30.1 INTRODUCTION

- *Any material that can be magnetised by the application of external magnetic field is called a* ***magnetic material***.
- Diamagnetic, paramagnetic, ferro-magnetic, antiferromagnetic and ferrimagnetic materials are the most important magnetic materials. These magnetic materials are widely used in industry.

First let us define the important terms involved in magnetism.

(*i*) **Magnetic induction (*B*) or magnetic flux density.** *The magnetic induction (B) in any material is the number of lines of magnetic force passing perpendicular through unit area* (Fig. 30.1).

- Its unit is Wbm^{-2} or Tesla.
- The larger the number of field lines crossing per unit normal area, the larger is the magnitude of the magnetic field B.

(*ii*) **Magnetic field intensity (H).** *The magnetic field intensity (H) at any point in the magnetic field is the force experienced by a unit north pole placed at that point.*

- Its unit is Am^{-1}.
- The magnetic induction B due to a magnetic field of intensity H applied in vacuum is

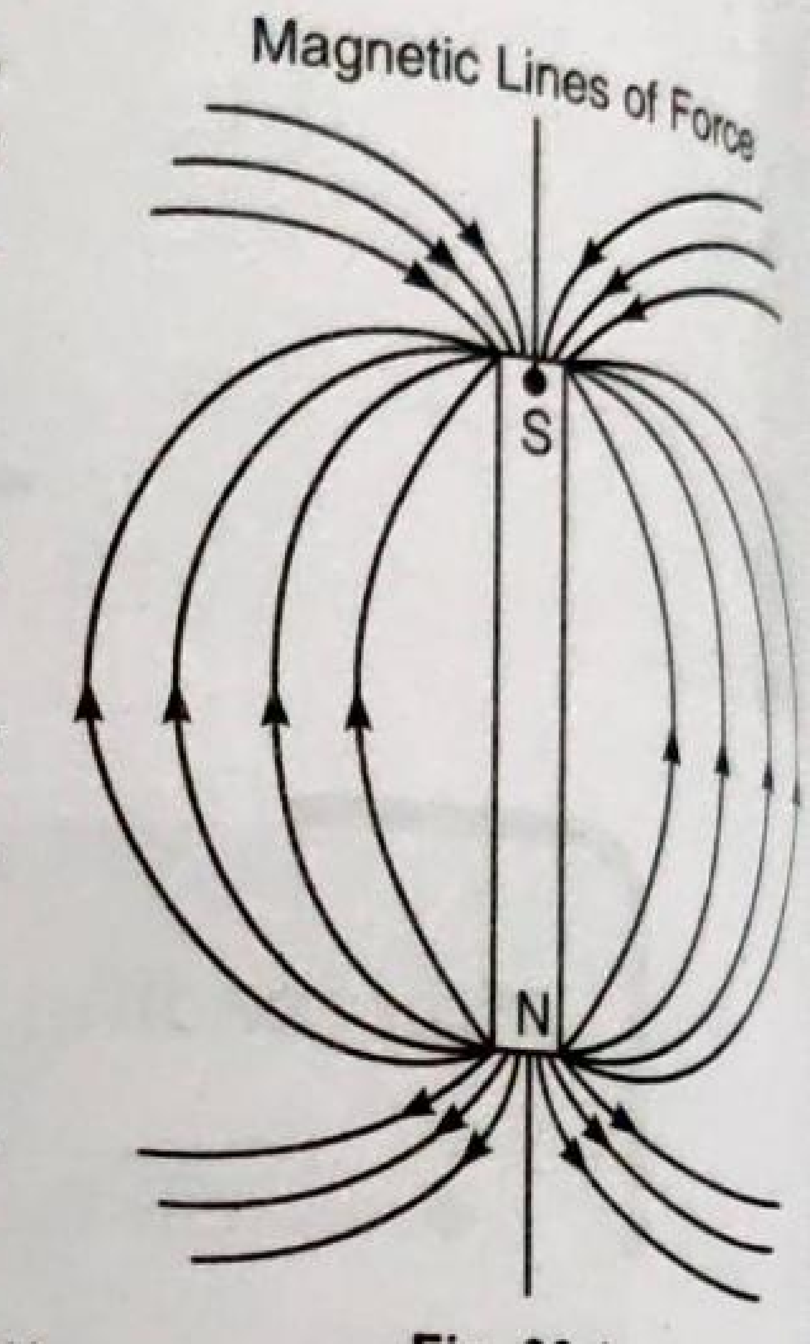


Fig. 30.1

$$B = \mu_0 H \qquad \text{... (1)}$$

Here, μ_0 is the *permeability of free space* (vacuum).

The premeability of free space has a value of $4\pi \times 10^{-7}\ Hm^{-1}$.

- If a magnetic field of intensity H is applied in a solid medium, the magnetic induction (B) in the solid is given by

$$B = \mu H \qquad \text{... (2)}$$

Here, μ is the *permeability* of the solid material through which the magnetic lines of force pass.

$$\mu = \frac{B}{H} \qquad \text{... (3)}$$

Hence the magnetic permeability (μ) of any material is the ratio of the magnetic induction (B) in the sample to the applied magnetic field intensity (H).

The ratio of μ/μ_0 is called the relative premeability (μ_r) of the solid.

$$\mu_r = \frac{\mu}{\mu_0} \qquad \text{... (4)}$$

(*iii*) **Intensity of Magnetization (*M*).** *Intensity of magnetisation (M) of a material is defined as the magnetic moment per unit volume.*

- Its unit is Am^{-1}.

$$M = \frac{\mu_m}{V}$$

μ_m → magnetic moment of the substance

V → volume of the specimen.

(iv) Magnetic susceptibility (χ)

Definition. *Magnetic susceptibility (χ) of a material is the ratio of the intensity of magnetisation (M) produced in the sample to the magnetic field intensity (H) which produces the magnetisation.*

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

- It has no units.
- The sign and magnitude of the magnetic susceptibility are used to determine the nature of the magnetic materials.
- Relation between μ_r and χ is

$$\mu_r = 1 + \chi$$

DIAMAGNETISM

- The individual atoms of a diamagnetic material do not possess a permanent magnetic moment (Fig. 30.2).

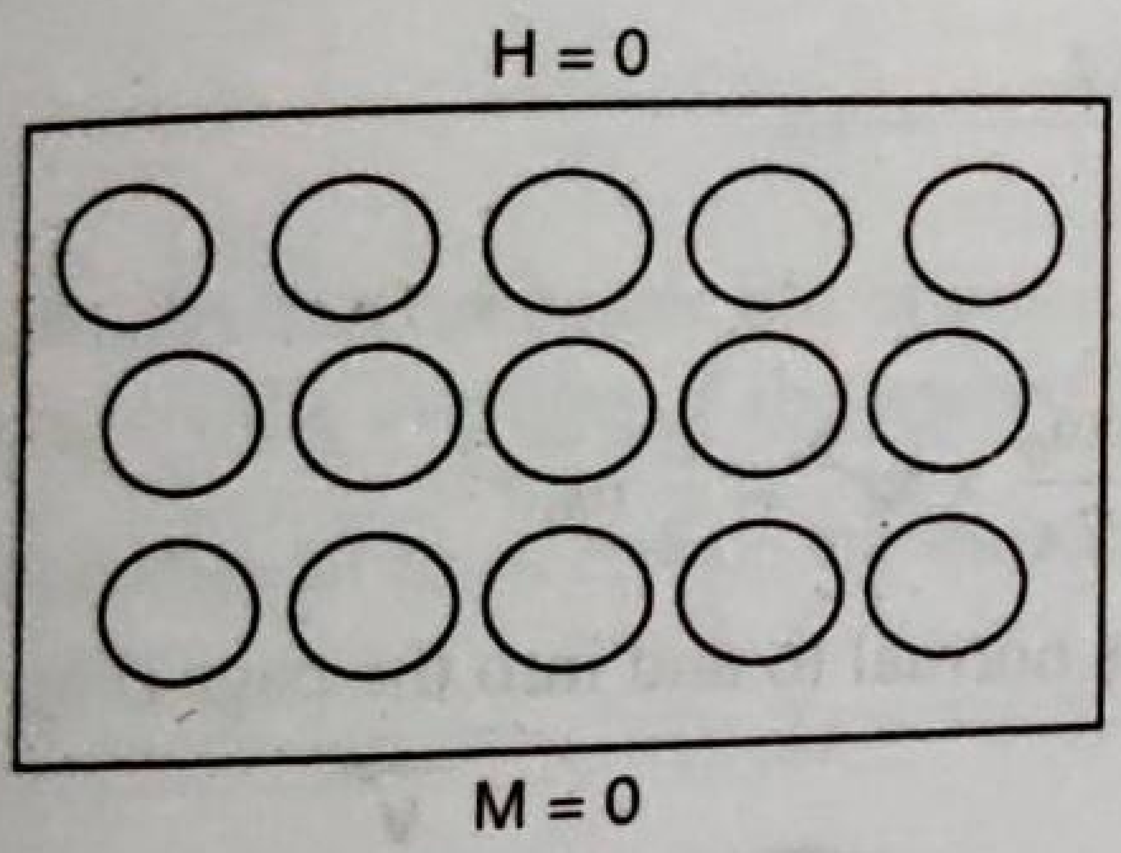


Fig. 30.2

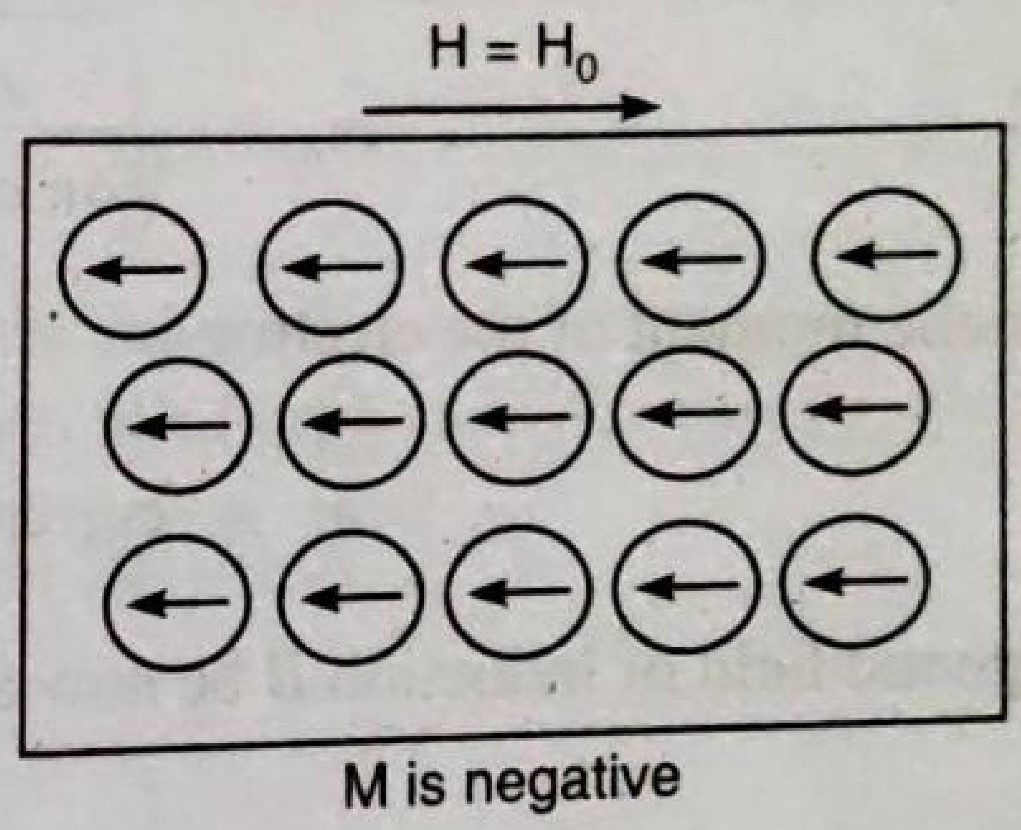


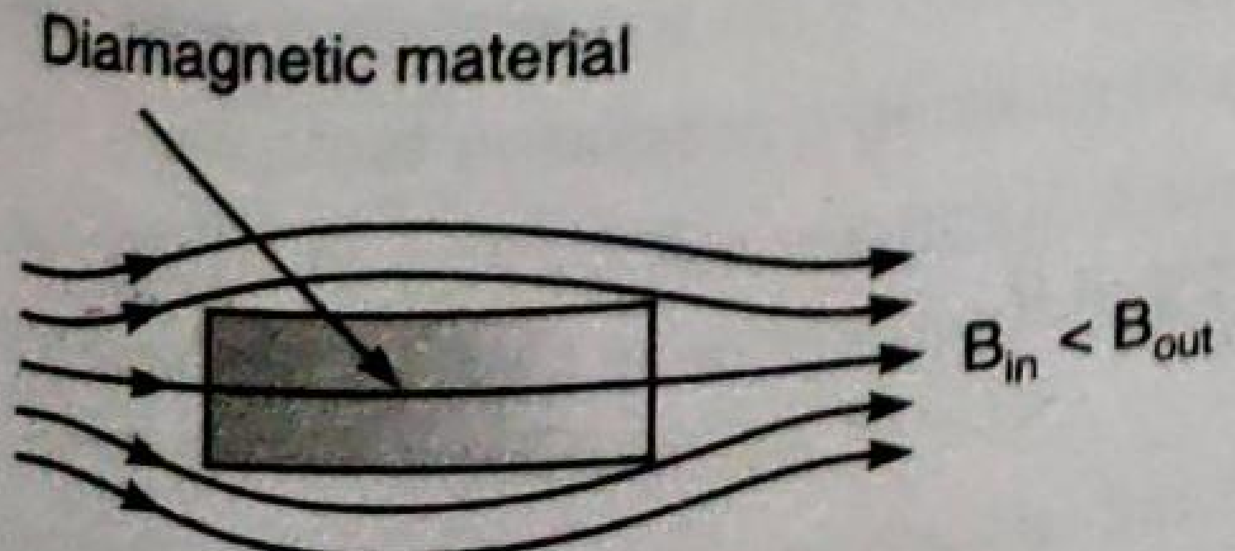
Fig. 30.3

- When an external magnetic field H_0 is applied, the atoms acquire a small induced magnetic moment in a direction opposite to the direction of applied field (Fig. 30.3). The strength of the induced magnetic moment is directly proportional to the applied field H_0. The induced dipoles and magnetization vanish as soon as the applied magnetic field is removed.
- Diamagnetism is a property of all atoms because of the influence of an applied magnetic field on the motion of electrons in their oribits.

Properties of diamagnetic materials

(1) Permanent dipoles are absent. There is no permanent dipole moment.

- Antimony, bismuth, mercury, gold and copper are some examples of diamagnetic substances.



