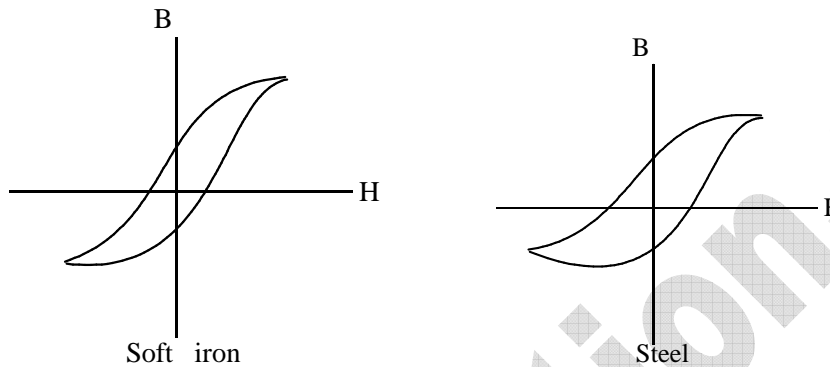
When H is reduced, I reduces but is not zero, when $H = 0$. The remainder value of magnetisation when $H = 0$ is called the residual magnetism or Retentivity.

The property by virtue of which the magnetism (I) remains in a material even on the removal of magnetising field is called Retentivity or Residual magnetism.

Coercivity or Coercive Force:

When magnetic field H is reversed, the magnetisation decreases and for a particular value of H , denoted by H_c , it becomes zero when $I = 0$. This value of H is called the coercivity.

Hysteresis curve:



Soft Iron and steel:

Soft Iron has high susceptibility, Permeability and Retentivity where coercivity and hysteresis are small than that of steel

Cores of dynamos, transformers, electromagnetic ----- soft iron

Permanent magnetic ----- steel

Magnetic hard substance (steel) - High coercivity

Magnetic soft substance (soft iron) - Low coercivity.

6. If B is the magnetic field produced at the centre of a circular coil of one turn of length L carrying current I then what is the magnetic field at the centre of the same coil which is made into 10 turns?

A. $B = \frac{\mu_0 ni}{2r}$ and $l = \pi 2r$

$$\frac{B_1}{B_2} = \left(\frac{n_1}{n_2}\right)^2 \Rightarrow \frac{B}{B_2} = \left(\frac{1}{10}\right)^2$$

$\therefore B_2 = 100B$

7. If the number of turns of a solenoid is doubled, keeping the other factors constant, how does the magnetic field at the axis of the solenoid change?

A. For a solenoid, $B \propto n$

$$\frac{B_1}{B_2} = \frac{n_1}{n_2} \Rightarrow \frac{B}{B_2} = \frac{n}{2n}$$

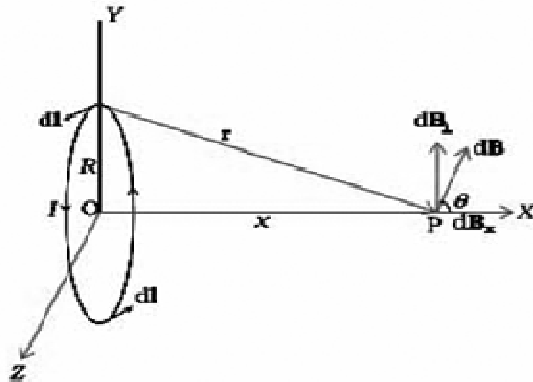
$$\therefore B_2 = 2B$$

Long Answer Questions

1. Derive an expression for the magnetic field at a point on the axis of a current carrying circular loop.

A. Consider a loop of radius 'R' carrying a current 'I' in the XZ plane. Let P be a point on the axis of coil at a distance 'x' from the centre O of the coil. Consider a conducting element \overline{dl} of the loop. From Biot - Savart law the magnetic induction due to \overline{dl} is given by, $d\overline{B} = \frac{\mu_0}{4\pi} \frac{I \overline{dl} \times \overline{r}}{r^3}$

