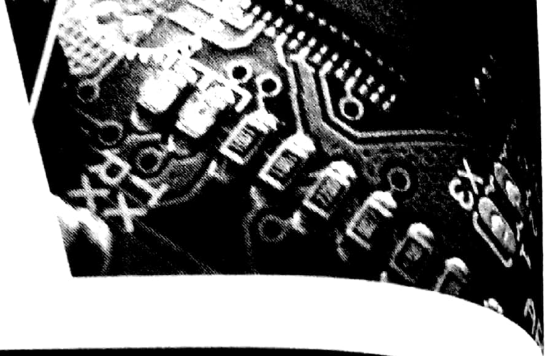
# MAGNETIC PROPERTIES



## 6.1 INTRODUCTION

*The materials which can be magnetised by application of external magnetic field are called magnetic materials.* They play an important role in modern technology. They are widely used in electronics and computer industry. All substances (i.e., solid, liquid or gas) generally reveal the phenomenon of magnetism. The magnetic materials are normally classified into five different categories. They are (i) diamagnetic, (ii) paramagnetic, (iii) ferromagnetic, (iv) antiferromagnetic and (v) ferrimagnetic materials. Before studying the various properties of different magnetic materials, we will first discuss the various following terms used in magnetism.

### 6.1.1 Magnetising Field

*The uniform magnetic field in which magnetic material is placed to magnetise it is called magnetising field.*

### 6.1.2 Magnetic Moment ($\mu_m$)

It is defined as *the moment of the couple acting upon a magnet when it is placed with its axis at right angles to a uniform magnetic field of unit strength.*

It is measured by the **product of the magnetic pole strength** $(m)$ and **the distance** $(2l)$ **between the two poles.**

$$\therefore \quad \mu_m = m \times 2l \qquad \cdots(6.1.2.1)$$

The unit of magnetic moment is ampere · metre$^2$ $(A \cdot m^2)$

### 6.1.3 Intensity of Magnetisation (or Magnetisation $M$)

It gives the measure of magnetisation of a magnetic material subjected to a magnetising field.

Intensity of magnetisation of a magnetised specimen is defined as the **magnetic moment developed per unit volume of the magnetised substance.**

If a magnetised *substance of volume* $V$ acquires magnetic *dipole moment* $\mu_m$ due to magnetising field, then

$$M = \frac{\mu_m}{V} \qquad \cdots(6.1.3.1)$$

**SI unit :** $M = \frac{\mu_m}{V} = \frac{\text{ampere} \cdot \text{metre}^2}{\text{metre}^3}$

$= \textbf{ampere} \cdot \textbf{metre}^{-1} (\mathbf{A \cdot m^{-1}})$

The intensity of magnetisation and the magnetic intensity have same unit.

**Special Note**

For a substance of length $2l$ and uniform cross section of area $a$,

$$M\left(=\frac{\mu_m}{V}\right) = \frac{m \times 2l}{a \times 2l} = \frac{m}{a} = (\text{Wb/m}^2) \qquad \ldots (6.1.3.2)$$

The intensity of magnetisation may also be defined as the *pole strength developed per unit area of cross section of the specimen.*

### 6.1.4 Magnetic Field and Magnetic Field Intensity ($H$)

*The region over which a magnetic pole experiences a magnetic force is called a magnetic field.*

*The intensity of magnetic field (or magnetic field intensity) at any point is defined as the force experienced by a unit north pole placed at that point and is directed along the direction of force.*

**SI unit : ampere · metre$^{-1}$(A · m$^{-1}$)**

**CGS unit :** oersted(Oe)

### 6.1.5 Magnetic Flux Density ($\vec{B}$) or Magnetic Induction

*A magnetic field is schematically represented in diagram by magnetic lines of force.*

**The magnetic flux density in any material is defined as the number of magnetic lines of force passing normally through its unit area.**

**Unit:** The SI unit of magnetic induction is **tesla** (**T**) or **weber · metre$^{-2}$**(**Wb · m$^{-2}$**). The SI unit of magnetic flux is **weber** (**Wb**).

The CGS unit of magnetic induction is **gauss** (**G**).

$$\mathbf{1T = 10^4 G}$$

If a magnetic field of intensity $H$ is applied **in vacuum**, the magnetic induction ($B_o$) due to this field is given by,

$$\vec{B_0} = \mu_0 \vec{H} \qquad \ldots (6.1.5.1)$$

where $\mu_0$ = permeability of free space = $4\pi \times 10^{-7}\ \mathbf{H \cdot m^{-1}}$

But, if a magnetic field of intensity $H$ is applied in a **solid medium** of **permeability** $\mu$, the **magnetic induction** ($\vec{B}$) in solid is given by,

$$\vec{B} = \mu \vec{H} \qquad \ldots (6.1.5.2)$$

## 6.1.6 Relative Permeability ($\mu_r$)

We know, the *magnetic permeability* ($\mu$) *of a magnetic substance is defined as the ratio of the magnetic* **induction** ($B$) **in the sample** of the medium to the **applied magnetic intensity** ($H$).

i.e. $$\mu = \frac{B}{H} \qquad \cdots (6.1.6.1)$$

**Unit:** Its unit is **tesla** · **metre** · **ampere**$^{-1}$ i.e. $\mathrm{T \cdot m \cdot A^{-1}}$ (or, $\mathrm{Wb \cdot m^{-1} \cdot A^{-1}}$)

*The relative permeability* ($\mu_r$) *is the ratio of magnetic permeability* ($\mu$) *of the medium to the magnetic permeability* ($\mu_o$) *of the free space.*

i.e. $$\mu_r = \frac{\mu}{\mu_0} \qquad \cdots (6.1.6.2)$$

The magnetic permeability of a magnetic substance **measures its magnetising power by the passage of magnetic lines of induction through it.**

The relative permeability of **free space is 1**.

## 6.1.7 Magnetic Susceptibility ($\chi$)

The magnetic susceptibility of a magnetic substance indicates its **capability to acquire magnetism**.

We know, the intensity of magnetisation ($\vec{M}$) of a magnetic material is proportional to the applied magnetic field ($\vec{H}$). So

$$\vec{M} \propto \vec{H}$$

or, $$\vec{M} = \chi \vec{H} \qquad \cdots (6.1.7.1)$$

where the constant $\chi$ is known as **magnetic susceptibility**.