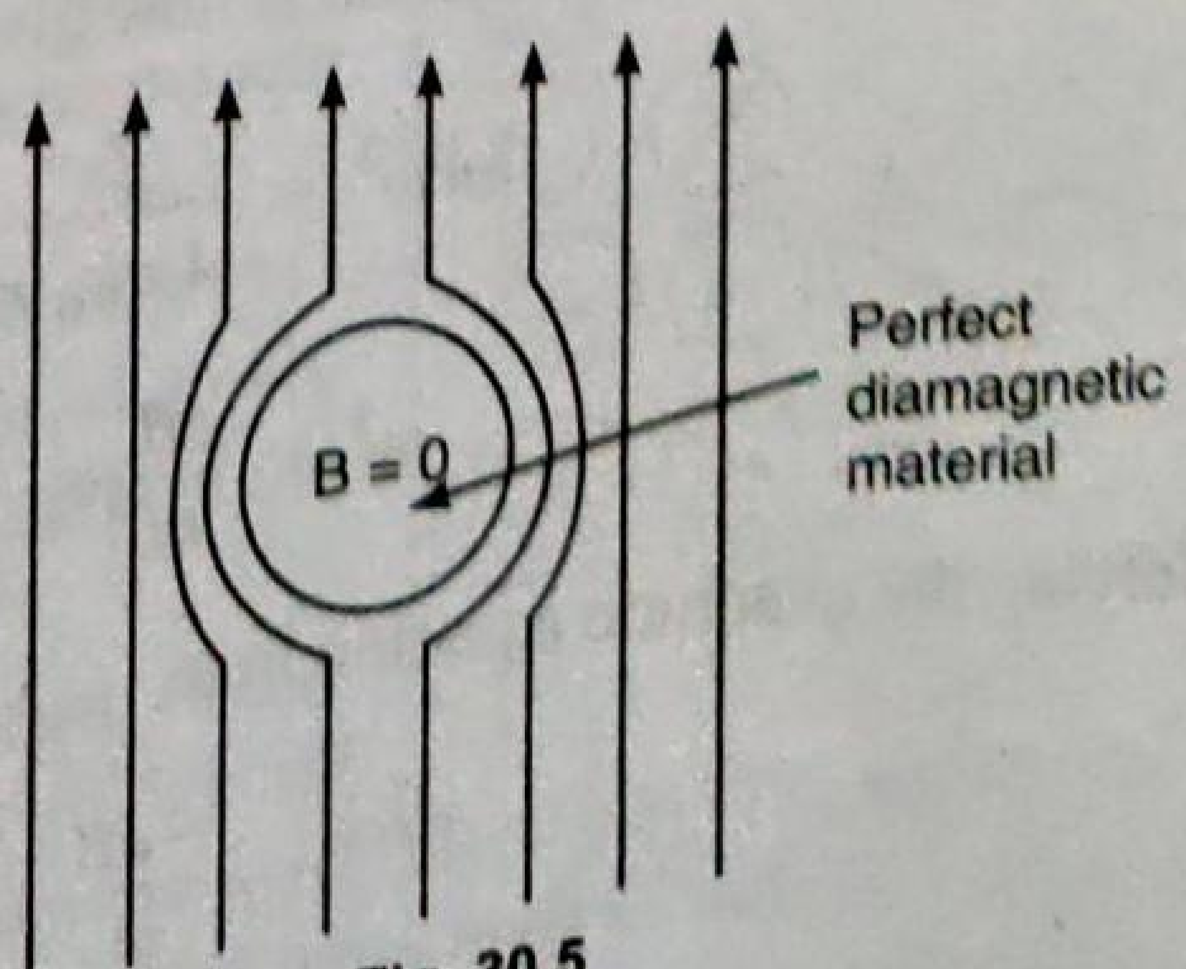


Fig. 30.5

(2) Figure 30.4 shows a bar of diamagnetic material placed in an external *magnetic* field. The magnetic lines of force are repelled or expelled. The field inside the material is reduced.

Figure 30.5 shows the behaviour of a *perfect diamagnetic material* in the presence of the magnetic field.

- *Diamagnetic materials repel the magnetic lines of force.*
- The magnetic flux density B is less inside than outside.

(3) The magnetic susceptibility is negative ($\chi < 0$), i.e., magnetisation opposes the applied field. Magnetic susceptibility is independent of temperature and applied magnetic field strength.

(4) Relative permeability is slightly less than unity ($\mu_r < 1$).

30.2 LANGEVIN'S THEORY OF DIAMAGNETISM

Consider an electron (mass = m, charge = e) rotating about the nucleus (charge = Ze) in a circular orbit of radius r. Let ω_o be the angular velocity of the electron. Then

$$F_o = m\omega_0^2 r = Ze^2/(4\pi \in_0 r^2)$$

or

$$\omega_0 = \sqrt{\frac{Ze^2}{4\pi \in_0 mr^3}} \qquad \text{...(1)}$$

The magnetic moment of the electron is

$$\vec{m} = \text{current} \times \text{area} = \frac{e\omega_0}{2\pi} \times \pi r^2 = \frac{e}{2}\,\omega_0\, r^2 \qquad \text{...(2)}$$

Let a magnetic field of induction $\mathbf{B}$ be now applied. $\mathbf{B}$ is normal to and into the page (Fig. 30.6).

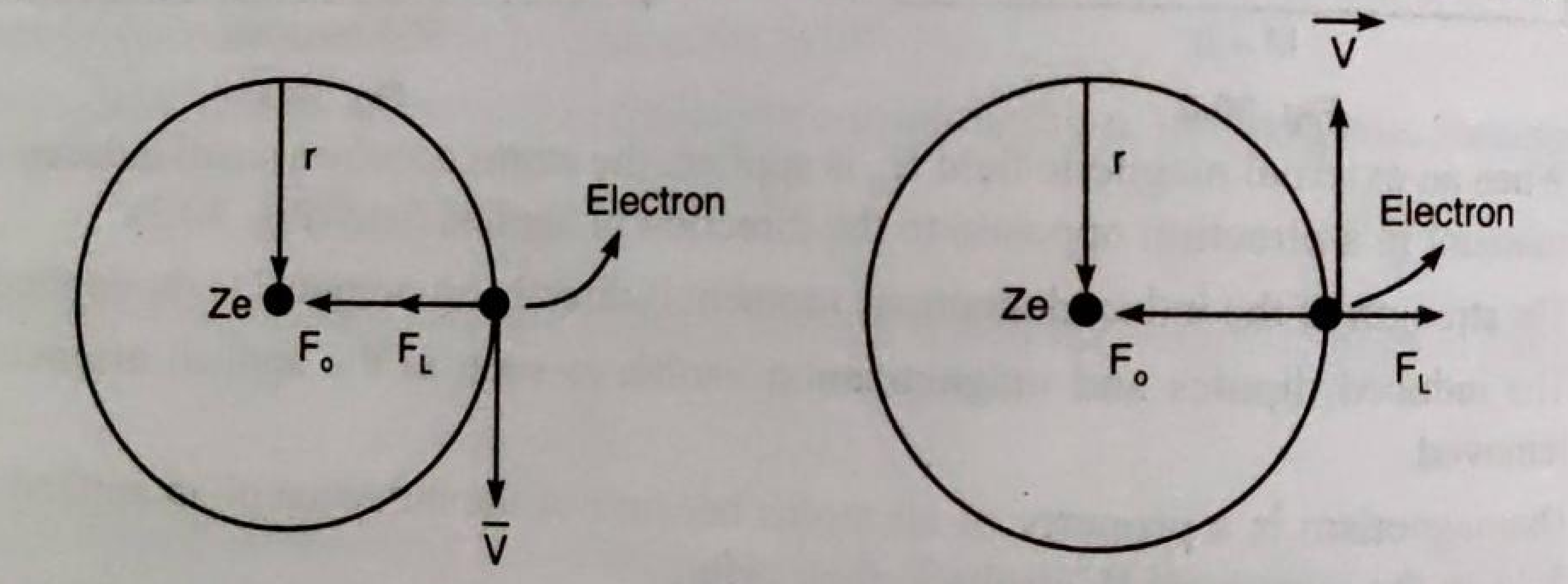


Fig. 30.6

An additional force F_L called Lorentz force, acts on the electron.

$$\mathbf{F}_L = -e\,(\mathbf{v} \times \mathbf{B}) = -eBr\omega$$

The condition of stable motion is now given by

$$mr\omega^2 = \frac{Ze^2}{4\pi \in_0 r^2} - eBr\omega \qquad \text{...(3)}$$

or

$$\omega^2 + \frac{eB}{m}\omega - \frac{Ze^2}{4\pi \in_0 mr^3} = 0$$

Solving the quadratic equation in ω,

$$\omega = \frac{\frac{-eB}{m} \pm \sqrt{\left(\frac{eB}{m}\right)^2 + 4\left(\frac{Ze^2}{4\pi \in_0 mr^3}\right)}}{2} = \pm\sqrt{\omega_0^2 + \left(\frac{eB}{2m}\right)^2} - \frac{eB}{2m}$$

or

$$\omega = \pm\omega_0 - \frac{eB}{2m} \qquad \left(\because \frac{eB}{2m} << \omega_0\right) \qquad ...(4)$$

Thus the angular frequency is now different from ω_0. The result of establishing a field of flux density **B** is to set up a precessional motion of the electronic orbits with angular velocity $-(e/2m)$ **B**. This is called Larmor theorem. Then

$$\left.\begin{array}{l}\text{change in frequency of}\\ \text{revolution of the electron}\end{array}\right\} = \delta n = -\frac{eB}{4\pi m}$$

The corresponding change in the magnetic moment of the electron is

$$\Delta m = \text{current} \times \text{area} = \left\{e \times \left(\frac{-eB}{4\pi m}\right)\right\} \times \pi r^2 = -\frac{Be^2r^2}{4m} \qquad ...(5)$$

On summing over all electrons in the atom, the induced moment per atom becomes

$$\Delta m_{atom} = -\frac{Be^2\Sigma r^2}{4m}$$

Let N be the number of atoms per unit volume. Then the magnetisation M is given by

$$M = -\frac{NBe^2\Sigma r^2}{4m} \qquad ...(6)$$

All the electron orbits are not oriented normal to the magnetic field. Hence r^2 in Eq. (6) should be replaced by the average of the square of the projection of orbit radii for various electrons in a plane perpendicular to B. Hence we should replace r^2 in Eq. (6) by $\frac{2}{3}r^2$.

$$\therefore \qquad M = -\frac{NBe^2\Sigma r^2}{6m}$$

Volume susceptibility of the material

$$\chi = \frac{M}{H} = -\frac{NBe^2\Sigma r^2}{6mH} = -\frac{\mu_0 Ne^2\Sigma r^2}{6m} \qquad (\because B = \mu_0 H)$$

$$\therefore \qquad \chi = -\frac{\mu_0 Ne^2\Sigma r^2}{6m} = -\frac{\mu_0 e^2}{6m} NZ <r^2> \qquad ...(7)$$

Eq. (7) shows that χ is independent of the field strength and temperature. This is in accord with Curie's experimental results.

PARAMAGNETISM

(*i*) **In the absence of external magnetic field.** The individual atoms of paramagnetic material possess a permanent magnetic dipole moment of their own (Fig. 30.7).

- Each atom possesses a permanent magnetic moment.
- When $H = 0$, all the magnetic moments are randomly oriented because of the ceaseless random thermal motion of the atom. So the net magnetization $M = 0$.

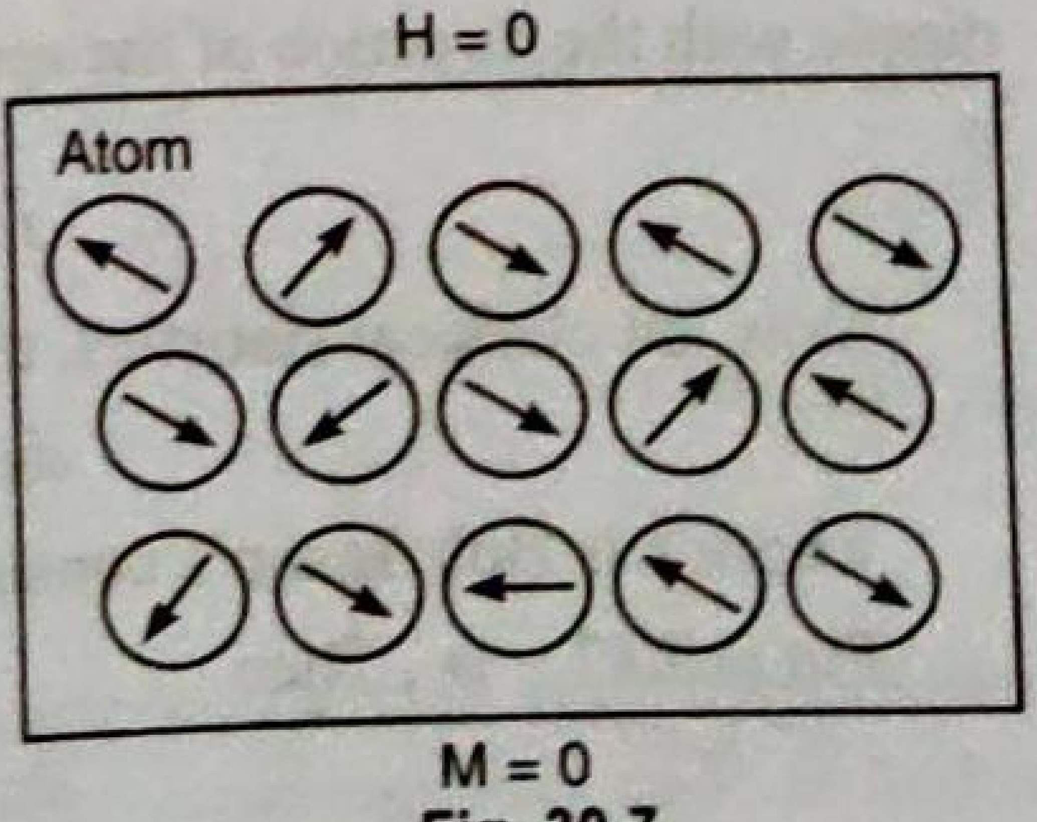


Fig. 30.7

(*ii*) **When an external magnetic field is applied.** When an external magnetic field H_0 is applied, the magnetic dipoles tend to align themselves in the direction of the magnetic field (Fig. 30.8). The individual atomic dipole moments point in the same direction. The material becomes magnetized. This effect is called *paramagnetism.*

- Magnetisation M and magnetic field H are in the same direction. Since $\chi = M/H$, the susceptibility χ is positive.
- **Examples of paramagnetic materials:** Platinum, aluminium, ferric oxide, ferrous sulphate, nickel sulphate, etc.

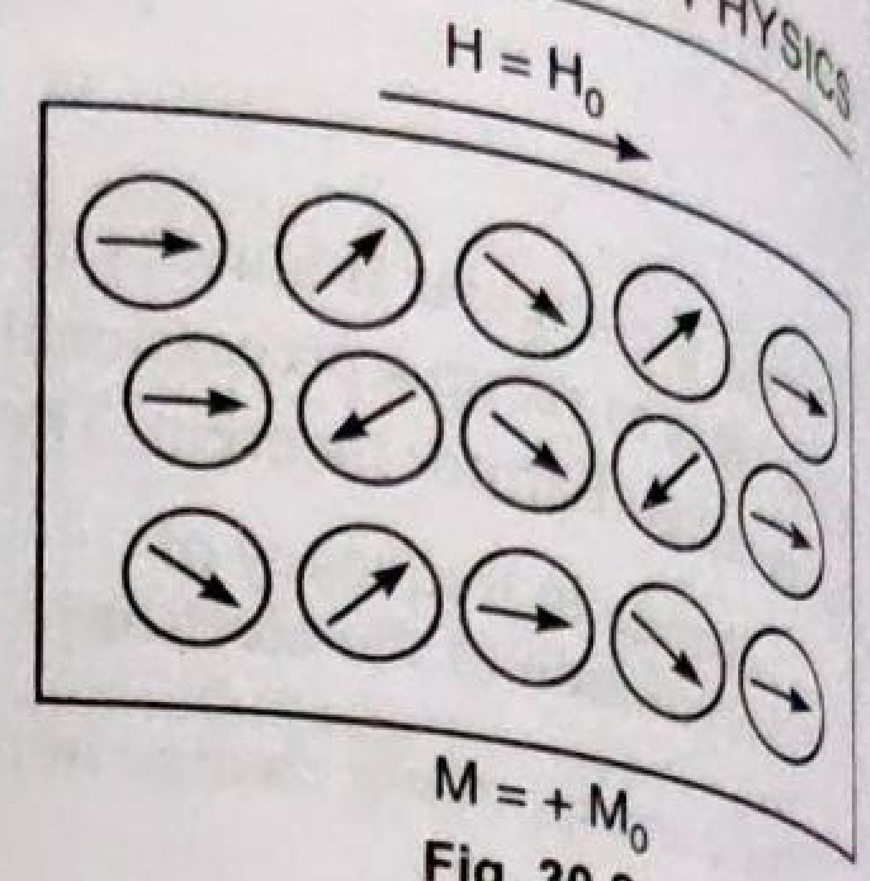


Fig. 30.8

30.3 PROPERTIES OF PARAMAGNETIC MATERIALS

(1) Paramagnetic materials possess permanent magnetic dipoles.