Any element of the loop is perpendicular to the position vector from the element to the axial point. Hence $|\overline{dl} \times \overline{r}| = r dl$ and $r^2 = (x^2 + R^2)$.



$$\therefore dB = \frac{\mu_0}{4\pi} \frac{I dl}{(x^2 + R^2)}$$

As for every current element there is a symmetrically situated opposite element, the component of the field perpendicular to the X-axis cancel each other while along the axis add up. Net induction along X-axis $d\overline{B}_x = dB \cos \theta$.

$$\text{But, } \cos \theta = \frac{R}{(x^2 + R^2)^{1/2}}$$

$$\therefore dB_x = \frac{\mu_0 I dl}{4\pi} \frac{R}{(x^2 + R^2)^{3/2}}$$

The total magnetic induction due to the coil ($dl = 2\pi R$),

$$B = \frac{\mu_0 I R^2}{2(x^2 + R^2)^{3/2}}$$

At the centre of the coil i.e. at $x = 0$, $B = \frac{\mu_0 I}{2R}$

2. Prove that a bar magnet and a solenoid produce similar fields?

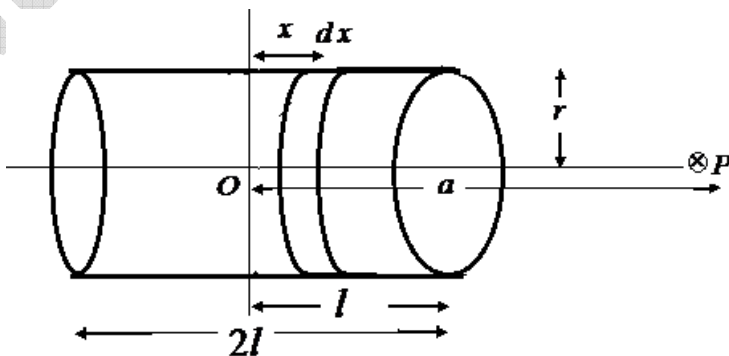
- A. Consider a solenoid consisting of 'n' turns per unit length and carrying current 'i'. Let the length of the solenoid be $2l$ and 'r' be its radius. Consider a point P at a distance 'a' from the centre 'O' of the solenoid.

Consider a circular element of thickness dx of the solenoid at a distance 'x' from the centre. It consists of ndx turns. Let 'i' be the current through the solenoid. The magnitude of the field at the point P due to the circular element is

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

The total magnetic induction is obtained by integrating between the limits $x = -l$ to $x = +l$

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



If $r \gg a$ and $r \gg l$, then $\left[(a-x)^2 + r^2 \right]^{-3/2} \approx a^{-3}$

$$\therefore B = \frac{\mu_0 n i r^2}{2 a^3} \int_{-l}^{+l} dx = \frac{\mu_0 n i}{2} \frac{2lr^2}{a^3}$$

But the magnetic moment of the solenoid $m = n(2l)I(\pi r^2)$

$$\therefore B = \frac{\mu_0}{4\pi} \frac{2m}{a^3}$$

This is similar to the magnetic field on the axial line of a bar magnet, where 'm' is the magnetic moment.

Hence a bar magnet and a solenoid produce similar fields.

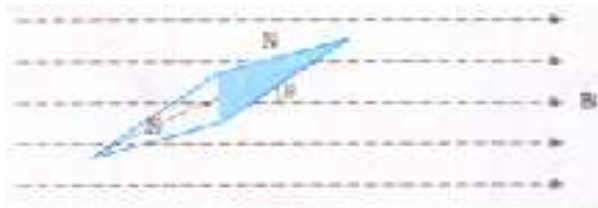
3. A small magnetic needle is set into oscillations in a magnetic field B. Obtain an expression for the period of oscillation?

A: A small magnetic needle of moment 'm' is set into oscillations in a uniform magnetic field B.