**The magnetic susceptibility of a magnetic material is defined as the ratio of intensity of magnetisation induced in it to the magnetising field.**

*The greater the value of susceptibility of a material, the material can be magnetised more easily.*

**Unit:** It has **no unit** (since $\vec{M}$ and $\vec{H}$ have the same unit).

The value of **magnetic susceptibility of vacuum is zero,** because there is no magnetisation in vacuum.

## 6.1.8 Relation among $B$, $H$ and $M$

When a magnetic material is placed in a uniform magnetic field of intensity $H$, two types of lines of force are passing through it. One is *due to the magnetising field* ($H$) *and the other is due to the magnetisation of the magnetic substance.*

So, the magnetic induction inside the material ($B$) is the sum of the **magnetic induction ($B_0 = \mu_0 H$) in free space** surrounding a source of magnetic field and the **magnetic induction ($\mu_0 M$) produced due to the magnetisation of the material.** Thus

$$B = B_0 + (\mu_0 M) \quad \text{or,} \quad B = \mu_0 H + \mu_0 M$$

$$\therefore \quad \boldsymbol{B = \mu_0 (H + M)} \qquad \cdots (6.1.8.1)$$

## 6.1.9 Relation between Permeability ($\mu$) and Magnetic Susceptibility ($\chi$)

We know, $\quad B = \mu_0 (H + M)$

Dividing both sides by $H$, we get

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

or,

$$\boldsymbol{\mu = \mu_0 (1 + \chi)} \qquad \cdots (6.1.9.1)$$

Therefore the relative permittivity

$$\boldsymbol{\mu_r = \frac{\mu}{\mu_0} = 1 + \chi} \qquad \cdots (6.1.9.2)$$

**PROBLEM 1** **An aluminium rod of 0.5 cm$^2$ area of cross section is subjected to a magnetising field of 1200A $\cdot$ m$^{-1}$. If the susceptibility of aluminium is $2.3 \times 10^{-5}$, find (i) magnetic permeability, (ii) magnetic induction, (iii) produced magnetic flux, (iv) magnetisation of the material (or intensity of magnetisation) and (v) relative permeability ($\mu_r$).**

**Solution** Here, $A$ = cross sectional area of the rod $= 0.5 \times 10^{-4} \text{m}^2$

$H$ = magnetising field $= 1200 \text{ A} \cdot \text{m}^{-1}$

$\chi$ = magnetic susceptibility of iron $= 2.3 \times 10^{-5}$

$\mu_0$ = magnetic permeability of the free space $= 4\pi \times 10^{-7} \text{T} \cdot \text{A}^{-1} \cdot \text{m}$

**i** Magnetic permeability

$$\mu = \mu_0 (1 + \chi_m) = 4\pi \times 10^{-7} (1 + 2.3 \times 10^{-5})$$

$$= 4\pi \times 10^{-7} \times 1.000023 = 12.56 \times 10^{-7} \text{T} \cdot \text{m} \cdot \text{A}^{-1}$$

**ii** Magnetic induction of the medium

$$B = \mu H = 12.56 \times 10^{-7} \times 1200 = 15072 \times 10^{-7} \text{T}$$

**iii** Magnetic flux

$$\phi = BA = 15072 \times 10^{-7} \times 0.5 \times 10^{-4} = 7536 \times 10^{-11} \text{Wb}$$

**iv** Intensity of magnetisation

$$M = \chi H = 2.3 \times 10^{-5} \times 1200 = 2760 \times 10^{-5} \text{ A/m}$$

We can also find magnetic induction ($B$) from intensity of magnetisation ($M$).

$$\therefore \quad B = \mu_0 (H + M) = 4\pi \times 10^{-7} = (1200 + 2760 \times 10^{-5}) = 1.5079 \times 10^{-3}$$

**v** Relative permeability

$\mu_r = 1 + \chi = (1 + 2.3 \times 10^{-5}) = 1.000023$

**PROBLEM 2** **A magnetic material has a magnetic field intensity $10^5$ A/m. The susceptibility of the material is $2.3 \times 10^{-5}$. Calculate (i) intensity of magnetisation of the material and (ii) magnetic induction.**

**Solution** Here,

$H$ = magnetic field intensity = $10^5$ A/m

$\chi$ = susceptibility = $2.3 \times 10^{-5}$

$\mu_0$ = permeability of the free space = $4\pi \times 10^{-7}\ \mathrm{H \cdot m^{-1}}$

**i** The intensity of magnetisation

$M = \chi H = 2.3 \times 10^{-5} \times 10^5 = 2.3$ A/m

**ii** Magnetic induction or magnetic flux density

$B = \mu_0(H + M) = 4\pi \times 10^{-7}(10^5 + 2.3)$

$= 4\pi \times 10^{-7}(100002.3)\mathrm{T} = 0.125\mathrm{T}$

**PROBLEM 3** **If a magnetising field produces a magnetic flux of $3 \times 10^{-5}$ weber in a bar of a ferromagnetic material of cross section $0.3 \times 10^{-4}\mathrm{m}^2$, find (i) magnetic flux density, (ii) permeability and (iii) susceptibility of the material. The magnetsing field is 2000 A/m.**

**Solution** Here, the magnetising field, $H = 2000$ A/m

Magnetic flux, $\phi = 3 \times 10^{-5}$ Wb

Area of the material, $A = 0.3 \times 10^{-4}\mathrm{m}^2$

Therefore,

**i** the magnetic flux density, $B = \dfrac{\phi}{A} = \dfrac{3 \times 10^{-5}}{0.3 \times 10^{-4}} = 1.0\ \mathrm{Wb/m^2}$

**ii** magnetic permeability, $\mu = \dfrac{B}{H} = \dfrac{1}{2000} = 5 \times 10^{-4}\ \mathrm{T \cdot m \cdot A^{-1}}$

**iii** susceptibility, $\chi = \dfrac{\mu}{\mu_0} - 1 = \dfrac{5 \times 10^{-4}}{4\pi \times 10^{-7}} - 1 = 0.39 \times 10^3 - 1 = 389$