(2) In the absence of an external applied field, the dipoles are randomly oriented. Hence the net magnetization in any given direction is zero.

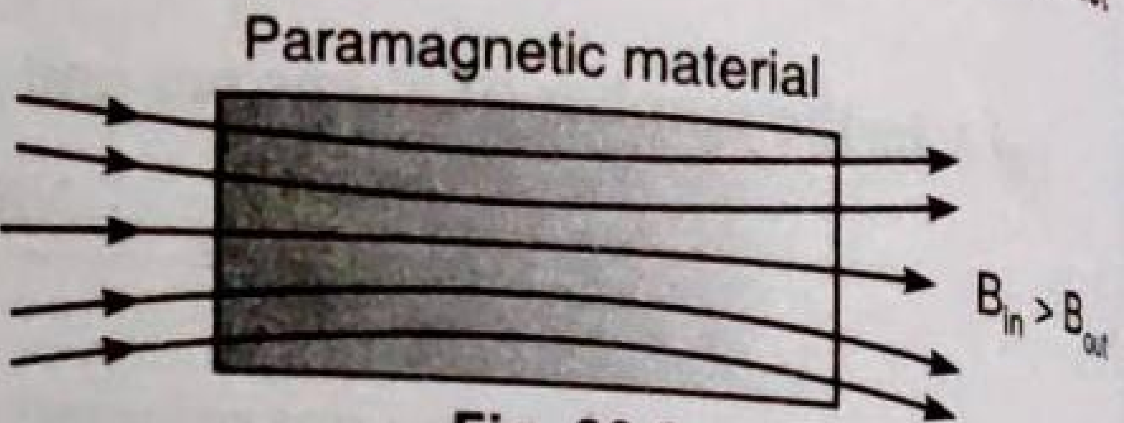


Fig. 30.9

(3) When placed inside a magnetic field, it attracts the magnetic lines of force (Fig. 30.9). The field lines get concentrated inside the material, and the field inside is enhanced. This enhancement is slight, being one part in 10^5.

(4) Paramagnetic susceptibility is positive and depends on temperature.

- $\chi = \dfrac{C}{T}$ is Curie's law.
- $\chi = \dfrac{C}{T - \theta}$ is called *Curie-Weiss law.*

Here, C is *Curie constant* and θ is a constant called *paramagnetic Curie temperature.*

(5) The value of the paramagnetic susceptibility is independent of the applied magnetic field strength.

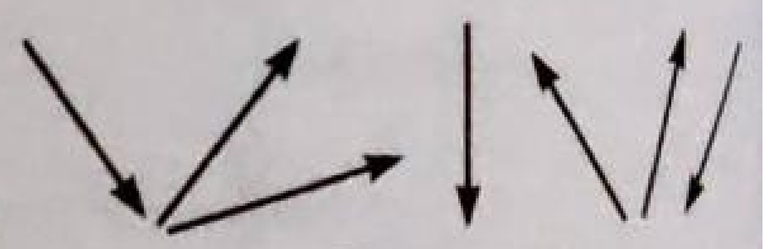


Fig. 30.10

(6) Spin allignment is random (Fig. 30.10).

30.4 LANGEVIN'S THEORY OF PARAMAGNETISM

He assumes that each atom has a permanent magnetic moment m. The only force acting on the atom is that due to the external field $\boldsymbol{B}$. Let θ be the angle of inclination of the axis of the atomic dipole with the direction of the applied field $\boldsymbol{B}$. Then magnetic potential energy of the atomic dipole is

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

Now, on classical statistics, the number of atoms making an angle between θ and $\theta + d\theta$ is

$$dn = Ce^{mB\cos\theta/kT}\sin\theta\, d\theta$$

where k is Boltzmann's constant and T is the absolute temperature.

Put $mB/kT = \alpha$. Then

$$dn = Ce^{\alpha\cos\theta}\sin\theta\, d\theta \quad \text{...(1)}$$

Hence the total number of atomic magnets in unit volume of the paramagnetic material

$$n = \int_0^{\pi} dn = \int_0^{\pi} Ce^{\alpha\cos\theta}\sin\theta\, d\theta \quad \text{...(2)}$$

Put $\cos\theta = x$. Then $-\sin\theta\, d\theta = dx$.

$$n = \int_{+1}^{-1} -Ce^{\alpha x}\, dx = C\int_{-1}^{+1} e^{\alpha x}\, dx$$

$$\therefore \quad C = \frac{n\alpha}{e^{\alpha} - e^{-\alpha}} \qquad \text{...(3)}$$

The component of each dipole moment parallel to B in $m\cos\theta$. The total magnetic moment of all the n atoms contained in unit volume of the gas is the magnetisation M. It is given by

$$M = \int_0^{\pi} m\cos\theta\, dn = \int_0^{\pi} m\cos\theta\, Ce^{\alpha\cos\theta}\sin\theta\, d\theta \qquad \text{...(4)}$$

Put $\cos\theta = x$. Then, $-\sin\theta\, d\theta = dx$. Therefore, we get

$$M = \int_{+1}^{-1} -mxCe^{\alpha x}\, dx = Cm\int_{-1}^{+1} xe^{\alpha x}\, dx$$

Evaluating this integral and substituting the value of C from (3), we get

$$M = mn\left[\frac{e^{\alpha} + e^{-\alpha}}{e^{\alpha} - e^{-\alpha}} - \frac{1}{\alpha}\right]$$

$$= mn\left[\coth\alpha - \frac{1}{\alpha}\right]$$

$$= mn\, L(\alpha) \qquad \text{...(5)}$$

where $L(\alpha) = \left[\coth\alpha - \frac{1}{\alpha}\right]$ is called the *Langevin function.*

The variation of M with α is shown in Fig. 30.11.

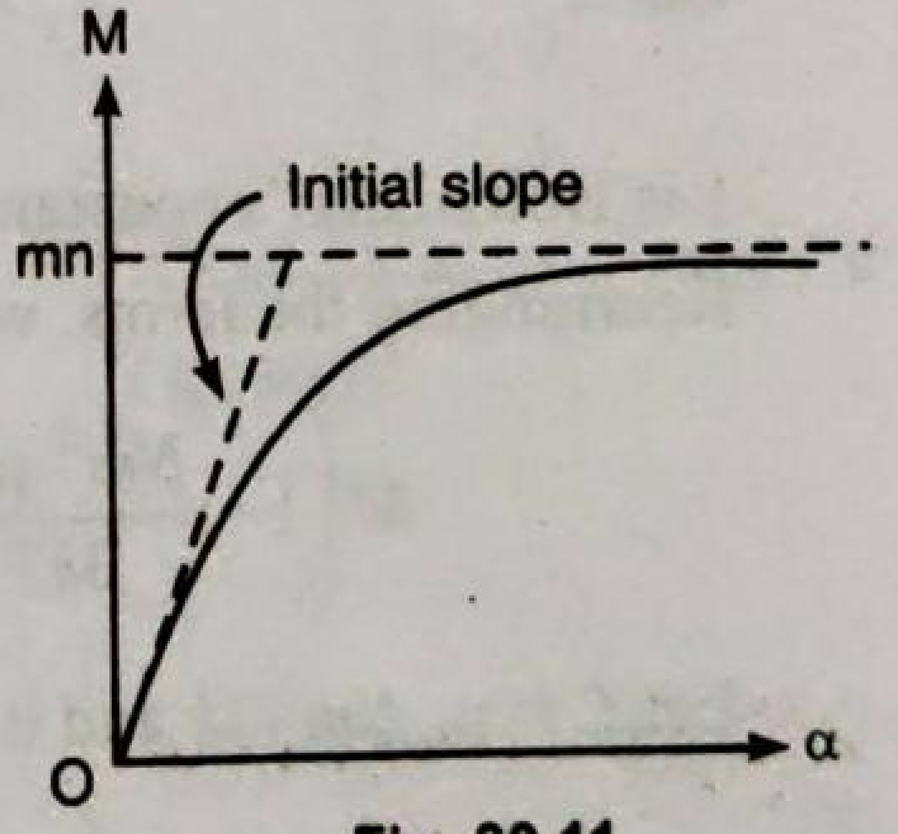


Fig. 30.11

Case (*i*): At low temperatures or large applied field,

$L(\alpha) \to 1$.

Hence, magnetisation M in this case will be

$$M = mn \qquad \text{...(6)}$$

So saturation is reached when all the atomic dipoles are parallel to B.

Case (*ii*) : Under normal conditions α is very small. Then,

$$L(\alpha) = \coth\alpha - \frac{1}{\alpha} \approx \frac{\alpha}{3} \qquad \text{...(7)}$$

$$\therefore \quad M = mn\frac{\alpha}{3} = \frac{nm^2B}{3kT} = \frac{nm^2\mu_0 H}{3kT} \qquad \text{...(8)}$$

$$\chi = \frac{M}{H} = \frac{\mu_0 nm^2}{3kT} = \frac{C}{T} \qquad \text{...(9)}$$

where $C = \mu_0 nm^2/3k$ is called the Curie constant.

Failure of Langevin Theory. (*i*) Langevin's theory was unable to explain a more complicated dependence of susceptibility upon temperature exhibited by several paramagnetics such as highly compressed and cooled gases, very concentrated solutions of salts, etc.

(*ii*) Langevin's theory could not account for the intimate relation between para-and ferro-magnetism.

Weiss Modification: Langevin's theory applies strictly only to gases, where the molecules are sufficiently far apart for their mutual interactions to be negligible. In liquids and solids such interactions may be large, and many substances obey the modified *Curie-Weiss law*

$$\chi = C/(T-\theta) \qquad ...(10)$$

θ is called the *Curie temperature* and is characteristic of the substance. Eq. (10) holds only at temperatures where $T > |\theta|$. Eq. (10) is of the same form as Eq. (9), except that the origin of temperature is shifted from 0 to θ.

30.5 WEISS THEORY OF PARAMAGNETISM

Weiss introduced the concept of *internal molecular field* in order to explain the complicated type of dependence of susceptibility. In a real gas, the molecules are mutually influenced by their magnetic moments and consequently, there should exist within the gas a molecular field. This field produced at any point by all the neighbouring molecules, is proportional to and acting in the same sense as the intensity of magnetization (M). Let this internal molecular field be H_i. Now

$$H_i = \lambda M \qquad ...(1)$$

Here, λ is molecular field coefficient.

Therefore, the net effective field should be

$$H_e = (H + H_i) \qquad ...(2)$$

Here, H is external applied field.

Following the Langevin theory along with this effective field,

$$M = \frac{Nm^2\mu_0 H_e}{3kT} = \frac{Nm^2\ \mu_0\ (H + \lambda\ M)}{3kT} \quad \text{[Refer Eq. (8) in Langevin theory]}$$

Here, N = number of dipoles/unit volume,

m = magnetic moment of each atomic dipole,

k is Boltzmann's constant and T is the absolute temperature.

Rearranging the terms, we get

$$M\left(1 - \frac{Nm^2\ \mu_0\lambda}{3kT}\right) = \frac{Nm^2\ \mu_0 H}{3kT}$$

Let $C = \mu_0\ Nm^2/3k$ and $\theta = C\lambda$. Then we get

$$M\left(1 - \frac{\theta}{T}\right) = \frac{CH}{T}$$

$$\therefore \qquad \chi = \frac{M}{H} = \frac{C}{T\left(1 - \frac{\theta}{T}\right)} = \frac{C}{T - \theta} \qquad ...(3)$$

Here C is called the Curie constant.

θ is called *paramagnetic Curie point* or the *Curie temperature.*

Eq. (3) is called *Curie-Weiss law.*

Below Curie temperature ($T < \theta$), susceptibility becomes negative; *i.e.*, paramagnetics would become diamagnetics. However, for most of the paramagnetic substances, Curie temperature is quite low so that a situation for which $T < \theta$ is rare.

The spin entropy

$$\sigma_S = k_B \ln (2S+1)^N = Nk_B \ln (2S+1) \qquad ...(1)$$

This spin entropy is reduced by a magnetic field if the lower levels gain in population when the field separates the $2S + 1$ states in energy.

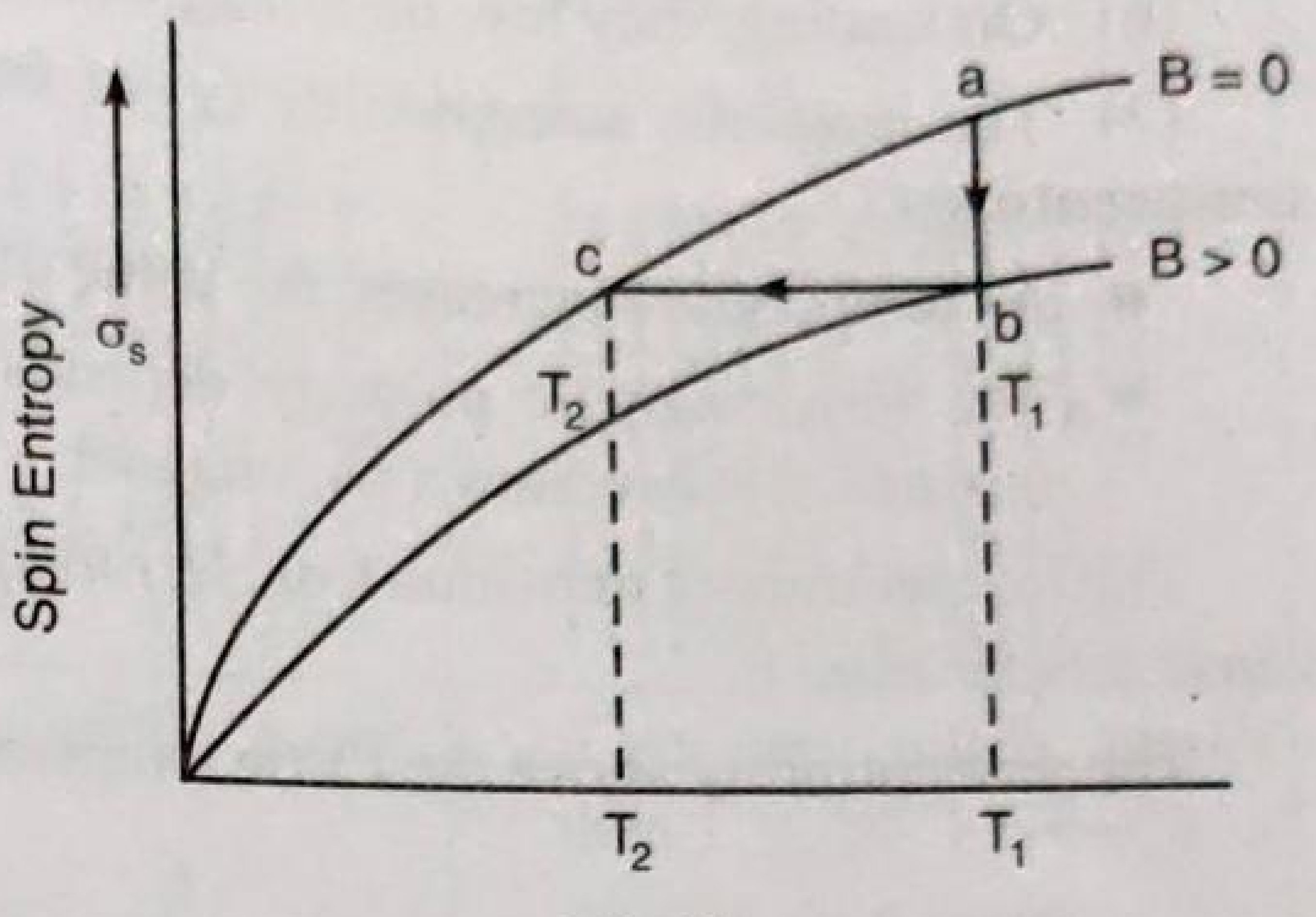


Fig. 30.18

Steps in the cooling process. Fig 30.18 shows the steps carried out in the cooling process.