The restoring torque acting on the magnetic needle is given by,

$$\text{Restoring Torque } (\tau) = -m B \sin \theta$$

Where θ is the small angular amplitude given to the needle.



If I is the moment of inertia of the bar magnet about the suspension axis and is the angular acceleration produced, then by definition,

$$\text{Torque} = I \frac{d^2 \theta}{dt^2}$$

$$\therefore I \frac{d^2 \theta}{dt^2} = -m B \sin \theta$$

When θ is small $\sin \theta = \theta$,

$$\therefore \frac{d^2\theta}{dt^2} = -\left(\frac{mB}{I}\right)\theta$$

Hence for a given magnet, the angular acceleration (α) is directly proportional to angular displacement which is the condition for SHM. Hence the time period of the magnet is given by

$$T = 2\pi \sqrt{\frac{\text{Angular displacement}}{\text{Angular acceleration}}}$$

Time period of vibrating magnet, $T = 2\pi \sqrt{\frac{I}{mB}}$

4. A bar magnet, held horizontally, is set into angular oscillations in the Earth's magnetic field. It has time periods T_1 and T_2 at two places, where the angles of dip are θ_1 and θ_2 respectively. Deduce an expression for the ratio of the resultant magnetic fields at the two places?

A. The time periods of bar magnet at two given places

$$T_1 = 2\pi \sqrt{\frac{I}{MB_{H_1}}}$$

$$T_2 = 2\pi \sqrt{\frac{I}{MB_{H_2}}}$$

$$\frac{T_1}{T_2} = \sqrt{\frac{B_{H_2}}{B_{H_1}}} \Rightarrow \frac{B_{H_1}}{B_{H_2}} = \frac{T_2^2}{T_1^2} \dots\dots\dots(i)$$

Also $B_H = B_E \cos \theta$

$$\therefore B_{H_1} = B_{E_1} \cos \theta_1 \text{ and } B_{H_2} = B_{E_2} \cos \theta_2$$

$$\therefore \frac{B_{E_1}}{B_{E_2}} = \frac{B_{H_1} \cos \theta_2}{B_{H_2} \cos \theta_1} \dots\dots\dots(ii)$$

From equations (i) and (ii) $\frac{B_{E_1}}{B_{E_2}} = \frac{T_2^2 \cos \theta_2}{T_1^2 \cos \theta_1}$

5. Define magnetic susceptibility of a material. Name two elements one having positive susceptibility and other having negative susceptibility?

A. The ratio of magnitude of intensity of magnetisation to that of magnetising field is called

Magnetic Susceptibility i.e. $\chi = \frac{I}{H}$.

It is a scalar with no units and dimensions and physically represents the ease with which a magnetic material can be magnetised, i.e., large value of implies that the material is more susceptible to the field and hence can be easily magnetised. Is maximum for soft iron

i) Aluminium, calcium, chromium, etc having positive susceptibility

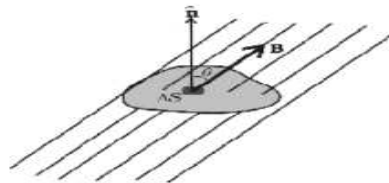
ii) Bismuth, copper, Diamond, etc having negative susceptibility.

6. Obtain Gauss's law for magnetism and explain it?

A. Gauss Law:

The net magnetic flux out of any closed surface is zero. This amounts to a statement about the sources of magnetic field.

Consider small vector area elements Δ of a closed surface as shown. The magnetic flux through Δ s is given by



$$\Delta\phi_B = B \cdot \Delta s$$

Where B is the magnetic field at Δs . Hence the net flux is given by

$$\phi_B = \sum_{all} \Delta\phi_B = \sum_{all} B \cdot ds = 0$$

Explanation:

For a magnetic dipole, any closed surface the magnetic flux directed inward towards the South Pole will equal the flux outward from the North Pole. The net flux will always be zero for dipole sources. If there were a magnetic monopole source, this would give a non-zero area integral. Gauss's law for magnetic fields indicates that there are no magnetic monopoles. The simplest magnetic element is a dipole or a current loop.