**PROBLEM 4** **An iron rod of length 1.5 m is in the form of a closed ring. The cross section of an iron ring having 300 turns of wire on it is $5 \times 10^{-4}\mathrm{m}^2$. The permeability of iron is $40 \times 10^{-4}\ \mathrm{Wb \cdot m^{-1} \cdot A^{-1}}$. Calculate, (i) the magnetic flux density, (ii) the number of turns per meter and (iii) the current and the number of ampere turns required to produce a magnetic flux of $6 \times 10^{-4}$ Wb through the ring.**

**Solution** Here, length of the iron rod, $L = 1.5\mathrm{m}$

Magnetic flux, $\phi = 6 \times 10^{-4}$ Wb

Area of the ring, $A = 5 \times 10^{-4}\ m^2$

permeability, $\mu = 40 \times 10^{-4}\ Wb \cdot m^{-1} \cdot A^{-1}$

Total number of turns in the winding = 300

i The magnetic flux density, $B = \frac{\phi}{A} = \frac{6 \times 10^{-4}}{5 \times 10^{-4}}\ Wb/m^2 = 1.2\ Wb/m^2$

ii The number of turns per meter, $N = \frac{300}{1.5}$ turns/m = 200 turns/m

iii The required current, $I = \frac{B}{\mu N} = \frac{1.2}{(40 \times 10^{-4})(200)}\ A$

$\therefore$ The required ampere turn, $NI = \frac{B}{\mu} = \left(\frac{1.2}{40 \times 10^{-4}}\right) = 0.03 \times 10^4 A/m$

## 6.2 ATOM AS A MAGNETIC DIPOLE (OR ORIGIN OF MAGNETIC MOMENT OF AN ATOM)

Atom consists of central positively charged massive nucleus and electrons. The electrons revolve around the nucleus in different circular orbits. But, *when an electron moves around a fixed point in a circular orbit, it produces magnetic field perpendicular to the plane of the orbit.* **So, if a charged particle has an angular momentum, it behaves as an elementary magnet.** Thus, an atom possesses magnetic dipole moment and behaves as a magnetic dipole.

**In an atom, the permanent magnetic moment arises** due to the following three angular momenta–

1. *orbital angular momentum* of the electrons in atom,
2. *spin angular momentum* of the electrons in atom and
3. *spin angular momentum* of the nucleus.

The total angular momentum of the atom is the sum of these three momenta.

### 6.2.1 Orbital Magnetic Moment of the Electrons

Suppose an electron of mass $m_e$ and charge $-e$ revolves in a circular orbit of radius $r$ around the positive nucleus [Fig. 1]. The negative sign is due to the negative charge of the electron.

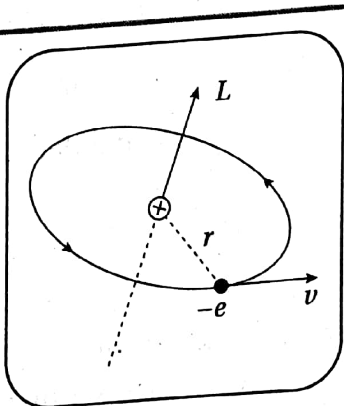


Fig. 1 ▷ Angular momentum of an orbiting electron

If $v$ is the velocity of revolution of the electron around the nucleus, the **orbital angular momentum** of the electron due to its orbital motion is given by

$$L = m_e vr \quad \dots(6.2.1.1)$$

The direction of angular momentum vector $\vec{L}$ is along normal to the plane of the electron orbit. Here it is shown in upward direction [Fig.1].

The time period ($T$) of orbital motion of an electron around the nucleus is very small[1]. As a result, the electron moving around the nucleus will not behave as an isolated particle. Thus, the orbital motion of each electron around the nucleus may be treated as a current loop [Fig. 2] and it sets up a magnetic field. **The orbital motion of electron is now equivalent to a current.** *The electric current due to the moving electron is*

$$I = -\frac{e}{T}$$

Now, the period of revolution of the electron is given by $T = \frac{2\pi}{\omega} = \frac{2\pi r}{v}$ $\left[\because \omega = \frac{v}{r}\right]$

$$\therefore \quad I = -e\left(\frac{1}{2\pi r/v}\right)$$

or, $$I = -\frac{ev}{2\pi r} \quad \cdots(6.2.1.2)$$

Now, the area of the current loop $(A)$ = the area of the electron orbit $= \pi r^2$

We know that the current flowing through a circular coil produces a magnetic field in the direction perpendicular to the plane of the coil and the coil is identical to a magnetic dipole. Thus, the **magnitude of the magnetic moment** $\mu_m$ (i.e., **dipole moment**) of the atom is the product of the current and the area of the loop. Thus,

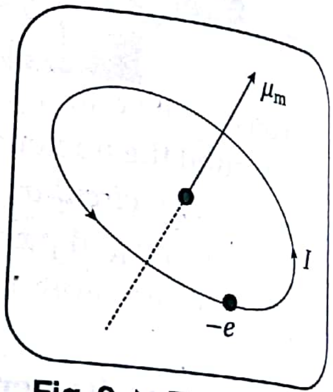



**Fig. 2** ▷ The electron current loop

$$\mu_m = IA = \frac{-ev}{2\pi r} \times \pi r^2 = \frac{-evr}{2} = \frac{-emvr}{2m}$$

$$= \frac{-eL}{2m} \quad [\because L = mvr]$$

$$\therefore \quad \boxed{\mu_m = -\frac{1}{2}\frac{e}{m}L} \quad \cdots(6.2.1.3a)$$

**The negative sign indicates** that, the magnetic moment vector and the angular momentum vector are aligned in opposite direction (i.e. $\vec{\mu}_m$ **is antiparallel to** $\vec{L}$).