(*i*) Magnetic field is applied at temperature T_1 with the specimen in good thermal contact with the surroundings, giving the isothermal path *ab*. At temperature T_1, the thermal contact is provided by helium gas and by removing the gas with a pump the thermal contact is broken.

(*ii*) The specimen is then insulated ($\Delta\sigma = 0$) and the magnetic field is removed. Thus the specimen follows the constant entropy path *bc*, ending up at temperature T_2.

FERROMAGNETISM

- Ferromagnetism is the existence of a *spontaneous magnetization,* even in zero applied field. Ferromagnetic materials have a small amount of magnetisation even in the absence of an external magnetic field. This indicates that there is a strong internal field within the material which makes the atomic magnetic moments align with each other.
- When placed in a magnetic field, ferromagnetic materials become strongly magnetized in the direction of the applied field. The direction of magnetization is the same as that of the external field.

Origin of ferromangetism. Ferromagnetism arises due to permanent magnetic moments in the atoms or molecules of the material. When an external field is applied, the magnetic moments line up in the same direction as that of the applied field.

Examples of ferromagnetic materials. Iron (Fe), Cobalt (Co), Nickel (Ni), and Gadolinium (Gd).

30.8 PROPERTIES OF FERROMAGNETIC MATERIALS

(1) All the dipoles are aligned parallel to each other due to the magnetic interaction between any two dipoles. Figure 30.19 shows the dipole alignment.

(2) Ferromagnetic materials have permanent dipole moment.

(3) When placed inside a magnetic field, a ferromagnetic material attracts the magnetic line of forces very strongly (Fig. 30.20).

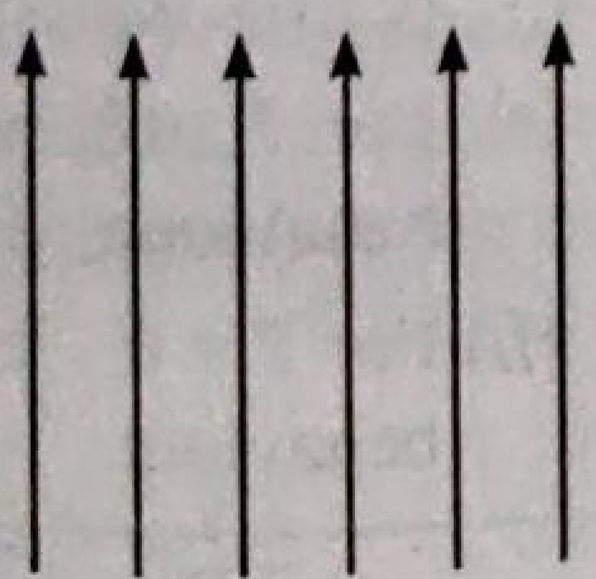


Fig. 30.19

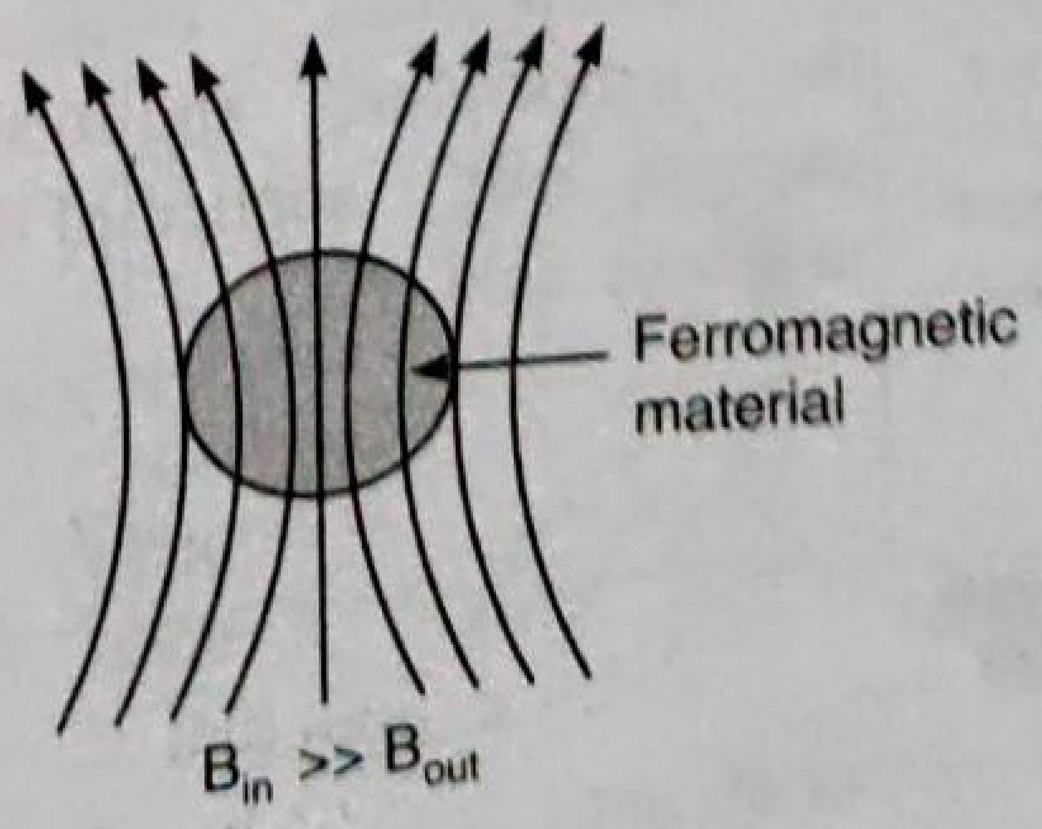


Fig. 30.20

(4) They exhibit magnetisation even in the absence of a magnetic field. This property of ferromagnetic materials is called **spontaneous magnetisation**.

(5) Ferromagnetic materials exhibit the phenomenon of hysteresis.

(6) On heating, they lose their magnetisation slowly.

(7) The magnetic susceptibility (χ) of ferromangetic materials is very high and depends on **temperature** (T).

- As temperature increases, the value of susceptibility decreases.
- The ferromagnetic property depends on temperature. At high enough temperatures, a ferromagnet becomes a paramagnet.

The temperature of transition from ferromagnetism to paramagnetism is called the *paramagnetic Curie temperature* θ.

The susceptibility above the Curie temperature, *i.e.*, in the paramagnetic phase is described by,

$$\chi = \frac{C}{T-\theta} \ (T > \theta).$$

Here, C is the Curie constant.

For $T > \theta$, paramagnetic behaviour.

For $T < \theta$, ferromagnetic behaviour.

Figure 30.21 shows the variation of susceptibility with temperature for ferromagnetic materials.

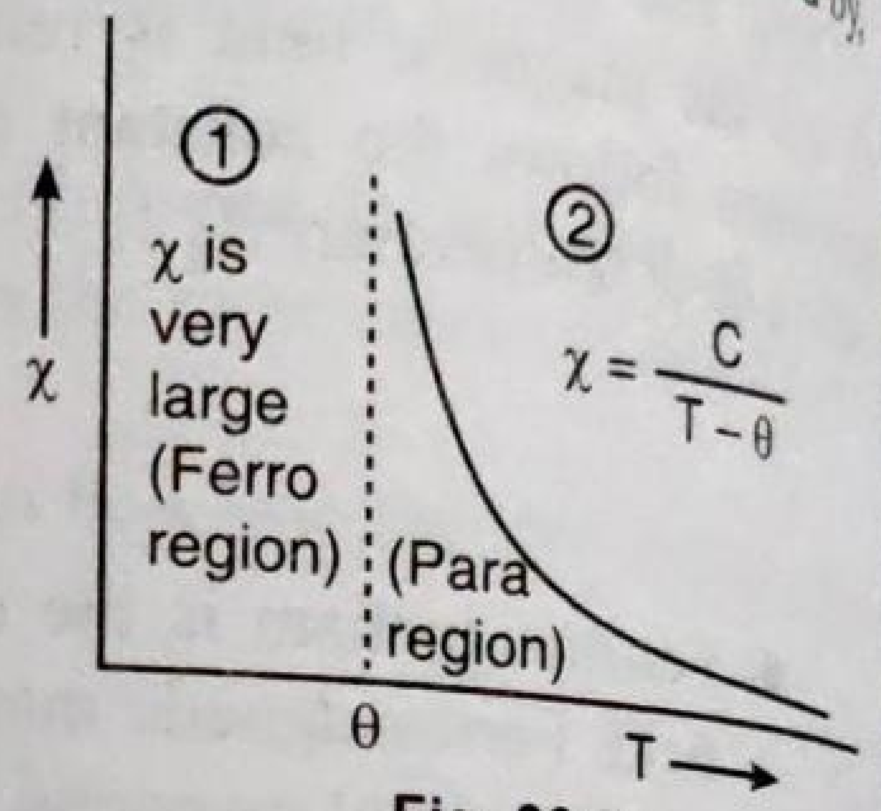
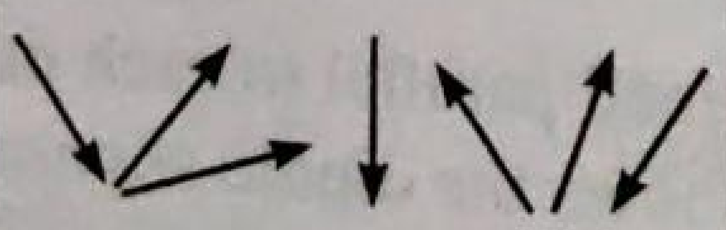
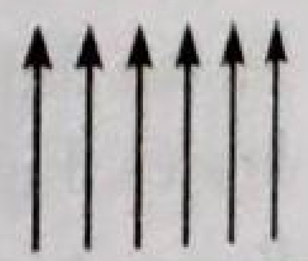
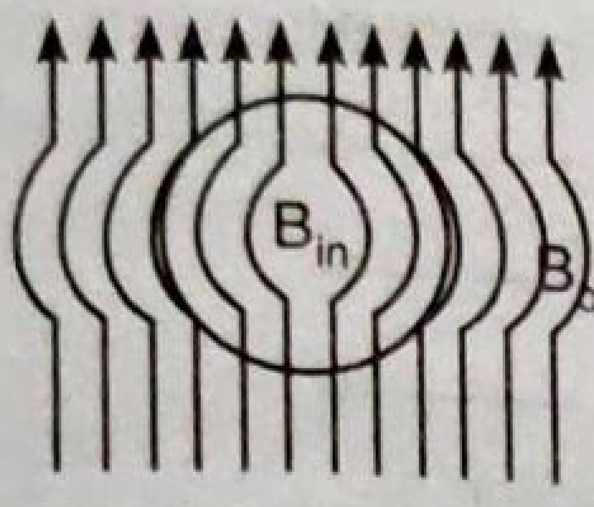
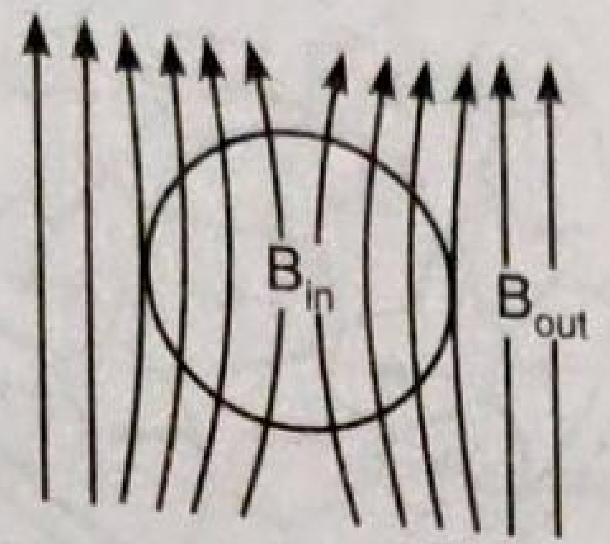
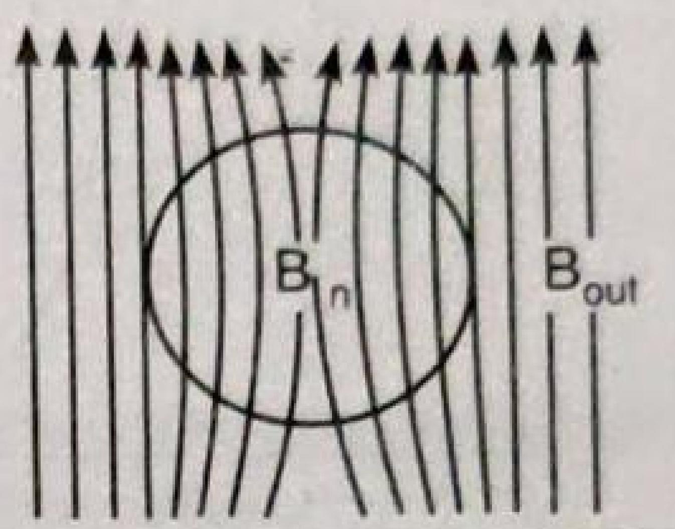


Fig. 30.21

(8) The relative permeability μ_r of ferromagnetic materials is very high. The relative magnetic permeability is > 1000!

Table 30.1. Comparison of dia, para and ferromagnetic materials

		Diamagnetic material	*Paramagnetic material*	*Ferromagnetic material*
1.	Magnetic moment	There is no permanent dipole moment (or) magnetic moment in each atom.	There is permanent dipole moment (or) magnetic moment in each atom.	There is enormous permanent dipole moment (or) magnetic moment in each atom.
2.	Spin alignment	No spin.	All spins are randomly oriented 	Spin alingment is parallel in the same direction. 
3.	Susceptibility and its temperature dependence	Susceptibility is always negative. It is independent of the temperature and strength of applied magnetic field.	It is always positive and small. It is inversely proportional to absolute temperature of the material. $\chi \propto \frac{1}{T}$ or $\chi = \frac{C}{T}$.	It is always positive and very large. $\chi = \frac{C}{T-\theta}$ (Curie-Weiss law) (*i*) For $T > \theta$, paramagnetic behaviour. (*ii*) For $T < \theta$, ferromagnetic behaviour.

4.	Behaviour of material in the presence of magnetic field	When the material is placed in the magnetic field, the magnetic lines of force are repelled away from the material. $B_{out} > B_{in}$.  	The magnetic lines of force are attracted towards the centre of the material. $B_{in} > B_{out}$.  	The magnetic lines of force are highly attracted towards the centre of the material. $B_{in} >> B_{out}$. 
5.	Relative magnetic permeability (μ_r)	μ_r is slightly less than 1.	μ_r is slightly greater than 1.	μ_r is very much greater than 1. $\mu_r >> 1$
6.	Examples	Hydrogen, bismuth, antimony, gold and super conducting materials like Niobium.	Aluminium, platinum, sodium, titanium, zirconium and chromium.	Iron, nickel, cobalt, gadolinium.

30.9 DOMAIN THEORY OF FERROMAGNETISM

What is domain theory of ferromagnetism?

- Weiss proposed the concept of *domains* in order to explain the properties of ferromagnetic materials.

Concept of magnetic domains. The group of atomic dipoles (atoms with permanent magnetic moment) organised into tiny bounded regions in the ferromagnetic materials are called *magnetic domains*. Ferromagnetic material contains a large number of domains.

- **Magnetic domain.** In demagnetized state, a ferromagnetic material is divided into a number of small regions called *domains*. Each domain is spontaneously magnetized.
- The *boundaries between different domains are called domain walls*. The domain walls are also called *Bloch walls*.
- In each individual domain, the magnetic moments of the atoms are aligned in the same direction.

Hence the domain is a region of the ferromagnetic material in which all the magnetic moments are aligned to produce a net magnetic moment in one direction only. Thus it behaves like a magnet with its own magnetic moment and axis.

