UNIT 3 MAGNETISM AND MAGNETIC EFFECTS OF ELECTRIC CURRENT

Warm greetings:

Dear students

Welcome all. Previous class we learnt about magnetism basics. In this section of physics class you get to learn about torque acting on a bar magnet in uniform magnetic field and magnetic properties.

TORQUE ACTING ON A BAR MAGNET IN UNIFORM MAGNETIC FIELD:

- Consider a magnet of length 2*l* and pole strength q_m kept in a uniform magnetic field $\vec{B}$ as shown in Figure 3.16.
- Each pole experiences a force of magnitude q_{mB} but acting in opposite directions.
- Therefore, the net force exerted on the magnet is zero and hence, there is no translatory motion.
- These two equal and opposite forces constitute a couple (about midpoint of bar magnet) tend to align the magnet in the direction of the magnetic field $\vec{B}$.

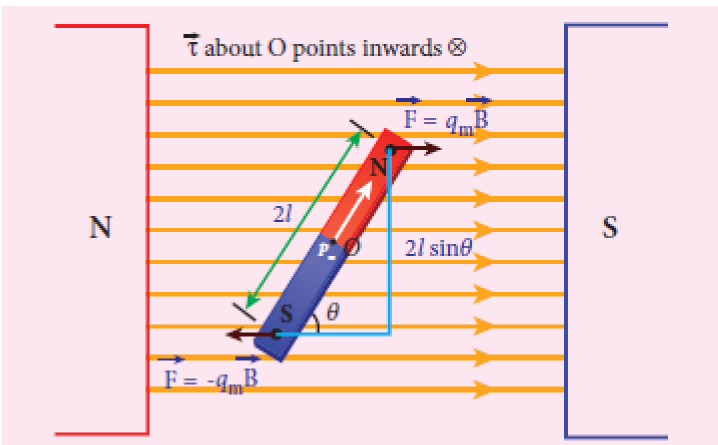

Figure 3.16 Magnetic dipole kept in a uniform magnetic field

The force experienced by north pole,

$$\vec{F}_N = q_m \vec{B} \quad (3.23)$$

The force experienced by south pole,

$$\vec{F}_S = -q_m \vec{B} \qquad (3.24)$$

Adding equations (3.23) and (3.24), we get the net force acting on the dipole as

$$\vec{F} = \vec{F}_N + \vec{F}_S = \vec{0}$$

bThe moment of force or torque experienced by north and south pole about point O is

$$\vec{\tau} = \overrightarrow{ON} \times \vec{F}_N + \overrightarrow{OS} \times \vec{F}_S$$
$$\vec{\tau} = \overrightarrow{ON} \times q_m \vec{B} + \overrightarrow{OS} \times \left(-q_m \vec{B}\right)$$

By using right hand cork screw rule, we conclude that the total torque is pointing into the paper. Since the magnitudes $\left|\overrightarrow{ON}\right| = \left|\overrightarrow{OS}\right| = l$ And l $\left|q_m \vec{B}\right| = \left|-q_m \vec{B}\right|$, the magnitude of total torque about point O

$$\tau = l \times q_m B \sin\theta + l \times q_m B \sin\theta$$
$$= 2l \times q_m B \sin\theta$$
$$\tau = p_m B \sin\theta \qquad (\therefore q_m \times 2l = p_m)$$
$$\text{In vector notation, } \vec{\tau} = \vec{p}_m \times \vec{B} \qquad (3.25)$$

Potential energy of a bar magnet in a uniform magnetic field:

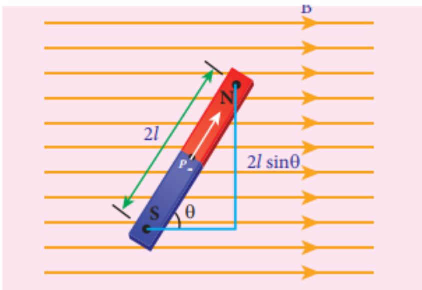

Figure 3.17: A bar magnet (magnetic dipole) in a uniform magnetic field

When a bar magnet (magnetic dipole) of dipole moment $\vec{p}_m$ is held at an angle θ with the direction of a uniform magnetic field $\vec{B}$, as shown in Figure 3.17 the magnitude of the torque acting on the dipole is

$$|\vec{\tau}_B| = |\vec{p}_m||\vec{B}|\sin\theta$$

If the dipole is rotated through a very small angular displacement $d\theta$ against the torque τ_B at constant angular velocity, then the work done by external torque τ_{ext} for this small angular displacement is given by

$$dW = |\vec{\tau}_{ext}|d\theta$$

The bar magnet has to be moved at constant angular velocity, which implies that $|\vec{\tau}_B| = |\vec{\tau}_{ext}|$

$$dW = p_m B\sin\theta\, d\theta$$

Total work done in rotating the dipole from θ' to θ is

$$W = \int_{\theta'}^{\theta} \tau d\theta = \int_{\theta'}^{\theta} p_m B\sin\theta d\theta = p_m B[-\cos\theta]_{\theta'}^{\theta}$$

b

$$W = -p_m B(\cos\theta - \cos\theta')$$

This work done is stored as potential energy in bar magnet at an angle θ (when it is rotated from θ' to θ) and it can be written as

