MAGNETISM AND MATTER

Bar magnet It is rectangular shaped magnet whose one end behave as a north pole and other end behave as south pole.

Bar magnet as an equivalent of solenoid

1. A current carrying solenoid suspended freely always comes to rest in north-south direction.
2. Two current-carrying solenoids exhibit mutual attraction and repulsion when brought closer to one another. This shows that their end faces act as N-and S-poles like that of a bar magnet.
3. Figure 5.24 shows the lines of force of a bar magnet while Fig. 5.25 shows the lines of force of a finite solenoid. The two patterns have a striking resemblance.

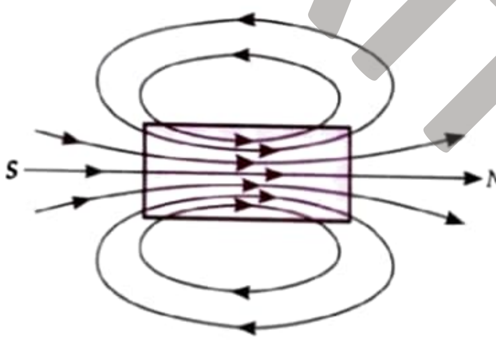


Fig. 5.24 **Field lines of a bar magnet.**

If we move a small compass needle in the neighbourhood of the bar magnet and the current carrying finite solenoid, we shall find that deflections of the needle are similar in the two cases. This again supports the similarity between the two fields.

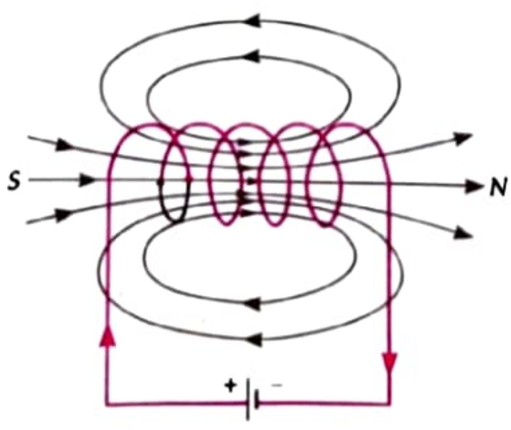


Fig. 5.25 **Field lines of a current carrying finite solenoid.**

A solenoid as an equivalent bar magnet. **A solenoid can be regarded as a combination of circular loops placed side by side, as shown in Fig. 5.26(*a*).** Each turn of the solenoid can be regarded as a small magnetic dipole of dipole moment IA. Then the solenoid becomes an arrangement of small magnetic dipoles placed in line with each other, as shown in Fig. 5.26(*b*). **The number of such dipoles is equal to the number of turns in the solenoid. The north pole of one touches the south of the adjacent one. The opposite poles** neutralise each other except at the ends. **Thus, a** current carrying solenoid can be replaced by just **a single south pole and a single north pole, separated by a distance equal to the length of the solenoid. Hence a current carrying solenoid is equal to a bar magnet as shown in Fig. 5.26(*c*).**

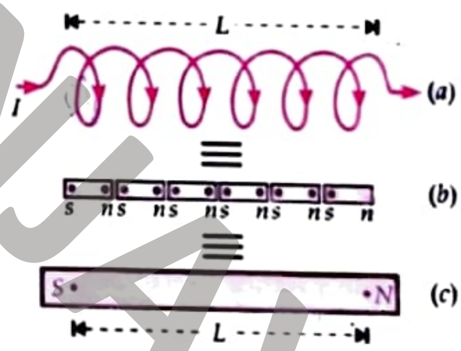
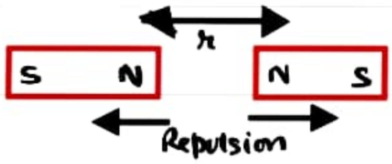


Fig. 5.26 **A solenoid as an equivalent bar magnet.**

A bar magnet and a finite solenoid produce similar magnetic field patterns, as shown in Fig. 5.24 and Fig. 5.25 respectively. It may be noted that the magnetic field inside the solenoid is in direction opposite to that we expect on the basis of the above pole model. ($N \rightarrow S$)

Coulombs law of Magnetic force



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

here m_1, m_2 = magnetic strength of poles
r = distance b/w the poles
μ_0 = Permeability of free space

Also,

$$\frac{\mu_0}{4\pi} = 10^{-7} \quad \text{(constant)}$$

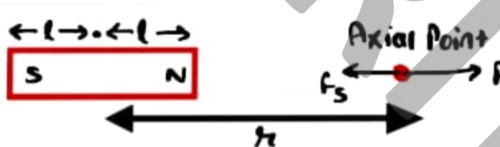
Magnetic dipole moment

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

here M = magnetic dipole moment
m = magnetic strength of pole
$2l$ = distance b/w two poles.