(*i*) **Magnetic domains in a demagnetized ferromagnetic material.** In a demagnetized ferromagnetic material, the domains are *randomly oriented* (Fig. 30.22). So the magnetization of the material as a whole is zero.

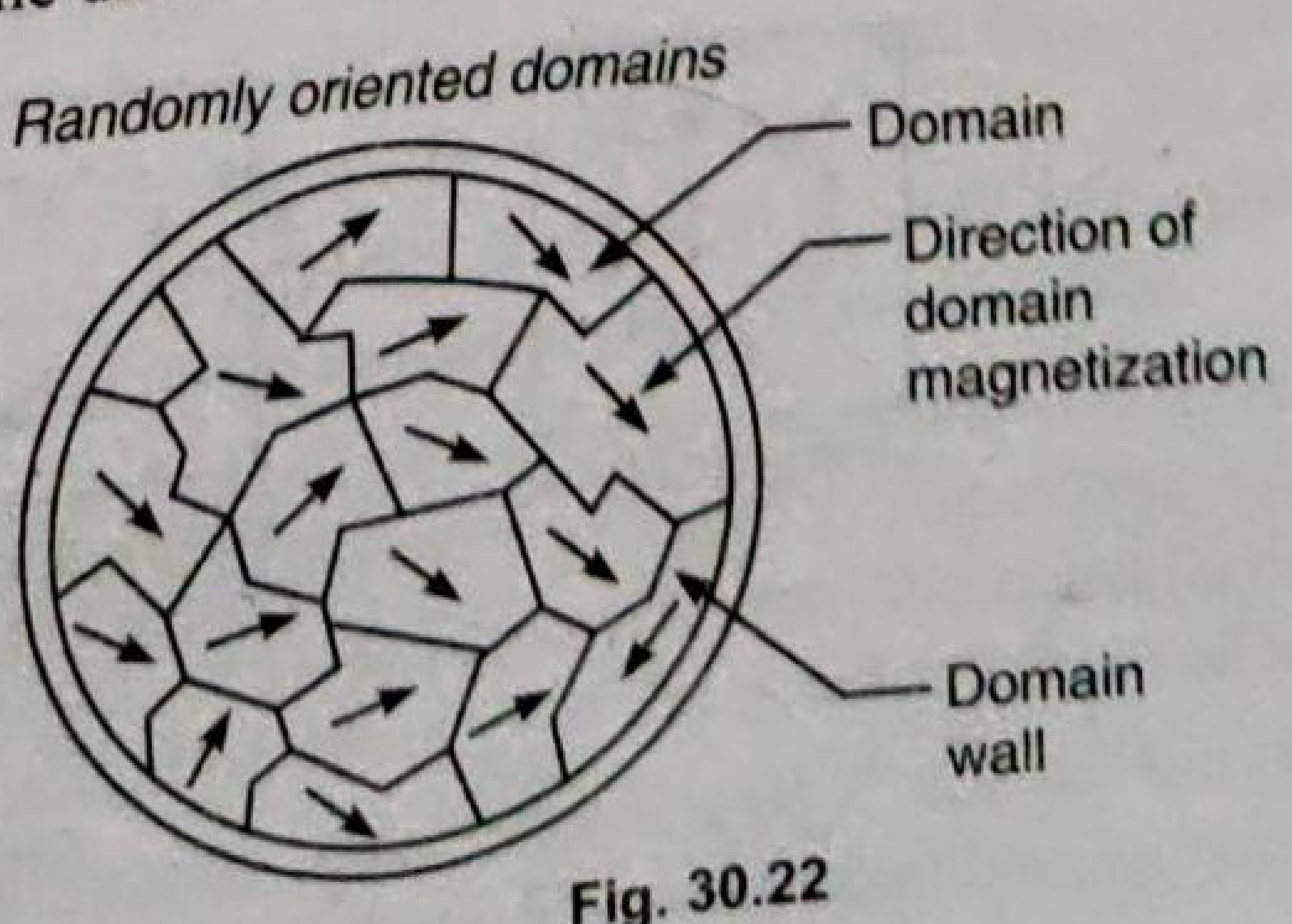


Fig. 30.22

The remanence B_r is the value of B at H = O.

(*i*) When a weak magnetic field is applied, domains where the magnetisation is parallel or at a small angle with the field grow at the expense of those where the magnetisation is antiparallel so that the boundary between domains is displaced. This boundary displacement is reversible and is indicated by the path *OA*.

(*ii*) When the magnetic field becomes stronger, the Bloch wall movement is sharp and is irreversible. The steeper part *AC* of the magnetisation curve is due to larger, irreversible displacements.

(*iii*) Above the knee of the curve (*CS*), magnetization proceeds by rotation of the direction of magnetization of whole domains. Such a process is rather difficult and the increase in magnetisation is relatively slow. At *S*, all the domains are in the field direction and the specimen is said to be saturated.

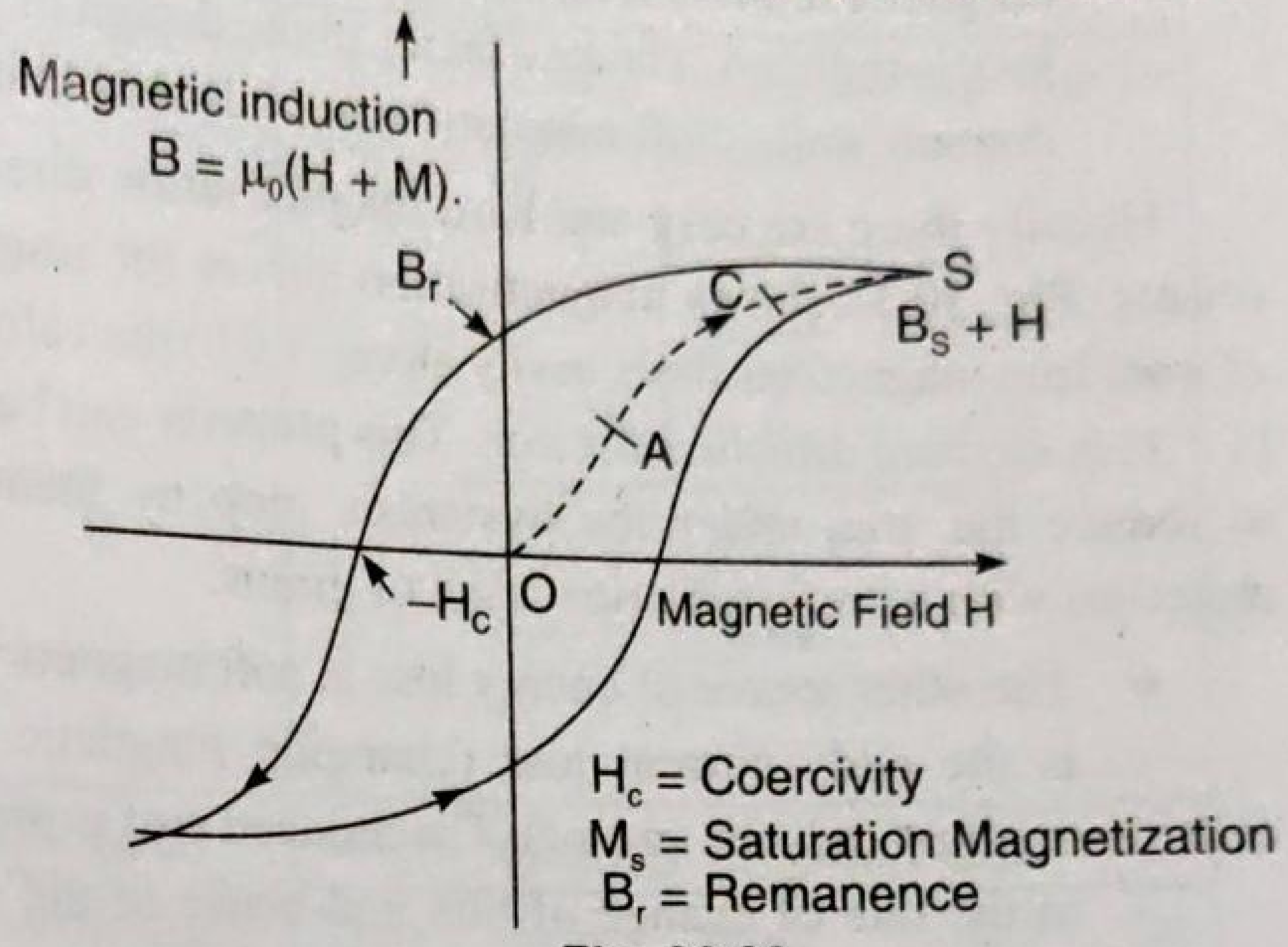


Fig. 30.30

(*iv*) When the applied field is reduced, there is a little change in the domain structure so that the magnetisation remains quite high, until high reverse fields are applied. Further even when the external field is zero, there is a residual magnetisation in the specimen and that can be destroyed by applying a high reverse field.

Thus the reversible and irreversible domain wall movements give rise to hysteresis in the ferromagnetic materials.

30.10 SOFT AND HARD MAGNETIC MATERIALS

The process of magnetisation of a ferromagnetic material consists of moving the domain walls so that favourably oriented domains grow and unfavourably oriented domains shrink.

- If the domain walls are easy to move, the coercive field is low. It is easy to magnetise the material. Such a material is called a *soft magnetic material.*
- If it is difficult to move the domain walls, the coercive field is large and the material is magnetically *hard.*

Fig. 30.31 shows *magnetisation curves for soft and hard magnetic materials.*

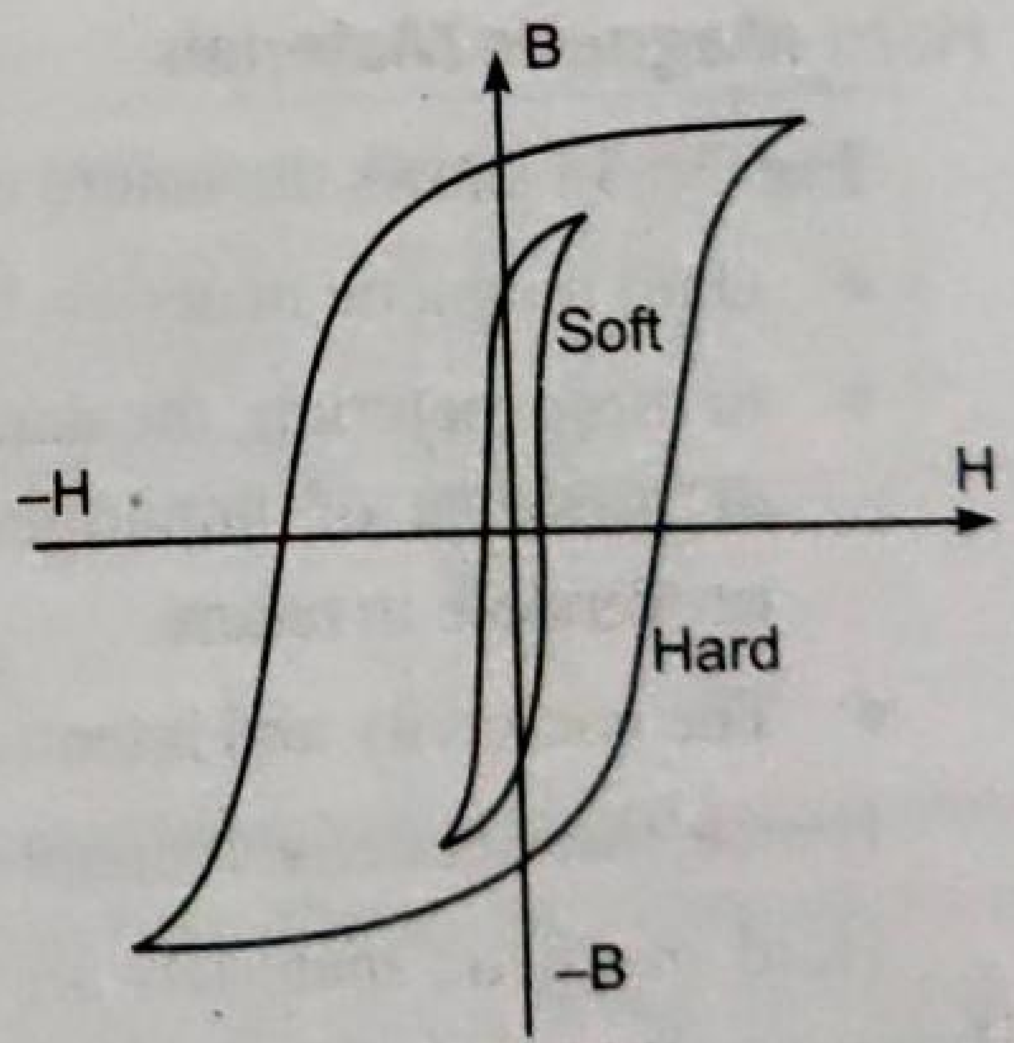
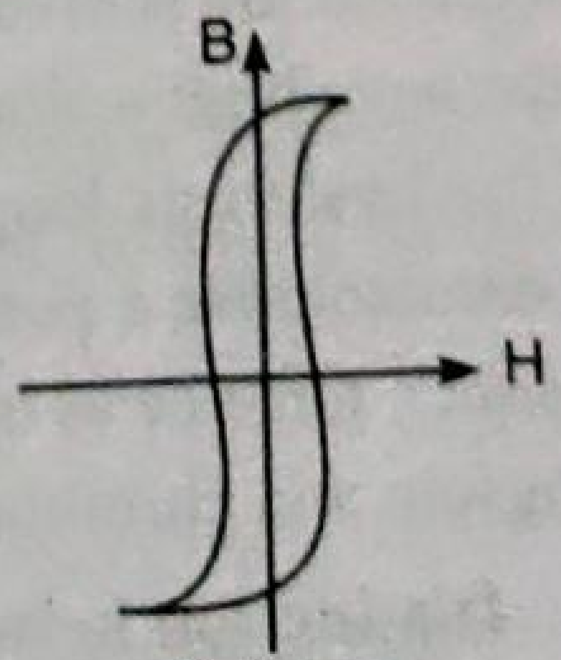


Fig. 30.31

Soft Magnetic Materials

Fig. 30.32 shows the nature of hysteresis loop of soft magnetic material (soft iron).

- Soft magnetic materials have low hysteresis loss due to small hysteresis loop area.
- In these materials, the domain wall movement is relatively easier. Even for small changes in the magnetizing field, magnetization changes by large amounts.
- The coercivity and retentivity are small. Hence these materials can be easily magnetized and demagnetized.



Soft iron
Fig. 30.32

- Soft magnetic materials are used in applications requiring frequent reversals of the directions of magnetisation such as cores of transformers.
- In soft magnetic materials, the hysterisis losses must be kept down to a minimum. When the magnetic induction is large for a small applied field, the loop area is small and the hysteresis loss is reduced. The key factor in the design of a soft magnet is then to have easily moving domain walls. Soft magnetic materials should be free of impurities and inclusions.