$$U = -p_m B(\cos\theta - \cos\theta') \qquad (3.26)$$

In fact, the equation (3.26) gives the difference in potential energy between the angular positions θ' and θ. If we choose the reference point as $\theta' = 90^b$, so that second term in the equation becomes zero, the equation (3.26) can be written as

$$U = -p_m B\,(\cos\theta) \qquad (3.27)$$

The potential energy stored in a bar magnet in a uniform magnetic field is given by

$$U = -\vec{p}_m \cdot \vec{B} \qquad (3.28)$$

Case 1

(i) If $\theta = 0^o$, then

$$U = -p_m B\,(\cos 0^\circ) = -p_m \mathrm{B}$$

(ii) If $\theta = 180^o$, then

$$U = -p_m B\,(\cos 180^\circ) = p_m \mathrm{B}$$

From the above two results, We infer that the potential energy of the bar magnet is minimum when it is aligned along the external magnetic field and maximum when the bar magnet is aligned anti-parallel to external magnetic field.

MAGNETIC PROPERTIES:

All materials are not magnetic in nature. Further, all the magnetic materials will not behave identically. So, in order to differentiate one magnetic material from another, some basic parameters are used. They are:

(a) Magnetising field

- **The magnetic field which is used to magnetize a sample or specimen is called the magnetising field.**
- Magnetising field is a vector quantity and is denoted by $\vec{H}$ and its unit is A m^{-1}

(b) Magnetic permeability:

- ✓ **The magnetic permeability is the measure of ability of the material to allow the passage of magnetic field lines through it or measure of the capacity of the substance to take magnetisation or the degree of penetration of magnetic field through the substance.**
- ✓ In free space, the permeability (or absolute permeability) is denoted by μ_0 and for any other medium it is denoted by μ.
- ✓ **The relative permeability μr is defined as the ratio between absolute permeability of the medium to the permeability of free space.**

$$\mu_r = \frac{\mu}{\mu_o} \qquad (3.29)$$

  - ✓ Relative permeability is a dimensionless number and has no units.
  - ✓ For free space (air or vacuum), the relative permeability is unity i.e., $\mu_r = 1$.

(c) Intensity of magnetisation

Any bulk material (any object of finite size) contains a large number of atoms. Each atom consists of electrons which undergo orbital motion. Due to orbital motion, electron has magnetic moment which is a vector quantity. In general, these magnetic moments orient randomly, therefore, the net magnetic moment is zero per unit volume of the material.

When such a material is kept in an external magnetic field, atomic dipoles are induced and hence, they will try to align partially or fully along the direction of external field. **The net magnetic moment per unit volume of the material** is known **as intensity of magnetisation.** It is a vector quantity. Mathematically

$$\overline{M} = \frac{\text{Magnetic moment}}{\text{Volume}} = \frac{\vec{p}_m}{V} \qquad (3.30)$$

The SI unit of intensity of magnetisation is ampere metre^{-1}.

The intensity of magnetisation for a bar magnet is

$$\overline{M} = \frac{\text{Magnetic moment}}{\text{Volume}} = \frac{q_m \overline{2l}}{2l\,A} \qquad (3.31)$$

In magnitude, equation (3.31) is

$$|\overline{M}| = M = \frac{q_m \times 2l}{2l \times A} \Rightarrow M = \frac{q_m}{A}$$

This means, **for a bar magnet the intensity of magnetisation can be defined as the pole strength per unit area (face area).**

(d) Magnetic induction or total magnetic field

When a substance like soft iron bar is placed in a uniform magnetising field $\underset{H}{\rightarrow}$, the substance gets magnetised. **The magnetic induction (total magnetic field) inside the specimen $\underset{B}{\rightarrow}$ is equal to the sum of the magnetic field $\underset{Bo}{\rightarrow}$ produced in vacuum due to the magnetising field and the magnetic field $\underset{Bm}{\longrightarrow}$due to the induced magnetism of the substance**.

$$\vec{B} = \vec{B}_o + \vec{B}_m = \mu_o \vec{H} + \mu_o \vec{M}$$

$$\Rightarrow \vec{B} = \vec{B}_o + \vec{B}_m = \mu_o(\vec{H} + \vec{M}) \qquad (3.32)$$

(e) Magnetic susceptibility

When a substance is kept in a magnetising field $\underset{H}{\rightarrow}$, magnetic susceptibility gives information about how a material responds to the external (applied) magnetic field.

In other words, the magnetic susceptibility measures how easily and how strongly a material can be magnetised. It is defined **as the ratio of the intensity of magnetisation $\underset{B}{\rightarrow}$ induced in the material to the magnetising field $\underset{H}{\rightarrow}$**

$$\chi_m = \frac{|\vec{M}|}{|\vec{H}|} \qquad (3.33)$$

- ✓ It is a dimensionless quantity.

✓ Magnetic susceptibility for some of the isotropic substances is given in Table 3.1.

Table 3.1 Magnetic susceptibility for various materials

Material	Magnetic susceptibility (χ_m)
Aluminium	2.3×10^{-5}
Copper	-0.98×10^{-5}
Diamond	-2.2×10^{-5}
Gold	-3.6×10^{-5}
Mercury	-3.2×10^{-5}
Silver	-2.6×10^{-5}
Titanium	7.06×10^{-5}
Tungsten	6.8×10^{-5}
Carbon dioxide (1 atm)	-2.3×10^{-9}
Oxygen (1 atm)	2090×10^{-9}