In vector notation, $\boxed{\vec{\mu}_m = -\frac{1}{2}\frac{e}{m}\vec{L}}$ $\cdots(6.2.1.3b)$

According to Bohr's atomic theory, an electron can only revolve in an stationary orbit in which its total angular momentum $(L)$ is an integral multiple of $\frac{h}{2\pi}$ i.e.

$$L = n\frac{h}{2\pi} \quad \cdots(6.2.1.4)$$

---

[1] For hydrogen atom

$$T = \frac{2\pi r}{v} = \frac{2\pi(0.5 \times 10^{-10})}{2.262 \times 10^6} = 1.39 \times 10^{-16}\ \text{s}$$

$$v = \left[\frac{1}{4\pi\epsilon_0}\frac{e^2}{mr}\right]^{1/2} = 2.262 \times 10^6\ \text{m/s}$$

where $n$ is an integer.

Now substituting the value of $L$ in equation (6.2.1.3a), we get

$$\mu_m = -\frac{1}{2}\frac{e}{m}\left(n\frac{h}{2\pi}\right) = -n\left(\frac{eh}{4\pi m}\right)$$

or, $$\mu_m = -n\left(\frac{e\hbar}{2m}\right) \quad \left[\text{where } \hbar = \frac{h}{2\pi}\right] \qquad \dots(6.2.1.5)$$

This equation implies that the **magnetic moment due to orbital motion of an electron must be an integral multiple of $\frac{e\hbar}{2m}$.**

### 6.2.1.1 Least Value of the Magnetic Moment of the Orbital Electron (or Bohr Magneton)

The least value of the magnetic moment ($\mu_B$) of an electron moving around the nucleus is obtained from equation (6.2.1.5) (by considering its magnitude only). For $n = 1$ its value is

$$\mu_B = \frac{e\hbar}{2m} \qquad \dots(6.2.1.1.1)$$

where $\mu_B$ is called the *Bohr magneton.*

**This Bohr magneton is the unit of measurement of atomic magnetic moment. Thus, Bohr magneton is the least value of the magnetic moment of the orbital electron.**

The **magnetic moment of an orbital electron** can be written from equation (6.2.1.5) as

$$\mu_m = -n\mu_B \qquad \dots(6.2.1.1.2)$$

where $n$ is an integer.

**Numerical value of Bohr magneton ($\mu_B$) :**

We know, $$\mu_B = \frac{e\hbar}{2m}$$

$$= \frac{eh}{4\pi m}$$

Now, $e = 1.6 \times 10^{-19}$ coulomb,

$h = 6.62 \times 10^{-34} \text{J} \cdot \text{s}$

$m = 9.1 \times 10^{-31} \text{kg}$

$$\therefore \quad \mu_B = \frac{(1.6 \times 10^{-19}\text{C}) \times (6.62 \times 10^{-34}\text{J} \cdot \text{s})}{4 \times 3.14 \times (9.1 \times 10^{-31}\text{kg})}$$

$$= 9.27 \times 10^{-24} \text{J} \frac{\text{C} \cdot \text{J} \cdot \text{s}}{\text{kg}}$$

$$= 9.27 \times 10^{-24} (\text{C} \cdot \text{s}^{-1} \cdot \text{m}^2)$$

$$= 9.27 \times 10^{-24}\ \text{A} \cdot \text{m}^2$$

**Special Note**

① Let an atom is placed in a magnetic field $B$. If the total angular momentum $L_l$ is along the direction of external magnetic field $B$, the possible orientation of the angular momentum vector is given by

$L_{l,B} = m_l\hbar$, where $m_l$ = orbital magnetic quantum number

Now, we get from equation (6.2.1.3a)

$$\mu_m = -\left(\frac{e}{2m}\right)m_l\hbar = -\left(\frac{e\hbar}{2m}\right)m_l = -\mu_B m_l$$

$$\therefore \quad \mu_m = -\mu_B m_l$$

② If an atomic electron with magnetic quantum number $m_l$ is placed in a magnetic field $B$, the corresponding energy of the electron is $m_l B\mu_B$.

### 6.2.1.2 Orbital Gyromagnetic Ratio

The ratio of magnetic moment of the atomic dipole to its angular momentum is called **gyromagnetic ratio** for the orbital motion.

Thus we can write from equation 6.2.1.3.(b), **the orbital gyromagnetic ratio**

$$= \frac{\mu_m}{L} = \frac{e}{2m} \qquad \cdots(6.2.1.2.1)$$

## 6.3 SPIN ANGULAR MOMENTUM OF THE ELECTRONS

In addition to orbital motion, an electron of an atom has also spinning motion. So, the electron possesses magnetic moment due to its spin motion also.

The spin magnetic momentum of an electron can be similarly written as

$$\vec{\mu}_s = \frac{e}{2m}\vec{S} \qquad \cdots(6.3.1)$$

where $\vec{S}$ = spin angular momentum $= \frac{1}{2}\frac{h}{2\pi}$

$$\therefore \quad \mu_s = \frac{1}{2}\frac{eh}{4\pi m} = \frac{1}{2}\left(\frac{e\hbar}{2m}\right) \qquad \cdots(6.3.2)$$

So, the ***magnitude of spin magnetic moment is half of Bohr magneton***. The *total magnetic moment of the electron* is the vector sum of its magnetic moments due to its orbital and spin motions.

**Special Note**

When we consider the electron spin along the direction of external field, the megnetic moment component due to electron spin along the field direction is

$$\mu_{SZ} = g \times \frac{1}{2}\left(\frac{e\hbar}{2m}\right) \qquad \cdots(6.3.3)$$

where $g$ is called **spectroscopic splitting factor** or **Lande g-factor**. The value of $g$-factor is given by

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \quad \cdots (6.3.4)$$

where $\vec{L}$ = orbital angular momentum

$\vec{S}$ = spin angular momentum

$\vec{J}$ = total angular momentum (i.e. $\vec{L} + \vec{S}$)

## 6.4 NUCLEAR MAGNETIC MOMENT (MAGNETIC MOMENT DUE TO NUCLEAR SPIN)

When a charged particle of mass $m$ moves in a closed path, it gives rise to a magnetic field. In the nucleus, a proton possesses an intrinsic spin in the same as an electron does. The vectorial sum of the spin of all the protons in the nucleus of an atom gives rise to the nuclear spin. Thus, **the nucleus of an atom has its intrinsic spin.** So it has a **nuclear magnetic moment**.