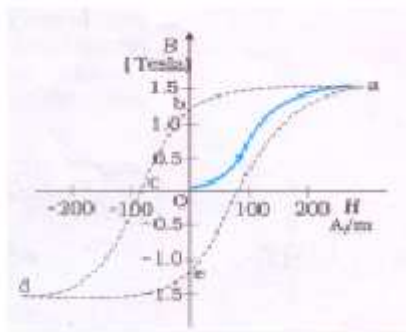
7. What do you understand by “hysteresis”? How does this property influence the choice of materials used in different appliances where electromagnets are used?

A. Hysteresis:

The phenomenon of lagging of flux density B behind the magnetising field H in a ferromagnetic substance subjected to a cycle of magnetisation is known as hysteresis.

Explanation:

The resultant B - H curve is a closed loop $abcdea$, when a piece of ferromagnetic material is subjected to one cycle of magnetisation. This loop is known as hysteresis loop. Here it can be observed that B always lags behind H . At point b , the value of H is zero but B has a finite positive value ob . Similarly at point e , value of H is zero and B has a finite negative value oe .



As H is increased by increasing magnetising current, B increases along oa and reaches its saturation value B_{\max} at a . At this stage all domains of the material are aligned in the direction of H . If now H is gradually decreased by decreasing the magnetising current, the curve follows ab instead of ao . At point b , it is observed that $H = 0$ but $B \neq 0$. The value of ob is known as “retentivity” or remanence. To reduce B in the material to zero, it is necessary to apply H in the reverse direction. This can be done by reversing the magnetising current. As H is gradually increased in the reverse direction, the curve follows bc . At point c , it is observed that $B = 0$ and $H = -H_C$. Here value of H needed to wipe out residual magnetism is called coercive force H_C . Now H is further increased in the reverse direction until point d is reached where the sample is saturated in the reverse direction ($-B_{\max}$). If now H is reduced to zero, point e is reached and the sample again retains magnetic flux density $-B_r$. The remaining part of the loop is obtained by increasing current to produce H in the original direction. The smaller the hysteresis loop area of the material, the smaller is the loss.

Appliances:

Soft Iron has high permeability and low Retentivity where coercivity and hysteresis are small than that of steel. Hence cores of dynamos, transformers are made with soft iron.

The hysteresis curve is used to select the materials for permanent magnets. The retentivity and coercivity are larger for steel than for soft iron. So, steel is quite suitable for making permanent magnets.

PROBLEMS

1. What is the torque acting on a plane coil of “n” turns carrying a current “i” and having an area A, when placed in a constant magnetic field B?

Sol: $F = i l B \sin \theta$

$\tau = \text{Force} \times \perp Lr$ distance between the forces

$$\tau = F \times b$$

$$= (i l B \sin \theta) \times b (\because A = lb)$$

$$\tau = i A B \sin \theta \text{ (For coil of 1turn)}$$

$$\therefore \tau = n i A B \sin \theta \text{ (For coil of 'n' turns)}$$

2. A coil of 20 turns has an area of 800mm^2 and carries a current of 0.5A. If it is placed in a magnetic field of intensity 0.3T with its plane parallel to the field, what is the torque that it experiences?

Sol: $\theta = 90^\circ$, $n = 20$, $A = 800 \text{ mm}^2 = 800 \times 10^{-6} \text{ m}^2$

$$i = 0.5\text{A} = \frac{1}{2} \text{A}$$

$$B = 0.3\text{T}$$

$$\tau = n i A B \sin \theta$$

$$\tau = 20 \left(\frac{1}{2} \right) (800 \times 10^{-6}) 0.3 \sin 90^\circ$$

$$\tau = 2400 \times 10^{-6} = 2.4 \times 10^{-3} \text{ Nm}$$

3. In the Bohr atom model the electrons move around the nucleus in circular orbits. Obtain an expression the magnetic moment (μ) of the electron in a Hydrogen atom in terms of its angular momentum L ?