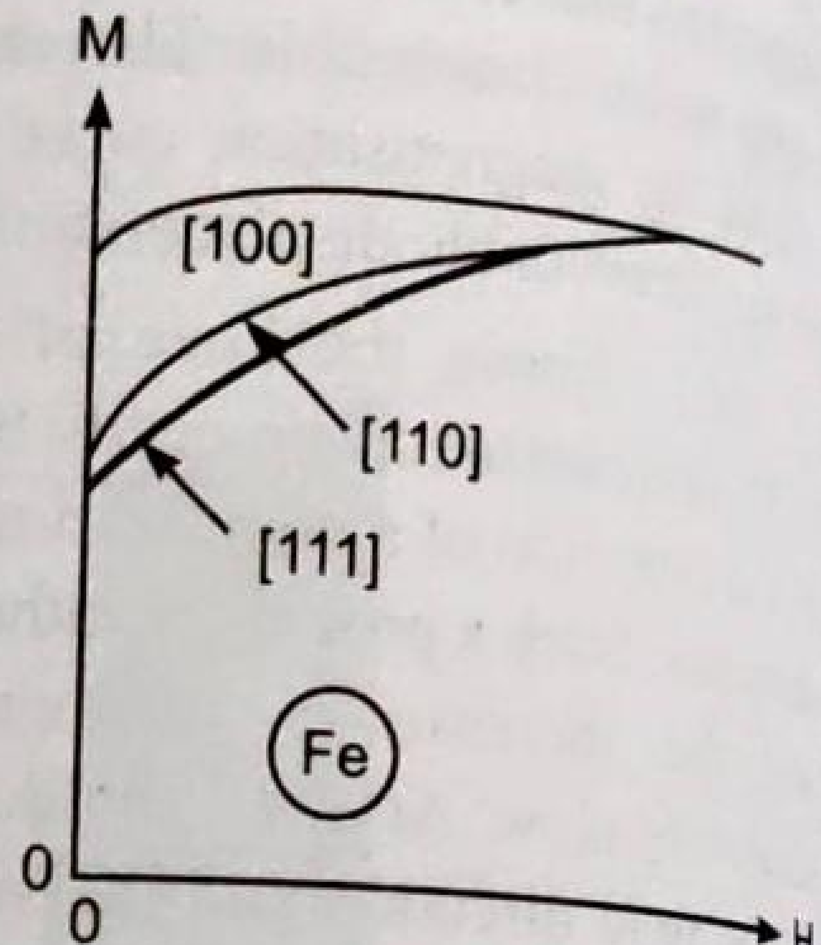


Fig. 30.33

Usually there are easy and hard magnetisation directions in a crystal. Fig. 30.33 shows magnetisation curves for single crystals of iron. Iron magnetises more easily along (1 0 0) than along (1 1 1). (1 1 1) is the hard direction for iron. This property can be exploited to reduce the area under the hysteresis loop by manufacturing materials with a preferred orientation of grains.

- The other source of energy loss in soft magnetic materials is the eddy current loss (changing magnetic flux in a medium induces an emf). The induced emf is proportional to the rate of change of flux and hence to the frequency of the alternating current. The induced emf sets up eddy current. The power loss due to these is equal to V^2/R. Here, V is the induced emf and R is the resistance of the medium. Eddy current losses can be minimised by increasing the resistivity of the medium.

Iron, which used to be the material for transformer cores, is now almost entirely replaced by Fe–Si alloys, which has substantially higher resistivity than iron. Fe–Si alloys are suitable for operation at power frequencies of 50–60 Hz. At microwave frequencies, ferrites (48% $MnO \cdot Fe_2O_3$, 52% $ZnO \cdot Fe_2O_3$; 36% $NiO \cdot Fe_2O_3$, 64% $ZnO \cdot Fe_2O_3$) and garnets ($3Y_2O_3 \cdot 5Fe_2O_3$) are preferred.

Hard Magnetic Materials

Fig. 30.34 shows the nature of hysteresis loop of hard magnetic material (steel).

- Hard magnetic materials have large hysteresis loss due to large hysteresis loop area.
- In these materials, the domain wall movement is difficult because of presence of impurities and crystal imperfections and it is irreversible in nature.
- The coercivity and retentivity are large.

Hence, these materials cannot be easily magnetized and demagnetized.

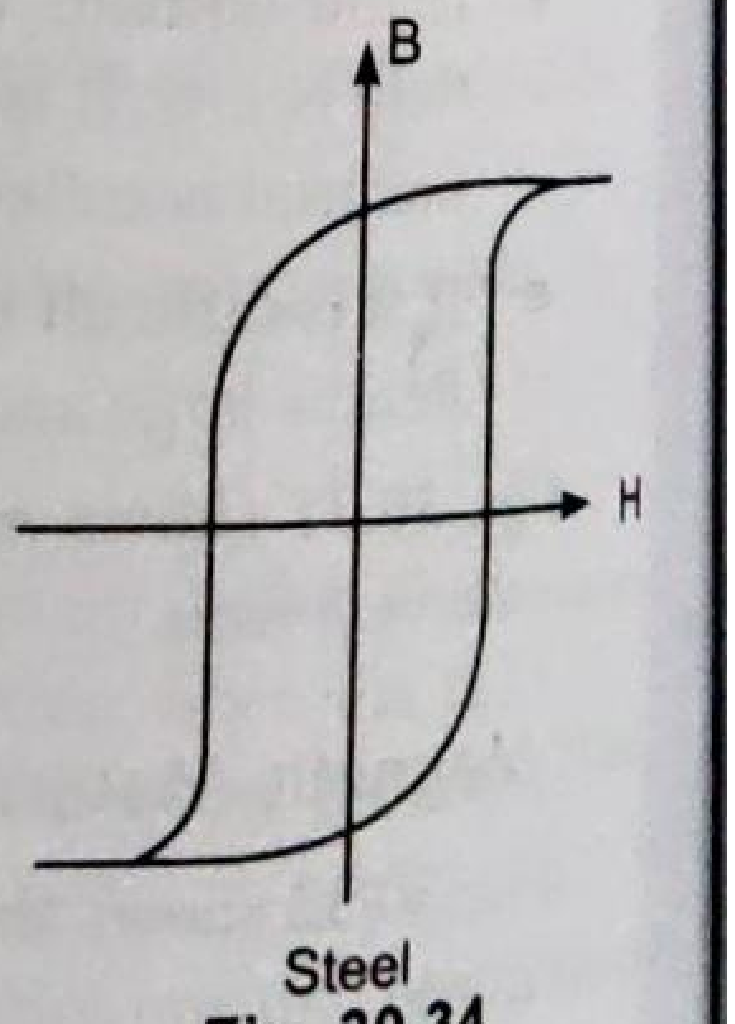


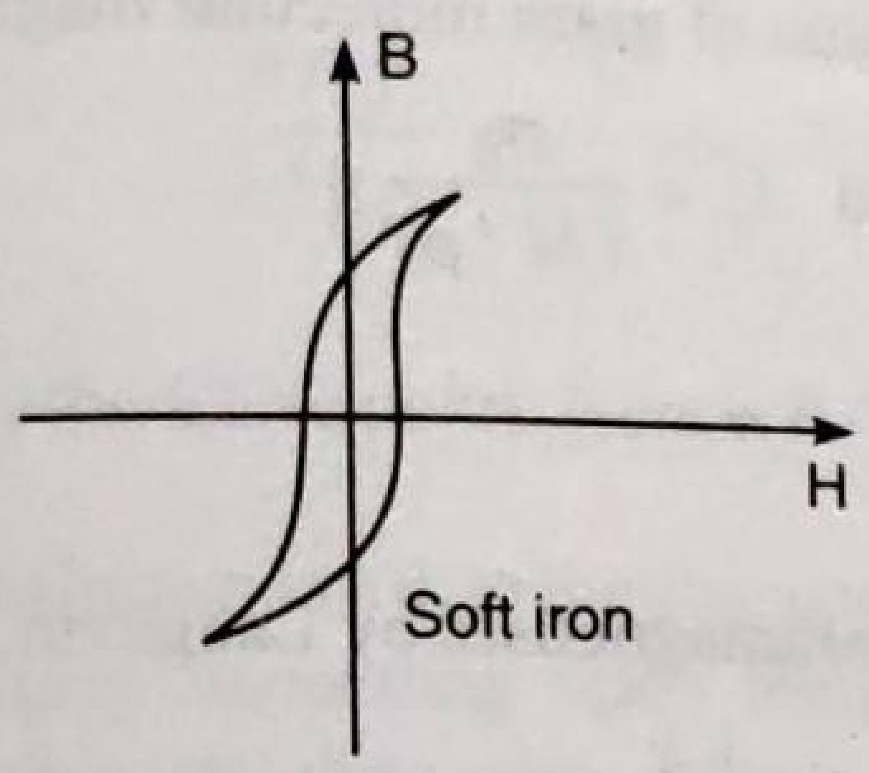
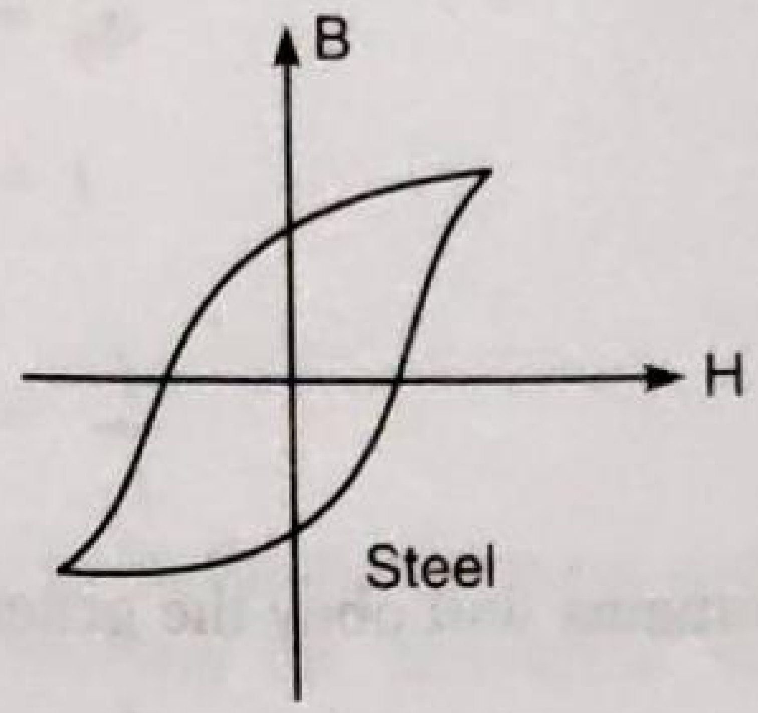
Fig. 30.34

Hard magnetic materials are used to produce permanent magnets. Hysteresis losses are of no significance here as no repeated reversals of magnetisation is involved in a permanent magnet. The permanent magnets must have high residual induction B, and large coercive field H_c. The area of the hysteresis loop between B_r and H_c represents the energy required to demagnetise a permanent magnet. The maximum value of this area ($= B_r H_r$), called the *energy product*, must be as large as possible for permanent magnets. High carbon steels and other low alloy tungsten and chromium steels are used for making permanent magnets.

Distinction between soft and hard magnetic materials.

Table 30.2 gives the "*Differences between Soft and Hard magnetic Materials*".

Table 30.2. Distinction between Soft and Hard Materials

S.No.	*Soft magnetic materials*	*Hard magnetic materials*
1.	They can be easily magnetised and demagnetised.	They cannot be easily magnetised and demagnetised.
2.	They have low hysteresis loss due to small hysteresis loop area.  	They have large hysteresis loss due to large hysteresis loop area. 
3.	Magnetic energy stored is not high.	Magnetic energy stored is high.
4.	They have large values for permeability and susceptibility.	They have small values for permeability and susceptibility.
5.	Coercivity and retentivity are small.	Coercivity and retentivity are large.
6.	The eddy current loss is small due to its high resistivity.	The eddy current loss is more due to its small resistivity.
7.	The domain walls are easy to move.	The domain walls are hard to move.
8.	They are used to make electromagnets.	They are used to make permanent magnets.
9.	**Examples:** Iron silicon alloy, Nickel iron alloy, silicon steels and ferrites.	**Examples.** Tungsten steel, Cobalt steel, Alini, Alnico and Cunife.
10.	They are free from irregularities (in the crystal structure) like strains or impurities. Their magnetostatic energy is very small.	In these materials, the irregularities (in the crystal structure) like mechanical strains will be more. Their magnetostatic energy is large.

30.11 WEISS THEORY OF FERROMAGNETISM

According to Weiss, the atomic magnets of a ferromagnetic substance are grouped into certain regions or *domains*. When the substance is in the unmagnetised condition, the domains form closed chains with no free poles. When the substance is magnetized, the chains break up and the domains gradually set themselves with their magnetic axes all pointing in the field direction. Thus ferromagnetism is a *crystal phenomenon*.

Weiss assumed that a molecular magnetic field exists at the position of every atom or molecule. This field arises due to the interaction of all neighbouring molecules. The molecular field is proportional to the magnetisation vector I.

$\therefore$ molecular field $B_i = \beta I$

Here, β = molecular field coefficient.

The effective field strength B_e may be regarded as the vector sum of external applied field strength B and the internal molecular field strength B_i.

A magnetic state is favoured when r_{AB}/r_0 is slightly larger than 3. For Fe, Co and Ni this ratio has the values 3.26, 3.64 and 3.94 respectively.

So Fe, Co, and Ni are ferromagnetic. For Cr and Mn this ratio has the value 2.60 and 2.24, *i.e.*, these are not ferromagnetic.

30.14 QUANTUM THEORY OF FERROMAGNETISM

Ferromagnetic substances are those substances which possess a spontaneous magnetic moment *i.e.*, a magnetic moment even in the absence of an applied magnetic field. The Curie temperature θ is the temperature at and above which the spontaneous magnetisation vanishes.

Weiss gave the theory of ferromagnetism on the basis of two hypotheses —

(1) A ferromagnetic specimen contains in general a large number of small regions called domains which are spontaneously magnetised. The spontaneous magnetisation of the specimen is determined by the vector sum of the magnetic moments of the individual domains.

(2) Within each domain the spontaneous magnetisation is due to existence of molecular field which tends to produce a parallel alignment of the atomic dipoles.

Existence of molecular moment leads to co-operation or interaction between the atomic dipoles. Tendency of co-operation is to produce parallel alignment.

To explain this fact Weiss assumed that magnetic field actually acting on the specimen is

$$H_{eff} = H + \lambda M \quad \text{...(1)}$$

On these assumptions we shall develop the quantum theory of ferromagnetism.

According to quantum theory, since the magnetic moments are quantized, the magnetic dipole moment μ and its component μ_z in the direction of the applied field can not have arbitrary values. We have, in general, a direct relationship between the magnetic dipole moment μ of an atom or ion in free space and its angular momentum J as

$$\mu = -g\,\mu_B\,J \quad \text{...(2)}$$

μ_B is the Bohr magneton. It is defined as $e\hbar/2m$.

The g factor is given by the Lande equation

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \quad \text{...(3)}$$

Here, S and L represent the spin and orbital quantum numbers of the dipole respectively.

The orientations of the magnetic moment μ with respect to the direction of the applied magnetic field are specified by the rule that the possible components of μ along the field direction are given by

$$\mu_z = -g\,\mu_B\,m_J \quad \text{...(4)}$$
$$m_J = J, (J-1), \ldots - (J-1), -J.$$

For each value of J, m_J can have $(2J+1)$ values which means that the magnetic moments of the atom can have $(2J+1)$ different orientations relative to the field.

The potential energy of the magnetic dipole in the presence of a magnetic field H is

$$U = -\vec{\mu}\,.\,\vec{H} = m_J\,\mu_B\,g\,H_{eff} \quad \text{...(5)}$$

The number of atoms with a given value of m_J is proportional to $\exp\,(m_J\,g\,\mu_B\,H_{eff}/kT)$.