Like the Bohr magneton, which is used to measure the magnetic moment of an electron, the *nuclear magnetic moment is expressed* in **the unit of nuclear magneton** $\mu_n$. **The nuclear magnetic moment,**

$$\mu_n = \frac{e\hbar}{2m_p} = 5.05079 \times 10^{-27}\ \text{J/T} \quad \cdots (6.4.1)$$

where $m_p$ is the mass of the proton. Since, the proton is 1836 times heavier than the electron, the **nuclear magneton $\mu_n$ is 1836 times smaller than the Bohr magneton $\mu_B$.**

Thus, the total magnetic moment of an atom will be essentially the vector sum of the orbital and the spin magnetic moments.

**PROBLEM 1**

**An electron revolves around a nucleus with frequency $4 \times 10^{15}$Hz in an orbit of radius of 0.53Å. Calculate (i) the electric current due to moving electron. (ii) the magnetic moment of the orbital electron and (iii) the value of Bohr magneton.**

**Solution**

**i** We know, the electric current ($I$) due to the moving electron is $I = \frac{e}{T}$

where $T$ = period of revolution of the electron $= \frac{1}{\text{frequency}} = \frac{1}{4 \times 10^{15}}$ s

$e$ = charge of an electron $= 1.6 \times 10^{-19}$ C

$\therefore \quad I = 1.6 \times 10^{-19} \times 4 \times 10^{15} = 6.4 \times 10^{-4}$ A

**ii** $A$ = area of the loop $= \pi r^2 = \pi \times (0.53 \times 10^{-10})^2$ m$^2$

$\therefore$ The magnetic moment of an electron revolving around a nucleus,

$$\mu_m = IA = [6.4 \times 10^{-4}][3.14 \times (0.53 \times 10^{-10})^2]$$

$$= 5.64 \times 10^{-24}\ A \cdot m^2$$

iii Bohr magneton, $\mu_B = \frac{e\hbar}{2m} = \frac{eh}{4\pi m}$

$$= \frac{1.6 \times 10^{-19} \times 6.62 \times 10^{-34}}{4 \times 3.14 \times (9.1 \times 10^{-31})}$$

$$= 9.27 \times 10^{-24}\ A \cdot m^2$$

## 6.5 CLASSIFICATION OF MAGNETIC MATERIALS

Magnetic field interacts with all substances to some extent. So **all the materials** (i.e. substances) **possess magnetic properties.** In some cases, this interaction is minimal and we can refer to the materials as nonmagnetic substances.

In general, **we can classify the magnetic material** depending **on the existence of** its **permanent magnetic dipoles of the atoms.** *If the atoms of the materials lack permanent magnetic dipoles, the materials are called diamagnetic. But, when the atoms of the material have permanent magnetic dipoles, the magnetic materials may be paramagnetic, ferromagnetic, antiferromagnetic or ferrimagnetic substances depending on the interaction among these permanent dipoles.* Thus, on the basis of the magnetic behaviour, magnetic materials can be divided into five different categories.

They are (i) diamagnetic materials, (ii) paramagnetic materials, (iii) ferromagnetic materials, (iv) antiferromagnetic materials and (v) ferrimagnetic materials.

Now we will discuss all the magnetic materials in detail.

## 6.6 DIAMAGNETIC MATERIALS

**The substances which when placed in a magnetic field become weakly (feebly) magnetised in a direction opposite to that of the applied magnetising field** are called **diamagnetic substances. The magnetism of diamagnetic materials** is called **diamagnetism.**

***Examples :*** Bismuth, antimony, gold, quartz, water, lead, copper, zinc, helium, hydrogen molecule etc.

The atoms of inert gas have **completely filled electronic shells.** So they have no permanent magnetic dipole moment. Due to this reason, **inert gases are diamagnetic.**

We know that an electron revolving around the nucleus is associated with magnetic moment. The produced magnetic field is perpendicular to the plane of the orbit. But the **orientations of various electronic orbits of an atom of the diamagnetic material** are **different.** Thus, **the resultant magnetic moment of this material is zero.**

When a diamagnetic substance is placed in an external magnetic field, the magnetic Lorentz force $(\vec{F} = -q\vec{v} \times \vec{B})$ acts on the electrons. In a diamagnetic material, there is no **unpaired electrons.** Due to the Lorentz force, the speed of one of the electrons in an electron pair increases, while that of the other decreases. So, an electron pair acquires a net small magnetic moment. Thus, **the diamagnetic material becomes weakly magnetised along a direction opposite to that of the applied field.**

If a bar of diamagnetic substance is placed in a magnetic field, the flux density ($B$) in it becomes less than the flux density ($B_0$) in the free space. So, the *flux density due to magnetisation is small and negative*. The relative permeability ($\mu_r$) is slightly less than unity.

### 6.6.1 Properties of Diamagnetic Materials

- It has **no permanent dipoles.**
- The **relative permeability** is **less than** *unity*.
- It is **feebly repelled** by a magnet.
- The magnetic **susceptibility** is **independent** of **temperature.**
- It shows **negative susceptibility.**
- If a bar of diamagnetic material is suspended between the poles of a magnet, it remains **parallel to the magnetic field.**
- If a diamagnetic substance is **placed in a nonuniform magnetic field,** it is attracted towards the weaker field (i.e. it tends to **move from stronger to weaker magnetic field**).

### 6.6.2 Langevin's Theory of Diamagnetism; Larmor Angular Frequency

The atoms of diamagnetic substances do not have a permanent magnetic moment. **When a diamagnetic material is placed in an external magnetic field, the atoms acquire an induced magnetic moment in a direction opposite to the field due to the change of orbital motion of the electrons.** In 1905, French physicists Langevin explained the diagmagnetism from the electronic theory of matter as given below.

Let us consider an electron of charge $e$ is moving around the nucleus of charge $Ze$ with an angular velocity $\omega_0$ in a circular orbit of radius $r$ in absence of any external magnetic field. Here, the time period of revolution of the electron, $T = \dfrac{2\pi}{\omega_0}$.