It is a vector quantity
Its direction is from South to North

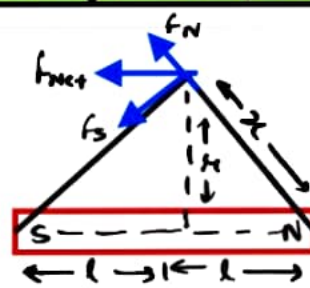
Magnetic field at axial point



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

here
B = magnetic field
M = Magnetic dipole moment = $m \times 2l$
r = distance of axial point from centre of magnet.
l = half length of the dipole

Magnetic field at equatorial point

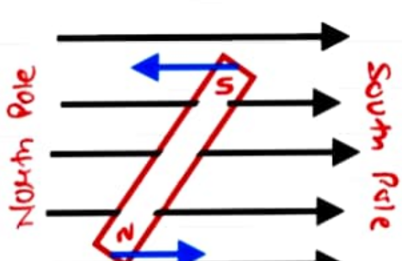


here $x = \sqrt{r^2 + l^2}$

$$\boxed{B_{equ} = \frac{\mu_0}{4\pi} \frac{M}{(r^2 + l^2)^{3/2}}}$$

here B = magnetic field
M = magnetic dipole moment = $m \times 2l$
r = distance of equatorial point from centre of magnet
l = half length of magnet.

Torque on a magnetic dipole in a magnetic field



The magnetic dipole will experience a Torque

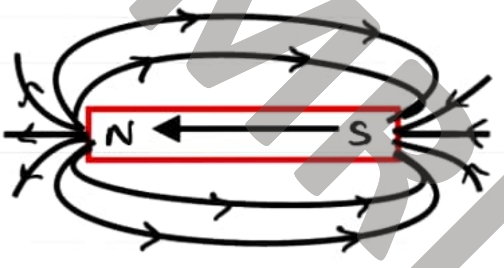
$$\boxed{\tau = mB\sin\theta}$$

here m = magnetic dipole moment
B = magnetic field.

when $\theta = 90$ $\theta = 0$
$\tau = mB$ (max) $\tau = 0$ (mini)

Magnetic field lines

A magnetic line of force may be defined as the curve line the tangent to which at any point gives the direction of the magnetic field at that point. It may also be defined as the path along - which a unit north pole would tend to move if free to do so



Properties of magnetic lines

1. Magnetic lines of force are closed curves which start in air from the N-pole and end at the S-pole and then return to the N-pole through the interior of the magnet.
2. The lines of force never cross each other. If they do so, that would mean there are two directions of the magnetic field at the point of intersection, which is impossible.
3. They start *from* and end *on* the surface of the magnet normally.
4. The lines of force have a tendency to contract lengthwise and expand sidewise. This explains attraction between unlike poles and repulsion between like poles.
5. The relative closeness of the lines of force gives a measure of the strength of the magnetic field which is maximum at the poles.

Some Important terms

1) **Magnetising field :-** The magnetic field which exist inside the Solenoid or toroid, that can magnetise a material is known as magnetising field

$$\boxed{B = \mu_0 n I}$$

2) **Magnetic Induction :-** The total magnetic field inside a magnetic material is the sum of the external magnetising field and the additional magnetic field produced due to magnetisation of material is called magnetic Induction.

3) **Magnetic field Intensity :-** The ability of a magnetising field to magnetize a material medium. is called magnetic field Intensity It is denoted by H.

$$\boxed{H = nI}$$

where n = no. of turns
I = current.

Also $B = \mu_0 n I$ Then, $B = \mu_0 H$

$$\boxed{H = \frac{B}{\mu_0}}$$

4) **Intensity of magnetisation :-** The magnetic moment developed per unit volume of a material when placed in a magnetising field is called Intensity of magnetisation.

$$\boxed{\vec{M} = \frac{m}{V}}$$

5) **Magnetic Permeability**:- The magnetic permeability of a material may be defined as the ratio of its magnetic induction B to the magnetic intensity H. It is denoted by μ

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

6) **Relative permeability**:- It is defined as the ratio of permeability of the medium to the permeability of free space. It is denoted by μ_r.