Consider a ferromagnetic solid containing N atoms per unit volume each having a total angular momentum number J. Then the magnetization in the direction of the field is given by

$$M = N.\frac{\sum_{m_J=-J}^{J} m_J\, g\mu_B.\exp.(m_J\, g\mu_B H_{eff} / kT)}{\sum_{m_J=-J}^{J} \exp(m_J\, g\mu_B H_{eff} / kT)} \qquad \text{...(6)}$$

Substituting $\frac{g\,\mu_B\, H_{eff}}{kT} = x$ in the above equation, we get

$$M = Ng\,\mu_B \frac{\sum_{m_J=-J}^{J} m_J \exp(m_J\, x)}{\sum_{m_J=-J}^{J} \exp(m_J\, x)} \qquad \text{...(7)}$$

After some algebraic manipulations, Eq. (7) reduces to,

$$M = Ng\mu_B\left[\frac{2J+1}{2}\coth\frac{2J+1}{2}x - \frac{1}{2}\coth\frac{x}{2}\right]$$

Substituting $x = a/J$ in the above equation, we get

$$M = Ng\mu_B\left[\frac{2J+1}{2}\coth\frac{2J+1}{2J}a - \frac{1}{2}\coth\frac{a}{2J}\right]$$

$$= Ng\mu_B J\left[\frac{2J+1}{2J}\coth\frac{2J+1}{2J}a - \frac{1}{2J}\coth\frac{a}{2J}\right]$$

or

$$M = Ng\,J\,\mu_B B_J(a) \qquad \text{...(8)}$$

Here $B_J(a)$ is the *Brillouin function* and it is defined as

$$B_J(a) = \frac{2J+1}{2J}\coth\left(\frac{2J+1}{2J}\right)a - \frac{1}{2J}\coth\left(\frac{a}{2J}\right) \qquad \text{...(9)}$$

From the two substitutions made in the above treatment, we have

$$\frac{a}{J} = \frac{g\mu_B\, H_{eff}}{kT}$$

or

$$a = \frac{gJ\mu_B\, H_{eff}}{kT} = \frac{g\,J\mu_B}{kT}(H + \lambda M) \qquad \text{...(10)}$$

For spontaneous magnetisation $H = 0$. Eq. (10) becomes

$$a = \frac{gJ\mu_B\,\lambda M}{kT} \qquad \text{...(11)}$$

$$\therefore \quad M(T) = \frac{akT}{gJ\mu_B\lambda} \qquad \text{...(12)}$$

As $T \to 0$ or $a \to \infty$, $B_J(a) \to 1$; the magnetic moments align themselves parallel to the field and the magnetization M becomes the *saturation magnetization*, $M_S(0)$. Thus, from Eq. (8), we get

$$M_S(0) = Ng\,J\,\mu_B \qquad \text{...(13)}$$

From Eqs. (12) and (13), we obtain,

$$\frac{M(T)}{M_S(0)} = \frac{akT}{\lambda Ng^2 J^2 \mu_B^2} \qquad \text{...(14)}$$

Eqs. (8) and (13) give

$$\frac{M(T)}{M_S(0)} = B_J(a)$$ ...(1

$\frac{M(T)}{M_S(0)}$ must simultaneously satisfy both equations (14) and (15). So its magnitude at a gi temperature is obtained graphically as the intersection of the two $\frac{M(T)}{M_S(0)}$ versus a plots (Fig. 30.4

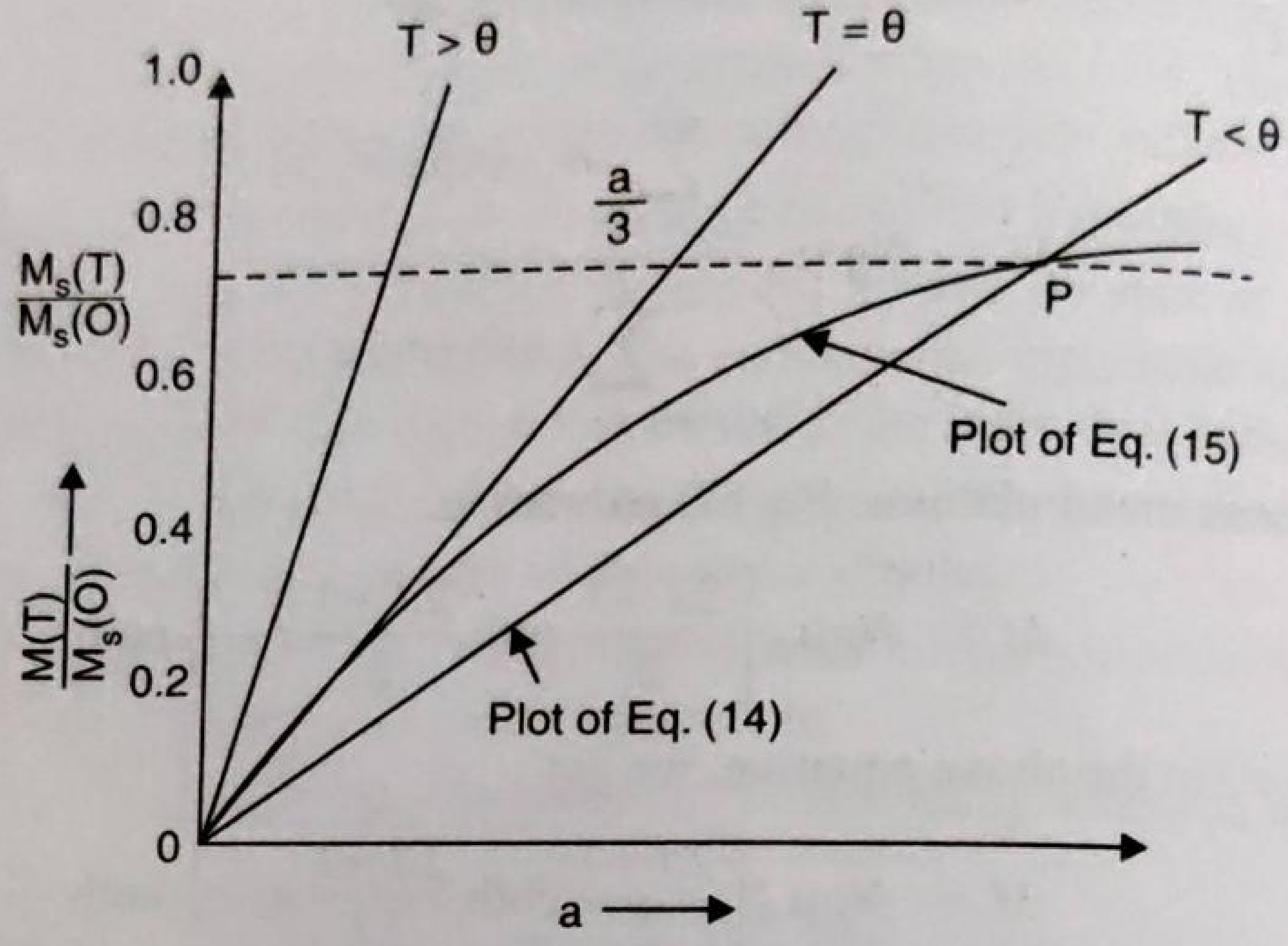


Fig. 30.40

(*i*) For $T < \theta$ (curie temperature), spontaneous magnetization results.

(*ii*) For $T \geq \theta$, the two curves do not intersect and there is no spontaneous magnetization.

ANTIFERROMAGNETISM

30.15 ANTIFERROMAGNETIC MATERIALS

- Antiferromagnetic materials are crystalline materials which possess a small positive susceptibility of the order of 10^{-3} to 10^{-5}.
- Consider an antiferromagnetic crystal containing two types of atoms A and B distributed over two interpenetrating lattices (Fig. 30.41).

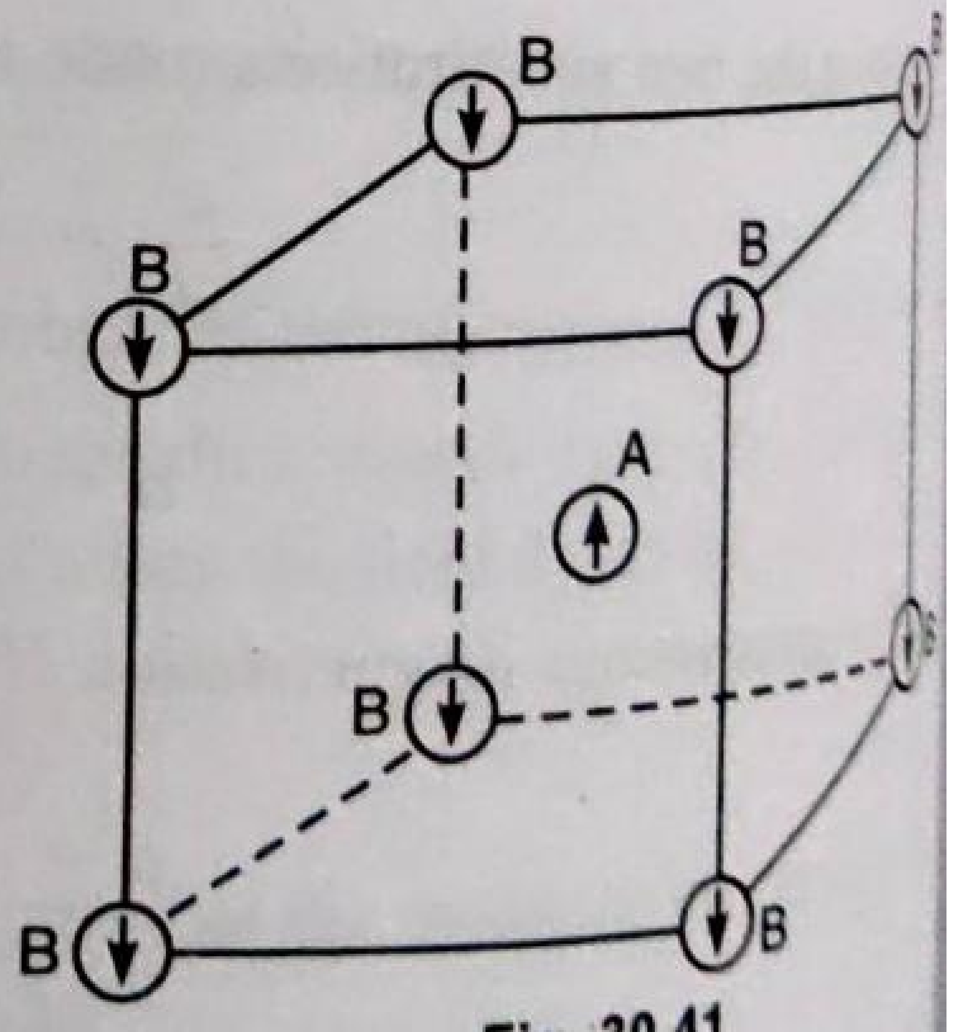


Fig. 30.41

B atoms occupy the corner points of a body centered cubic lattice.

A atoms occupy the body centres of these cubic lattices.

The atom at A-site has its spin up.

The atom at B-site has its spin down (Fig. 30.42).

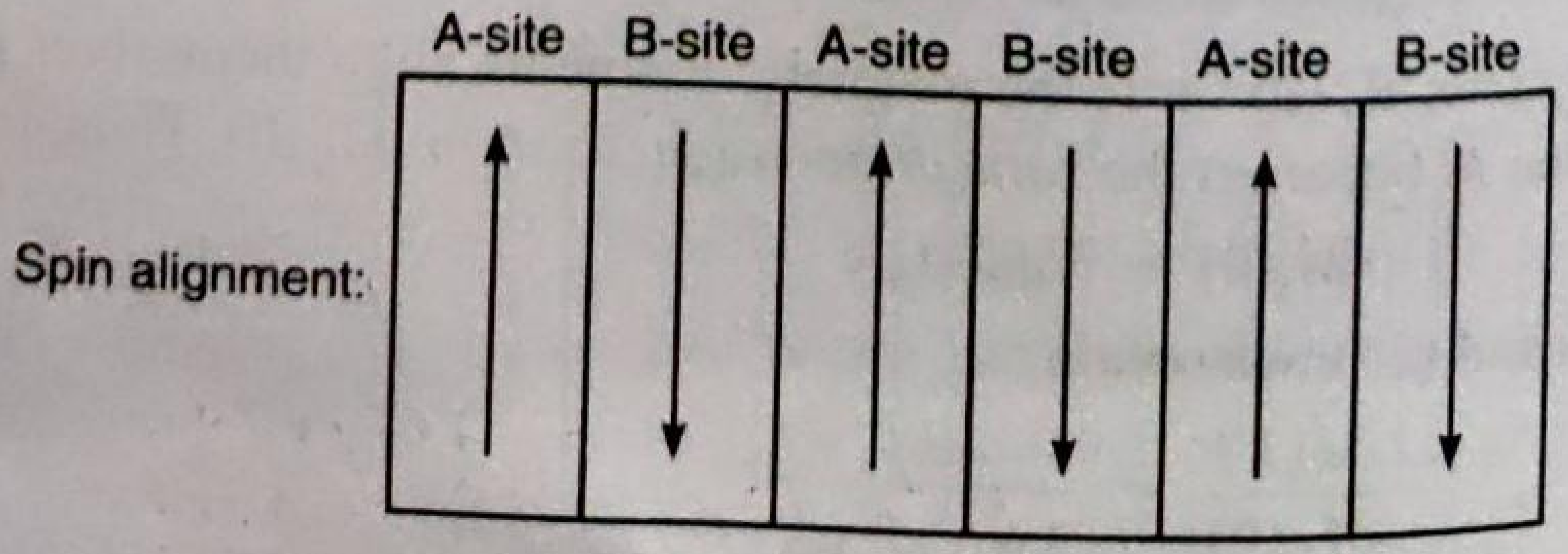


Fig. 30.42

The spin alignment of adjacent sites (A sites and B sites) is in an antiparallel manner. Hence their intensity of magnetisation is equal and opposite resulting in zero net magnetisation at $T = 0$K. Thus the susceptibility of antiferromagnetic materials at 0K is zero.

Above 0 K, the alignment of spin magnetic moments in A sites and B sites are varying in a different manner. This will lead to a positive and small value of susceptibility for these materials.

Examples. FeO (ferrous oxide), MnO (Manganese oxide), Cr_2O_3 (Chromium oxide) and salts of transition elements.

Definition of Antiferromagnetism

- If the A and B sublattice moments are exactly equal but opposite, the *net moment is zero*. This type of magnetic ordering is called *antiferromagnetism*.

In antiferromagnetism, the magnetic moments of sublattices in crystal cell are equal in magnitude but opposite in direction. So they cancel each other giving rise to net zero magnetization.

Variation of susceptibility with temperature of an antiferromagnetic material

Figure 30.43 shows the variation of susceptibility with temperature.

- The susceptibility increases with increasing temperature and it reaches a maximum at a certain temperature called *Neel temperature*, T_N.

$$\chi \propto T \text{ when } T < T_N.$$

The material is *antiferromagnetic* below T_N.