The orbital motion of the electron is equivalent to a current and produces a **magnetic moment,**

$$\mu_m = IA = \frac{e}{T}(\pi r^2) = \frac{e\pi r^2}{2\pi/\omega_0}$$

$$= \frac{1}{2} e r^2 \omega_0 \qquad \cdots(6.6.2.1)$$

In the absence of any external magnetic field, the **centrifugal force** ($F_c = m\omega_0^2 r$) of electron is balanced by the electrostatic Coulomb force ($Ze^2/4\pi\varepsilon_0 r^2$) of attraction between the nucleus and the revolving electron.

Thus, $\dfrac{Ze^2}{4\pi\varepsilon_0 r^2} = m\omega_0^2 r$ ...(6.6.2.2)

where $\varepsilon_0$ is the permittivity of free space.

When an external magnetic field $\vec{B}$ **is applied perpendicular to the plane of electron orbit,** the additional **Lorentz force** $(F_L)$ that **acting on the electron** is

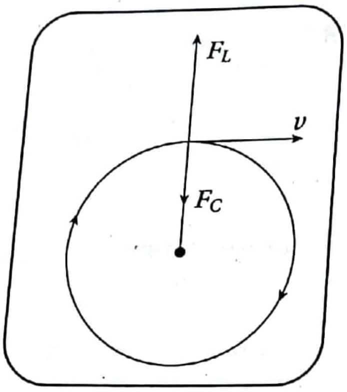



**Fig. 3a** ▷ The direction of Lorentz force $(F_L)$ for the clockwise motion of the electron

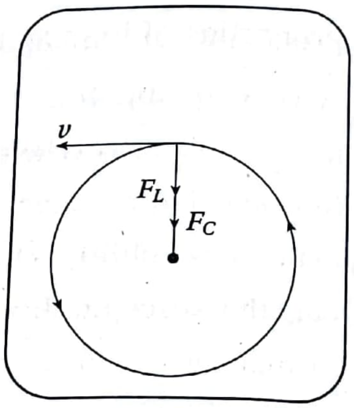



**Fig. 3b** ▷ The direction of Lorentz force $(F_L)$ for the anticlockwise motion of electron

$$F_L = -e|\vec{v}|\,|\vec{B}|\sin 90° = -evB \quad ...(6.6.2.3)$$

This magnetic force $(F_L)$ is a radial force. This force acts on the electron radially outward [Fig. 3a] or inward [Fig. 3b] for the clockwise or anticlockwise motion of the electron respectively. If $\omega$ is the new angular velocity of the electron in presence of magnetic field, the total force $(F_t)$ acting on the electron,

$$F_t = F_C \pm F_L$$

or, $$m\omega^2 r = \frac{Ze^2}{4\pi\epsilon_0 r^2} \pm evB$$

[(+) sign for anticlockwise motion and (–) sign for clockwise motion of electron with respect to field direction]

or, $m\omega^2 r = m\omega_0^2 r \pm er\omega B$ [from equation (6.6.2.2), $m\omega_0^2 r = \dfrac{Ze^2}{4\pi\epsilon_0 r^2}$]

or, $$m\omega^2 = m\omega_0^2 \pm eB\omega$$

or, $$m(\omega+\omega_0)(\omega-\omega_0) = \pm eB\omega \quad ...(6.6.2.4)$$

Since $\omega$ **differs slightly from** $\omega_0$ **even in strongest external magnetic field,** we can write, $\omega - \omega_0 = \Delta\omega$ (change in angular velocity of the electron) and $\omega + \omega_0 = 2\omega$.

Thus, we get from equation (6.6.2.4)

$$m2\omega\Delta\omega = \pm eB\omega$$

$$\Delta\omega = \pm\frac{eB\omega}{2\omega m}$$

or, $$\Delta\omega = \pm\frac{eB}{2m}$$

or, Thus, the **angular velocity** $(\omega)$ **of the electron under the influence of applied magnetic field** $B$, can be written as

$$\omega = \omega_0 + \Delta\omega \qquad \cdots(6.6.2.5)$$

or, $$\omega = \omega_0 \pm \frac{eB}{2m}$$

or, $$\omega = \omega_0 \pm \omega_L \qquad \cdots(6.6.2.6)$$

where $\omega_L$ **is called Larmor angular frequency** and is equal to $\frac{eB}{2m}$.

**Larmor frequency :** *The change in angular frequency of an orbital electron due to application of a magnetic field is called Larmor frequency.*

**Induced magnetic moment ($\mu_{\text{ind}}$) and intensity of magnetisation of diamagnetic material:**

The **change in angular velocity of an orbital electron** due to application of an external magnetic field **produces a change in magnetic moment.**

Thus the change in magnetic moment or **induced magnetic moment,**•

$$\mu_{\text{ind}}(=\Delta\mu_m) = -\frac{1}{2}er^2\omega_L$$

or, $$\mu_{\text{ind}} = -\frac{e^2r^2}{4m}B \quad \left[\because \omega_L = \frac{eB}{2m}\right] \qquad \cdots(6.6.2.7)$$

The negative sign indicates that **the induced magnetic moment takes place in a direction opposite to magnetic field** $(B)$.

**Susceptibility of a diamagnetic material:** In deriving the equation of induced magnetic moment, we have considered that the orbit of the electron is normal to the applied magnetic field $(\vec{B})$. But these orbits can have any orientation with the applied magnetic field. If we consider the direction of applied magnetic field is along the $Z$ axis, the radius $r$ of the orbit is replaced by **the projection** $(r_1)$ **of the radius** of the orbit on a plane perpendicular to the applied magnetic field $B$ i.e., in the $X$-$Y$ plane [Fig. 4].