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

6) **Magnetic Susceptibility**:- It is defined as the ratio of the intensity of magnetisation M to the magnetising field intensity H. It is denoted by χ_m.

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

Classification of magnetic material

1. **Diamagnetic substances.** *Diamagnetic substances are those which develop feeble magnetisation in the opposite direction of the magnetising field. Such substances are feebly repelled by magnets and tend to move from stronger to weaker parts of a magnetic field.*

Examples. Bismuth, copper, lead, zinc, tin, gold, silicon, nitrogen (at STP), water, sodium chloride, etc.

2. **Paramagnetic substances.** *Paramagnetic substances are those which develop feeble magnetisation in the direction of the magnetising field. Such substances are feebly attracted by magnets and tend to move from weaker to stronger parts of a magnetic field.*

Examples. Manganese, aluminium, chromium, platinum, sodium, copper chloride, oxygen (at STP), etc.

3. **Ferromagnetic substances.** *Ferromagnetic substances are those which develop strong magnetisation in the direction of the magnetising field. They are strongly attracted by magnets and tend to move from weaker to stronger parts of a magnetic field.*

Examples. Iron, cobalt, nickel, gadolinium and alloys like alnico.

Effect of Temperature on Ferromagnetic Substance

Modified Curie's law for ferromagnetic substances. When a ferromagnetic sample is heated, its magnetisation decreases due to the increase in the randomisation of its domains. At a sufficiently high temperature, the domain structure disintegrates and the ferromagnetic substance becomes paramagnetic. *The temperature at which a ferromagnetic substance becomes paramagnetic is called* ***Curie temperature*** *or* ***Curie point*** T_C.

Above the curie point *i.e.*, in the paramagnetic phase, the susceptibility varies with temperature as

$$\chi_m = \frac{C}{T - T_C} \qquad (T > T_C)$$

where C is a constant. This is *modified Curie's law* for a ferromagnetic material above the Curie temperature. It is also known as ***Curie-Weiss law***. This law states that *the susceptibility of a ferromagnetic substance above its Curie temperature is inversely proportional to the excess of temperature above the Curie temperature.*

Effect of Temperature on Paramagnetic Substance

Curie's law. From experiments, it is found that the *intensity of magnetisation* (M) of a paramagnetic material is

(*i*) *directly proportional to the magnetising field intensity* H, because the latter tends to align the atomic dipole moments.

(*ii*) *inversely proportional to the absolute temperature* T, because the latter tends to oppose the alignment of the atomic dipole moments.

Therefore at low H/T values, we have

$$M \propto \frac{H}{T}$$

or $$M = C \cdot \frac{H}{T}$$

or $$\frac{M}{H} = \frac{C}{T} \quad \text{or} \quad \chi_m = \frac{C}{T}$$

Here C is curie constant and χ_m is the susceptibility of the material. The above relation is called *Curie's law*. This law *states that far away from saturation, the susceptibility of a paramagnetic material is inversely proportional to the absolute temperature.*

Figure 5.44 shows the variation of intensity of magnetisation M as a function of H/T. Beyond the saturation value M_s, Curie law is not valid.

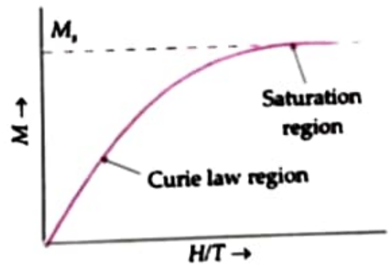


Fig. 5.44 **Magnetisation M as a function of H/T.**

Properties of Diamagnetic Substance

Properties of diamagnetic substances :

1. When placed in an external magnetic field, a diamagnetic substance develops feeble magnisation in the opposite direction of the applied field.

2. When a rod of a diamagnetic material is placed in a magnetic field, poles are induced on it in a direction opposite to that of the inducing field. So the lines of force prefer to pass through the surrounding air than to pass through the material itself *i.e.*, the lines of force get expelled or repelled, as shown in Fig. 5.47.