$$\text{Sol: } i = \frac{q}{t} = \frac{e}{t} = \frac{e}{\frac{2\pi r}{v}} = \frac{ev}{2\pi r}$$

$$\mu = iA \Rightarrow \mu = \frac{ev}{2\pi r} (\pi r^2)$$

$$\mu = \frac{evr}{2} = \frac{e(mvr)}{2m}$$

$$\Rightarrow \mu = \frac{eL}{2m} [\because L = mvr]$$

4. A Solenoid of length 22.5 cm has a total of 900 turns and carries a current of 0.8A. What is the magnetising field H near the centre and far away from the ends of the solenoid?

A. Magnetic induction on the axis of solenoid

$$B = \mu_0 ni ; \text{ But } H = \frac{B}{\mu_0}$$

$$N = 900, l = 22.5\text{cm} = 22.5 \times 10^{-2}\text{m}, i = 0.8 \text{ A}$$

$$H = ni \left[n = \frac{N}{l} \right]$$

$$H = \frac{N}{l} i$$

$$= \frac{900}{22.5 \times 10^{-2}} \times 0.8 = 3200 \text{ Am}^{-1}$$

5. A bar magnet of length 0.1m and with a magnetic moment of 5Am^2 is placed in a uniform magnetic field of intensity 0.4T. With its axis making an angle of 60° with the field. What is the torque on the magnet?

A. $\tau = MB \sin \theta$

$$= 5 \times 0.4 \sin 60^\circ$$

$$= 2 \frac{\sqrt{3}}{2} = \sqrt{3}$$

$$= 1.732\text{Nm}$$

6. If the Earth's magnetic field at the equator is about $4 \times 10^{-5}\text{T}$, what is its approximate magnetic dipole moment? (Radius of Earth = $6.4 \times 10^6\text{m}$)

A. Magnetic Induction $B = \frac{\mu_0}{4\pi} \cdot \frac{m}{R^2}$, $B = 4 \times 10^{-5} \text{ T}$, $R = 6.4 \times 10^6\text{m}$

$$\text{We have } M = m \times R \Rightarrow m = \frac{M}{R}$$

$$B = \frac{\mu_0}{4\pi} \times \frac{M}{R^3}$$

$$4 \times 10^{-5} = 10^{-7} \times \frac{M}{(6.4 \times 10^6)^3} \Rightarrow M = 1.048 \times 10^{23} \text{ A.m}^2$$

7. The horizontal component of the Earth's magnetic field at a certain place is $2.6 \times 10^{-5}\text{T}$. and the angle of dip is 60° . What is the magnetic field of the Earth at this location?

Sol: $B_H = 2.6 \times 10^{-5}\text{T}$

$$\phi = 60^\circ, \cos \phi = \frac{1}{2}$$

$$B_H = B \cos \phi \Rightarrow B = \frac{B_H}{\cos \phi}$$

$$= \frac{2.6 \times 10^{-5}}{\frac{1}{2}} = 5.2 \times 10^{-5}\text{T}.$$

8. A solenoid, of insulated wire, is wound on a core with relative permeability 400. If the number of turns per metre is 1000 and the solenoid carries a current of 2A. Calculate H, B and the magnetisation M?

Sol: $n = 1000$, $\mu_r = 400$

$$i = 2\text{A}$$

a) $H = \frac{B}{\mu_0} = \frac{\mu_0 n i}{\mu_0} = 10^3 \times 2 = 2000 \text{ A.m}^{-1}$

b) $B = \mu_0 \mu_r H$

$$= 4\pi \times 10^{-7} \times 400 \times 2000 = 1T$$

$$\text{c) } M = (B - \mu_o H) / \mu_o = (\mu_o \mu_r H - \mu_o H) / \mu_o = (\mu_r - 1) H = 399 \times 2000$$

$$= 8 \times 10^5 \text{ A / m.}$$

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