---

• The induced magnetic moment due to the motion of orbital electron,

$\mu_{\text{ind}} = IA$, (where $A = \pi r^2$ = area of the orbit)

$$= \frac{e}{T}(\pi r^2) = \frac{e(\pi r^2)}{2\pi/\omega} = \frac{1}{2}er^2\omega$$

So, the **induced magnetic moment**

$$\vec{\mu}_{ind} = -\frac{e^2 r_1^2}{4m}\vec{B} \quad \cdots(6.6.2.8)$$

Now, if $x$, $y$ and $z$ are the components of radius along $OX$, $OY$ and $OZ$ axes [Fig. 4] respectively, then

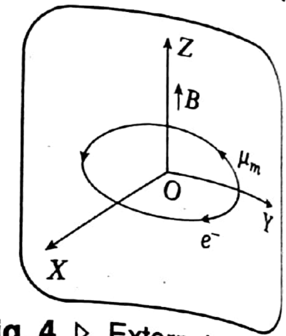



**Fig. 4** ▷ External magnetic field is applied perpendicular to the plane of electron orbit

$$r^2 = x^2 + y^2 + z^2$$

and $$r_1^2 = x^2 + y^2$$

Now, the average values of $r^2$ and $r_1^2$ can be written as

$$\bar{r}^2 = \bar{x}^2 + \bar{y}^2 + \bar{z}^2$$

and $$\bar{r}_1^2 = \bar{x}^2 + \bar{y}^2$$

where $\bar{x}, \bar{y}, \bar{z}$ are the average values of the components of radii.

Now, for spherically symmetric charge distribution,

$$\bar{x}^2 = \bar{y}^2 = \bar{z}^2 = \frac{\bar{r}^2}{3}$$

and so, $$\bar{r}_1^2 = 2\bar{x}^2 = \frac{2}{3}\bar{r}^2 \quad \cdots(6.6.2.9)$$

When each atom has $Z$ number of electrons, the total induced moment in the atom can be written from equation (6.6.2.8)

$$\mu_{ind} = \frac{-Ze^2 B}{4m}\bar{r}_1^2 \quad \cdots(6.6.2.10)$$

Now, if $N$ *is the number of atoms per unit volume* of the material and each atom has $Z$ number of electrons, the **intensity of magnetisation** (magnetic moment per unit volume) can be written with the help of equations (6.6.2.9) and (6.6.2.10) as

$$\vec{M} = N\vec{\mu}_{ind}$$

or, $$\vec{M} = N\left(-\frac{Ze^2\vec{B}}{4m}\right)\left(\frac{2}{3}\bar{r}^2\right)$$

or, $$\vec{M} = \frac{-NZe^2\vec{B}\bar{r}^2}{6m}$$

or, $$\vec{M} = -\frac{NZe^2(\mu_0\vec{H})}{6m}\bar{r}^2 \quad [\because B = \mu_0 H] \quad \cdots(6.6.2.11)$$

Therefore, the **magnetic susceptibility** of the diamagnetic substance is

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

or, $$\chi = -\frac{\mu_0 NZe^2}{6m}\bar{r}^2 \quad \cdots(6.6.2.12)$$

This equation is known as **Langevin equation**. It measures the susceptibility of a diamagnetic material. The equation gives us the following informations.

1. The **diamagnetic susceptibility is negative.**
2. It **does not depend** on the **temperature of the material.**
3. It **does not depend on intensity** of the **external magnetic field.**

**PROBLEM 1**

**The mean radius of the orbit of a He atom is $6 \times 10^{-11}$m and its number of atoms per unit volume is $28 \times 10^{26}$ per $m^3$. If an external magnetic field of 2 tesla is applied perpendicular to the plane of the electron orbit, find**

**(i) the change of angular frequency of the orbital electron i.e. Larmor frequency,**

**(ii) the change in magnetic moment or induced magnetic moment of the orbital electron and**

**(iii) the diamagnetic susceptibility of He atom.**

**Solution** Here,

$\bar{r}$ = mean radius of the orbit $= 6 \times 10^{-11}$m

$N$ = number of atoms per unit volume $= 28 \times 10^{26}$ atoms per $m^3$

$B$ = applied magnetic field = 2T

Also we have

$e$ = charge of electron $= 1.6 \times 10^{-19}$ C

$Z$ = atomic number of He = 2

$m$ = mass of electron $= 9.1 \times 10^{-31}$ kg

**i** Larmor frequency

$$\omega_L = \frac{eB}{2m} = \frac{1.6 \times 10^{-19} \times 2}{2 \times 9.1 \times 10^{-31}} = 0.176 \times 10^{12} \text{rad/s}$$

**ii** Induced magnetic moment

$$\mu_{\text{ind}} = \frac{e^2 \bar{r}^2}{4m} B = \frac{(1.6 \times 10^{-19})^2 \times (6 \times 10^{-11})^2}{4 \times 9.1 \times 10^{-31}} \times 2 = 5.12 \times 10^{-29} \text{A} \cdot \text{m}^2$$

**iii** The diamagnetic susceptibility

$$\chi = -\frac{\mu_0 N Z e^2}{6m} \bar{r}^2 = -\frac{(4\pi \times 10^{-7}) \times (28 \times 10^{26}) \times (2) \times (1.6 \times 10^{-19})^2 \times (6 \times 10^{-11})^2}{6 \times 9.1 \times 10^{-31}}$$

$$= -1187 \times 10^{-10}$$

**PROBLEM 2**

**For a diamagnetic material with its bcc structure of lattice constant 2.55Å, the susceptibility is $-5.6 \times 10^{-6}$. If we assume only one electron per atom is contributing to diamagnetism, find the mean radius of its atom.**

**Solution** We know, the magnitude of susceptibility of a diamagnetic material

Scanned by CamScanner

$$\chi = \frac{\mu_0 N Z e^2}{6m}\,\bar{r}^2 \quad \text{or,} \quad \bar{r} = \left(\frac{\chi 6m}{\mu_0 Z e^2 N}\right)^{1/2}$$

Here $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H \cdot m^{-1}}$

$\bar{r}$ = mean radius of the atom

$N$ = number of atoms per unit volume $= 2 \cdot \frac{1}{a^3}$ [∵ for a bcc structure crystal there are 2 electrons/unit cell, $a$ = lattice constant of bcc crystal = 2.55Å]

$$= \frac{2}{(2.55 \times 10^{-10})^3} = 1.206 \times 10^{29}\ \text{per m}^3$$

$Z$ = number of electrons per atom = 1

$e$ = charge of an electron $= 1.6 \times 10^{-19}$ C

$m$ = mass of an electron $= 9.1 \times 10^{-31}$ kg

$$\therefore \quad |\bar{r}| = \left[\frac{5.6 \times 10^{-6} \times 6 \times 9.1 \times 10^{-31}}{4\pi \times 10^{-7} \times 1 \times (1.6 \times 10^{-19})^2 \times 1.206 \times 10^{29}}\right]^{1/2} = 0.89\text{Å}$$