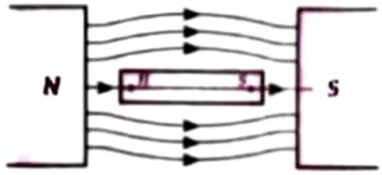


Fig. 5.47 **Reduction of lines of force in a diamagnetic rod.**

3. *When placed in a non-uniform magnetic field, a diamagnetic substance moves from stronger to the weaker parts of the field.*

When a watch glass containing a diamagnetic liquid is placed over two closely lying (3 – 4 mm apart) pole pieces of a magnet, the liquid is found to move towards the poles causing a depression in the middle [Fig 5.48(*a*)]. This indicates that the field is stronger in the middle than that near the poles. Now if the poles are moved apart sufficiently, the magnetic field at the middle becomes weaker than that near the poles. Consequently, the liquid accumulates in the middle and thins out near the poles [Fig. 5.48(*b*)].

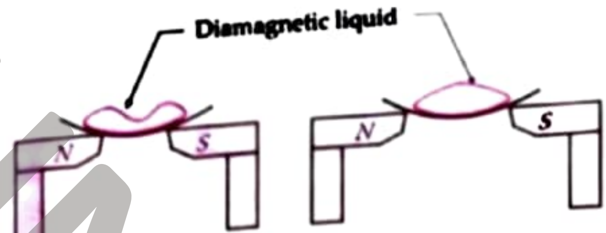


Fig. 5.48 **Effect of non-uniform magnetic field on a diamagnetic liquid when (*a*) poles are quite close to each other, (*b*) poles are sufficiently apart.**

4. When a rod of a diamagnetic material is suspended freely in a uniform magnetic field, it aligns itself perpendicular to the magnetising field (Fig. 5.49).

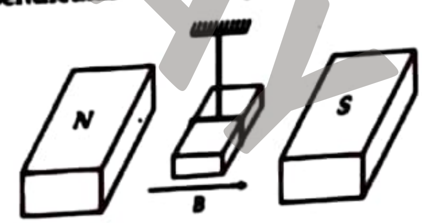


Fig. 5.49 **A freely suspended diamagnetic rod in a uniform field.**

5. As a diamagnetic substance develops a weak magnetisation in the opposite direction of the magnetising field, the susceptibility ($\chi_m = M/H$) of diamagnetic materials is small and negative. For bismuth, $\chi_m = -0.00015$.

6. The relative permeability μ_r $(= 1 + \chi_m)$ is positive but less than 1 for a diamagnetic material.

7. The susceptibility of diamagnetic substances is independent of the magnetising field and the temperature, as shown in Fig. 5.50.

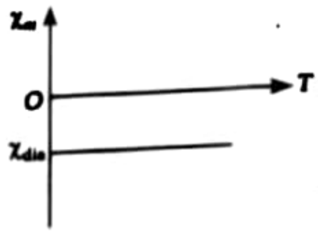


Fig. 5.50 χ_m-T graph for diamagnetic material.

8. The magnetisation of a diamagnetic substance lasts so long as the magnetising field is applied.

Properties of Paramagnetic Substance

Properties of paramagnetic substances

1. When placed in an external magnetic field, a paramagnetic substance develops feeble magnetisation in the direction of the applied field.
2. When a rod of paramagnetic material is placed in a magnetic field, the lines of force prefer to pass through it than through the surrounding air *i.e.*, the lines of force get slightly more concentrated inside the material.

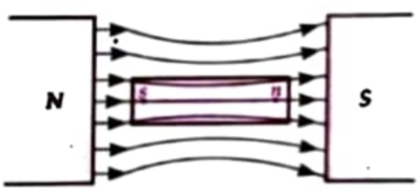
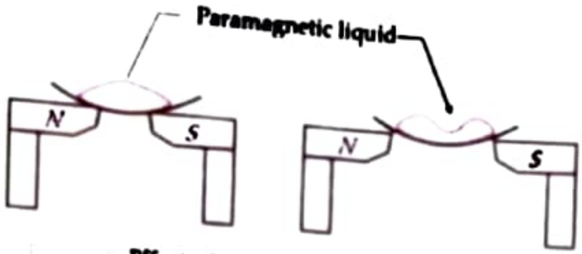


Fig. 5.51 Slightly cocentrated lines of force in a paramagnetic rod.

3. *When placed in a non-uniform magnetic field, a paramagnetic substance moves from weaker to the stronger parts of the field.*

When a watch glass containing a paramagnetic liquid is placed over two closely lying pole pieces of a magnet, the liquid accumulates and elevates in the middle and thins out near the poles [Fig. 5.52(*a*)]. This is because the field in the centre is the strongest. When the poles are moved apart, the field at the poles becomes stronger than that at the centre and the liquid moves towards the poles [Fig. 5.52(*b*)].



Effect of magnetic field on a paramagnetic liquid when (*a*) poles are quite close to each other, (*b*) poles are farther apart.