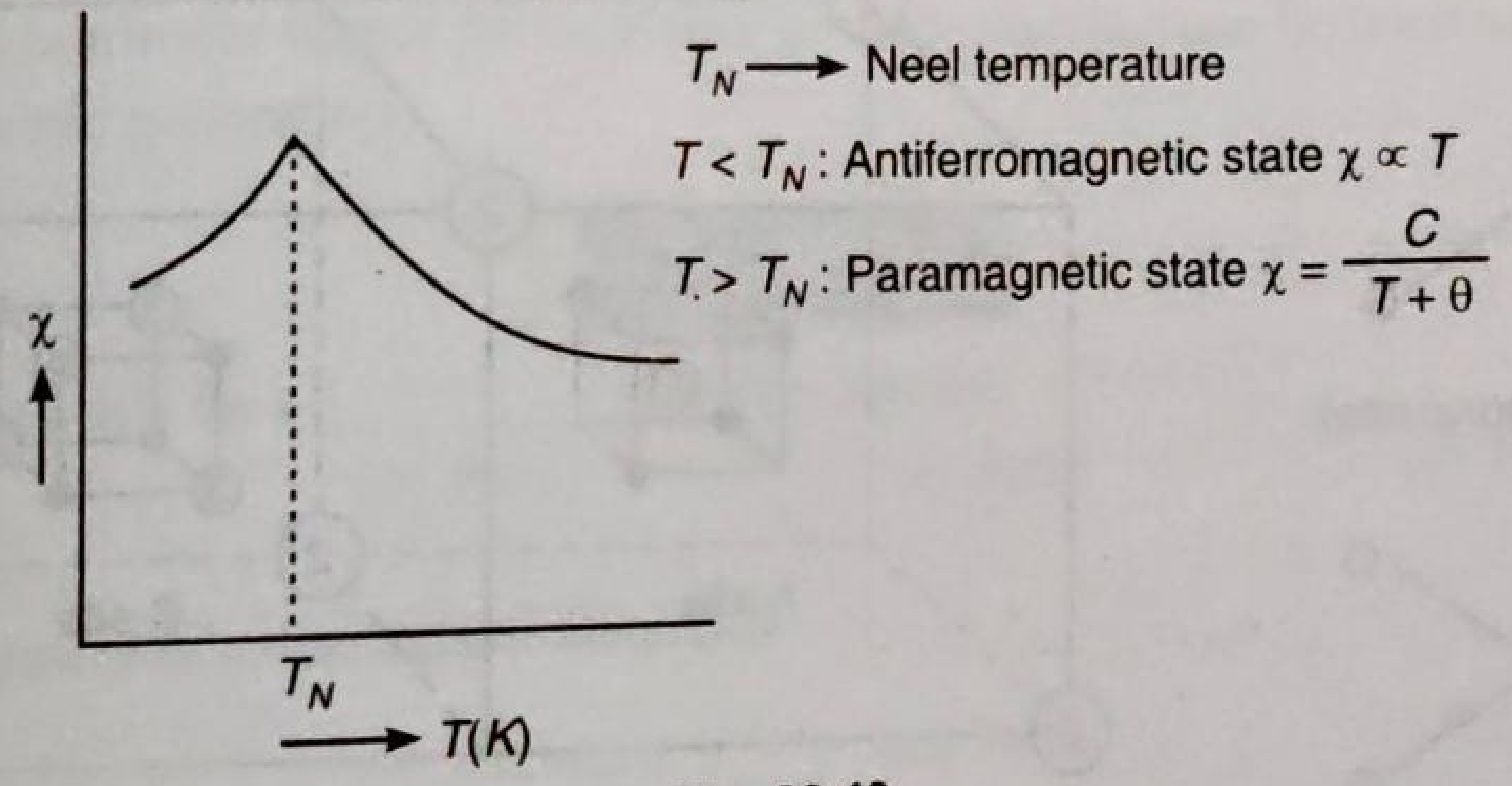


Fig. 30.43

- With further increase in temperature, the material reaches paramagnetic state. Above Neel temperature, the susceptibility decreases with temperature.

$$\chi = \frac{C}{T+\theta}.$$

Here, C is the *Curie constant* and θ the *paramagnetic Curie temperature*.

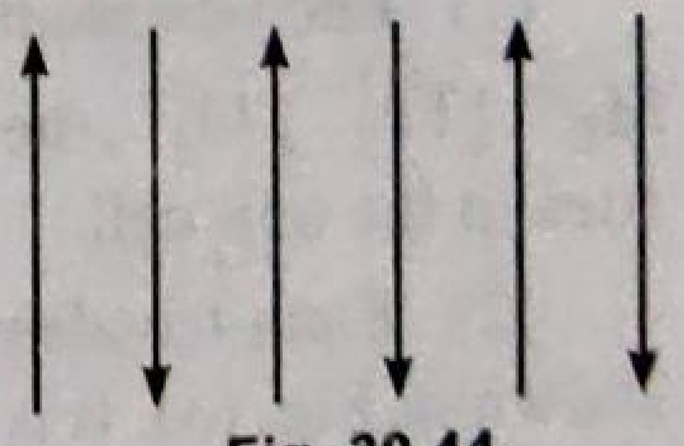


Fig. 30.44

Properties of Antiferromagnetic materials

(1) Electron spin of neighbouring atoms are aligned antiparalllel; *i.e.*, Spin alignment is antiparallel (Fig. 30.44).

(2) Antiferromagnetic susceptibility depends greatly on temperature.

Magnitude of susceptibility	*Temperature dependence*	*Examples*
Small, positive	$\chi \propto T$ when $T < T_N$ $\chi = \frac{C}{T+\theta}$ when $T > T_N$	FeO (ferrous oxide), MnO (Manganese oxide), Cr_2O_3 (chromium oxide), salts of transition elements.

FERRIMAGNETISM

30.16 FERRITES AND THEIR APPLICATIONS

- Ferrimagnetism is a special case of antiferromagnetism in which the opposite magnetic moments on each of the two sub-lattices are not exactly equal. Thus, when spontaneous anti-parallel arrangement of spins occurs, the material has a net paramagnetic moment and hence, a net magnetization too. This is called *ferrimagnetism*.

In *ferrimagnetic materials* (also called ferrites) such as $MnFe_2O_4$, the magnetic moments of adjacent ions are antiparallel and of unequal strength (Fig. 30.45). So there is a finite net magnetisation. Ferrites exhibit spontaneous magnetization below the ferromagnetic Neel temperature T_{FN}.

The general chemical formula of ferrites may be written as XY_2Z_4, where X is a divalent negative ion, Y is Fe^{3+}, and Z is mostly the divalent oxygen ion, O^{2-}. A familiar example is Fe_3O_4 (or $Fe^{2+}Fe^{3+}_2\,O^{2-}_4$).

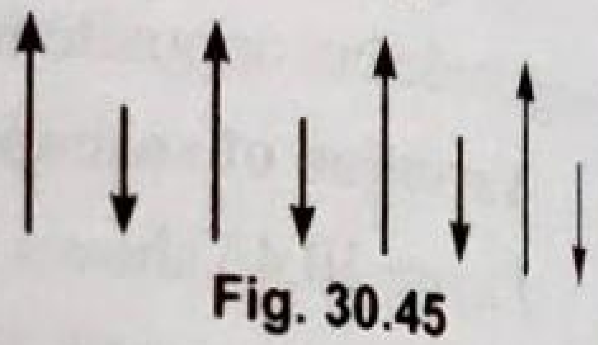
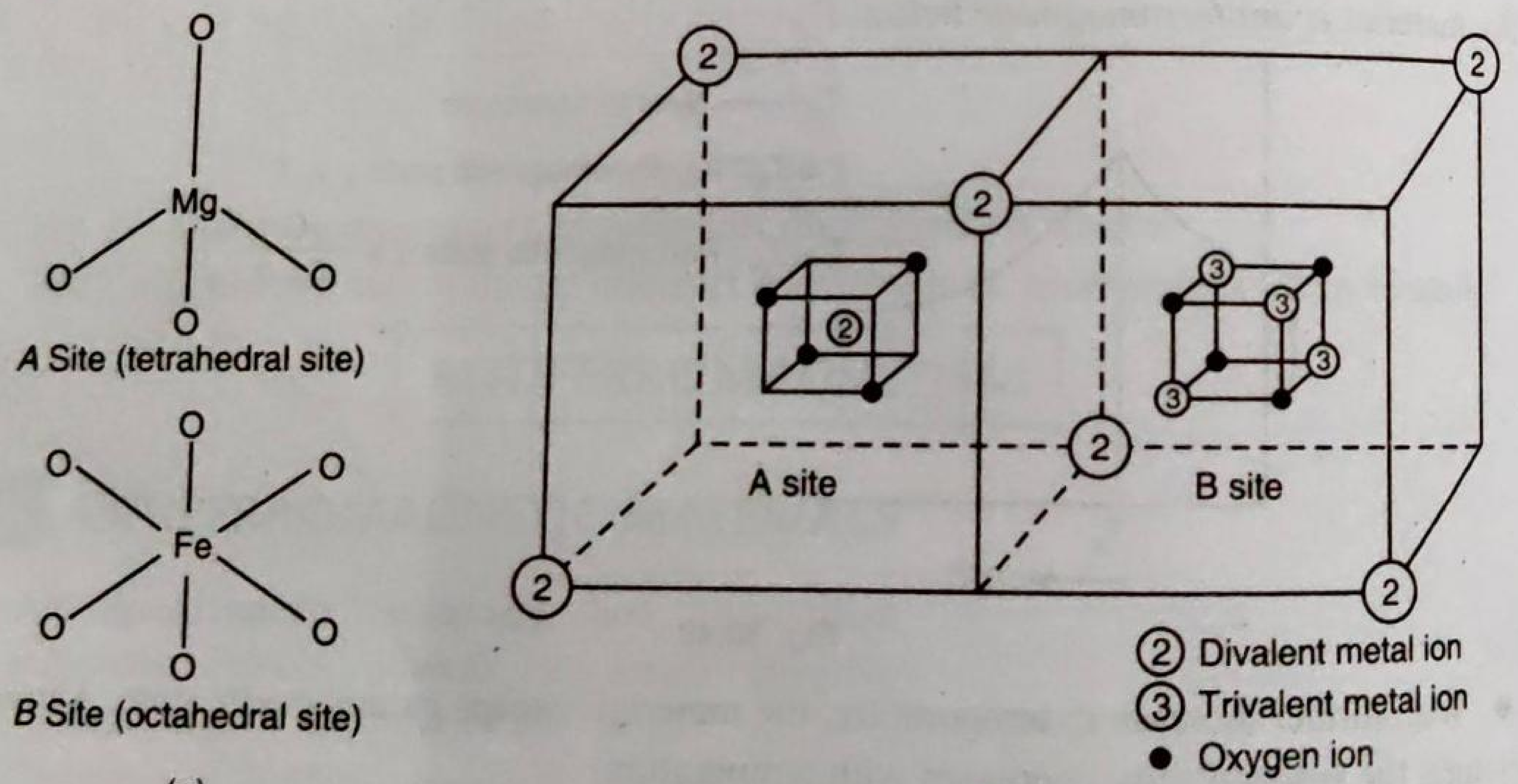


Fig. 30.45

Structure of Ferrites: A ferrite crystal has the *spinel* structure.

The mineral *spinel* is $MgAl_2O_4$.

Figure 30.46 shows the regular spinel structure.



(a) (b)

Fig. 30.46

(1) Each divalent metal ion is surrounded by O^{2-} ions in a *tetrahedral* fashion. For example, in $Mg^{2+}[Fe^{3+}_2]\,O^{2-}_4$, the structure of Mg^{2+} is given in Fig. (*a*). It is called *A* site. There are 8 tetrahedral sites in the unit cell.

(2) Each trivalent metal ion (Fe^{3+}) is surrounded by 6 O^{2-} ions in the *octahedral* fashion as shown in Fig. (*a*). It is called *B* site. There are 16 octahedral sites in the unit cell.

- Thus in a regular spinel, each divalent metal ion (Mg^{2+}) exists in a tetrahedral site (*A* site) and each trivalent metal ion (Fe^{3+}) exists in an octaheral site (*B* site).
- Hence, the sites *A* and *B* combine together to form a regular spinel ferrite structure as shown in Fig. (*b*).

Properties:

1. These are metal oxides, but not metals.
2. These materials exhibit hysteresis property.
3. They are insulators with very high electrical resistivity (~ 10^{12} Ω cm). As a consequence, there will be no eddy current loss as usually noted with iron, at high frequencies.
4. High microwave dielectric constant (~ 10 to 12) (low dielectric loss).
5. A high magnetic permeability (500 – 1000) for the mixed Ni-Zn ferrites ($Ni_{0.36}Zn_{0.64}Fe_2O_4$) at low frequencies and ~ 10 at high frequencies (≥ 300 MHz).

Applications of Ferrites

1. Ferrites are used to produce low frequency ultrasonic waves by magnetostriction principle. Further these are used in the electromechanical transducers.
2. Ferrite rods are used in radio receivers (particularly in medium wave coil) to increase the sensitivity and selectivity of receiver.
3. Ferrites like Nickel Zinc ferrites are used as cores in audio and T.V. transformers.
4. Since for ferrites eddy current loss and hysteresis loss are small at microwave frequencies, these are widely used in non-reciprocal microwave devices like *gyrator, circulator* and *isolator*.
5. Ferrites are also used in digital computers and data processing circuits. Normally here ferrites with rectangular hysteresis loops are used as magnetic storage elements.
6. Based on nonlinear tensor permeability property, ferrites can be used in devices for power limiting and harmonic generation.

EXERCISE

1. Gold is an example for a __________ magnetic material.

(*a*) Dia (*b*) Para (*c*) Ferro (*d*) Ferri (*B.U. 2011*)

2. Larmor frequency of a diamagnetic material is

(*a*) $\frac{em}{2B}$ (*b*) $(e/2m)B$ (*c*) $Bm/2e$ (*d*) $(2e/m)B$ (*B.U. 2011*)

3. When $\mu H > k_B T$, the Langevin function $L(\alpha)$ =

(*a*) 0 (*b*) – 1 (*c*) 1 (*d*) ∞ (*B.U. 2013*)

4. The susceptibility of a Paramagnetic substance is __________.

(*a*) negative (*b*) zero (*c*) positive (*d*) none of these (*B.U. 2014*)

5. The Curie-Langevin relation is

(*a*) $\chi = \frac{1}{H}$ (*b*) $\chi = CT$ (*c*) $\chi = \frac{C}{T}$ (*d*) $\chi = \frac{T}{C}$ (*B.U. 2012*)

6. Curie-Weiss law is

(*a*) $\chi = \frac{C}{T-\theta}$ (*b*) $\chi = \frac{T}{C-\theta}$ (*c*) $\chi = \frac{\theta}{C-T}$ (*d*) $\chi = \frac{C}{T-\mu}$ (*B.U. 2010*)

7. Paramagnetic curie point θ = __________

(*a*) $\frac{\lambda \mu N}{k_B}$ (*b*) $\frac{\lambda \mu N}{k_B T}$ (*c*) $\frac{\lambda \mu^2 N}{k_B}$ (*d*) $\frac{\lambda \mu^2 N}{3k_B}$ (*B.U. 2011*)

8. Domain formation is necessary feature of ________
(*a*) diamagnetism (*b*) paramagnetism (*c*) ferrimagnetism (*d*) ferromagnetism
(*B.U.* 2014)

9. At Curie temperature, the spontaneous magnetization for ferromagnetic material is ________
(*a*) one (*b*) infinity (*c*) zero (*d*) none of these
(*B.U.* 2012)

10. Ferrites are
(*a*) ferromagnetic material (*b*) ferrimagnetic material
(*c*) paramagnetic material (*d*) antiferromagnetic material
(*B.U. MSc.* 2006)

[**Ans.** 1. (*a*), 2. (*b*), 3. (*c*), 4. (*c*), 5. (*c*), 6. (*a*), 7. (*d*), 8. (*d*), 9. (*c*), 10. (*b*)]

11. Explain in detail Langevin's theory of diamagnetism. Find an expression for diamagnetic susceptibility. (*B.U.* 2012)

12. Distinguish between para and diamagnetism. (*B.U.* 2011)

13. Explain the Langevin's theory of paramagnetism. (*B.U.* 2013)

14. Obtain an expression for paramagnetic susceptibility using Langevin's theory. (*B.U.* 2010)

15. Discuss the origin and nature of Weiss molecular field. (*B.U. M.Sc.* 2006)

16. Give an account of the quantum theory of paramagnetism and derive an expression for the susceptibility. How does this theory account for the experimentally observed susceptibility of the rare earth ions? (*Raj.*, 1978)

17. Explain the quantum theory of Paramagnetism. (*B.U.* 2014)

18. Obtain an expression for χ_m from quantum theory of paramagnetism. (*B.U. M.Sc.* 2006)

19. Describe the process of cooling by adiabatic demagnetization of paramagnetic salts. (*B.U.* 2015)

20. Differentiate between paramagnetism and ferromagnetism. (*Madras* 2006)

21. Explain the domain theory of Ferromagnetism. (*B.U.* 2012)

22. Explain the domain structure in ferromagnetic materials. (*Madras*, 2006)

23. Discuss the Weiss theory of ferromagnetism. (*B.U.* 2011)

24. Explain the nuclear magnetic resonance. (*B.U.* 2013)

25. How was Weiss field in ferromagnets explained by Heisenberg?

26. Define Neel temperature. (*Madras* 2006)

27. Outline any five applications of ferrites. (*B.U. M.Sc.* 2006)

28. Give an account of quantum theory of ferromagnetism.

29. Explain Ferrimagnetism. What are ferrites? Discuss their applications. (*H.P.U.* 1992)