4. When a rod of paramagnetic material is suspended freely in a uniform magnetic field, it aligns itself parallel to the magnetising field (Fig. 5.53).

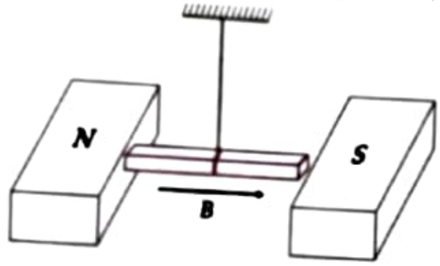


Fig. 5.53 A freely suspended paramagnetic rod in a uniform magnetic field.

5. A paramagnetic material develops small magnetisation in the direction of the magnetising field, so its susceptibility has small but positive value. For aluminium, $\chi = 1.8 \times 10^{-6}$.

6. The relative permeability $(\mu_r = 1 + \chi_m)$ for paramagnetic material has a value slightly great than 1.

7. The magnetic susceptibility of a paramagnet material varies inversely as the absolute temp rature, *i.e.*

$$\chi_m \propto \frac{1}{T}$$

or $$\chi_m = \frac{C}{T},$$

where C is a constant called the *Curie constan* and this equation is known as *Curie's law*.

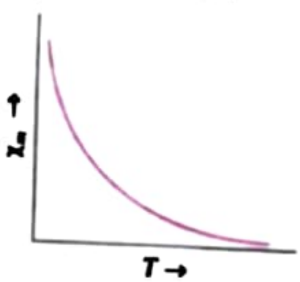


Fig. 5.54 χ_m-T graph for a paramagnetic material.

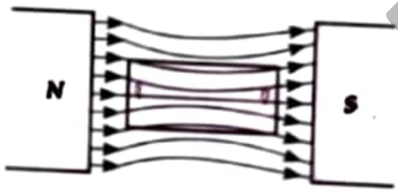
8. For a given temperature, the intensity of magnetisation is proportional to the magnetising field,

9. As soon as the magnetising field is removed, a paramagnetic substance loses its magnetism.

Properties of ferromagnetic Substance

Properties of ferromagnetic substances. Ferromagnetic substances exhibit properties similar to those of paramagnetic substances but in a highly dominant manner. These are as follows :

1. When placed in an external magnetic field, a ferromagnetic material develops strong magnetisation in the direction of the applied field.
2. When a ferromagnetic substance is placed in a magnetic field, the lines of force concentrate greatly into the material so that the magnetic induction B becomes much more than the magnetising field B_0.



3. When a ferromagnetic substance is placed in non-uniform magnetic field, it moves from weaker to the stronger parts of the field.
4. When a rod of a ferromagnetic material is suspended freely in a uniform magnetic field, it quickly aligns itself parallel to the magnetic field.
5. The intensity of magnetisation M is proportional to the magnetising field intensity H for its smaller values.

6. The susceptibility of a ferromagnetic material has a large positive value. This is because

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

and $M >> H$ for a ferromagnetic material. It is of the order of several thousands.

7. The relative permeability $(\mu_r = 1 + \chi_m)$ of a ferromagnetic material has a large positive value. It is of the order of several thousands. For iron, $\mu_r = 1000$.

8. The susceptibility of ferromagnetic material decreases with temperature in accordance with Curie-Weiss law :

$$\chi_m = \frac{C}{T - T_C}$$

9. At a certain temperature called the *Curie point*, the susceptibility suddenly falls and the ferromagnetic substance becomes paramagnetic.
10. The magnetisation developed depends not only on the value of magnetising field but also on the past magnetic and mechanical history of the material.
11. A ferromagnetic substance retains magnetism even after the magnetising field is removed.

Table 5.3 Comparative study of the properties of dia-, para- and ferromagnetic substances

Property	Diamagnetic substances	Paramagnetic substances	Ferromagnetic substances
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 magnetising 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)	Susceptibility is small and negative. $-1 \leq \chi_m < 0$	Susceptibility is small and positive. $0 < \chi_m < \varepsilon$, where ε is a small number	Susceptibility is 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 $1 < \mu_r < 1 + \varepsilon$	Of the order of thousands $\mu_r > 1000$
7. *Permeability value* (μ)	$\mu < \mu_0$	$\mu > \mu_0$	$\mu >> \mu_0$
8. *Effect of temperature*	Susceptibility is independent of temperature.	Susceptibility 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.