**PROBLEM 3** **The mean radius of He atom is $6.9 \times 10^{-9}$ m and the number of atoms in its unit volume is $28 \times 10^{26}$ per m$^3$. Find the diamagnetic susceptibility of He atom.**

**Solution** The magnitude of diamagnetic susceptibility of He atom,

$$\chi = -\frac{\mu_0 N Z e^2}{6m}\,\bar{r}^2$$

Here, $\mu_0 = 4\pi \times 10^{-7}\mathrm{H \cdot m^{-1}}$

$N$ = number of atoms per unit volume $= 28 \times 10^{26}$ per $m^3$

$Z$ = atomic number of He atom = 2

$e$ = charge of an electron $= 1.6 \times 10^{-19}$C

$\bar{r}$ = mean radius of He atom $= 6.9 \times 10^{-9}$m

$$\therefore \quad \chi = \frac{-(4\pi \times 10^{-7}) \times (28 \times 10^{26}) \times 2 \times (1.6 \times 10^{-19})^2 \times (6.9 \times 10^{-9})^2}{6 \times 9.1 \times 10^{-31}}$$

$$\approx -1.571 \times 10^{-3}$$

## 6.7 PARAMAGNETIC MATERIALS

**The substances which when placed in a magnetic field are weakly magnetised in the direction of the applied field, are called paramagnetic substances.** It is characterised by positive susceptibility.

***Examples:*** Aluminium, platinum, chromium, oxygen, manganese, $Fe_2O_3$, $Cr_2O_3$, $MnSO_4$ etc.

- **Paramagnetism on the basis of electron theory:** In a paramagnetic material, there is unpaired electron in the atom. The outermost orbit of the atom contains an odd number electrons. The atom of this material possesses magnetic moment due to the orbital motion of the unpaired electron in the atom and due to spin motion of the electrons. But the magnetic moments of the individual electron due to their orbital as well as spin motions do not cancel each other. So, **an individual atom of this material has a permanent dipole.**

In the *absence of magnetic* field, these **atomic magnets randomly orient in the** material due to thermal vibrations. So the **net magnetic moment of the substance is zero.**

When *an external magnetic field* is applied, these permanent magnetic dipoles **align themselves in the direction of applied field** but the temperature opposes this alignment. Therefore, when the temperature is low and the magnetic field is increased, more and more magnetic dipoles align themselves along the direction of the magnetic field. So, **the net magnetic moment of the substance is not zero** in an external magnetic field.

## 6.7.1 Properties of Paramagnetic Materials

1. It has **permanent dipoles.**
2. The **relative permeability** is slightly **more than unity** (i.e., $\mu_r > 1$).
3. It is **feebly attracted by a magnet.**
4. The magnetic susceptibility depends on temperature and decreases with the increase of temperature. So, **a paramagnetic substance tends to loss its magnetism due to rise of its temperature.**
5. It shows **positive magnetic susceptibility** (in the order of $10^{-6}$ approximately).
6. When a rod of paramagnetic material is suspended in a magnetic field, it slowly align itself in the direction of external magnetic field.
7. If a paramagnetic substance is **placed in a nonuniform field**, it is attracted towards the stronger field (i.e., it tends to **move from weaker to stronger magnetic field**).

## 6.7.2 Langevin's Theory of Paramagnetism; Curie Law

In 1905, French physicist Paul Langevin developed the theory of paramagnetism.

The atoms or molecules of a paramagnetic substance have permanent dipoles. To calculate the susceptibility of this material the following two assumptions are considered.

1. The separations of the dipoles are such that their **mutual magnetic interaction forces can be neglected.**
2. These **dipoles have all possible orientations.**

Let us consider that a paramagnetic material consists of $N$ number of magnetic dipoles per unit volume at a temperature $T$(K). These magnetic dipoles are oriented randomly. When a magnetic field $\vec{B}$ is applied on a paramagnetic material, the **torque experienced** by each dipole is $\vec{\mu}_m \times \vec{B}$, where $\mu_m$ is the **dipole moment.** This torque tends to orient the dipoles **in the direction of magnetic field**. The potential energy of atomic magnetic dipole inclined at an angle $\theta$ [Fig. 5] with the direction of external magnetic field is

$$U = -\mu_m B\cos\theta \quad \cdots(6.7.2.1)$$

According to **Maxwell Boltzmann statistics**, the **number of atoms having energy $U$** at a temperature $T$ is **proportional to** $e^{-U/kT}$, where $k$ is Boltzmann constant.

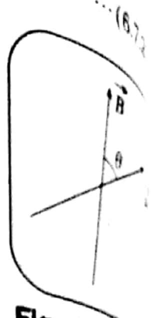


**Fig. 5** ▷ Align... of dipole in a magnetic field

If $dn$ is **the number of dipoles** in a direction **between $\theta$ and $\theta + d\theta$**, then

$$dn = Ce^{-U/kT}d\omega \quad \cdots(6.7.2.2)$$

where $C$ is proportionality constant and $d\omega$ is the solid angle between two hollow cones of semi-vertex angle $\theta$ and $\theta + d\theta$ and is given by

$$d\omega = 2\pi\sin\theta d\theta$$

Substituting this value of $d\omega$ and the value of $U$ from equation (6.7.2.1) in equation (6.7.2.2), we get

$$dn = Ce^{\mu_m B\cos\theta/kT} 2\pi\sin\theta d\theta$$

or, $$dn = A\, e^{q\cos\theta}\sin\theta d\theta \quad \cdots(6.7...)$$

where **$A(=2\pi C)$** is a constant

and $$q = \frac{\mu_m B}{kT} \quad \cdots(6.7...)$$

Therefore, the **total number of dipoles per unit volume,**

$$N = A\int_0^{\pi} e^{q\cos\theta}\sin\theta d\theta$$

---

- When a paramagnetic material is placed in a magnetic field $\vec{B}$, the atomic dipole of magnetic moment $\mu_m$ (lying in a direction making an angle $\theta$ with the direction of magnetic field) tend to align itself in the direction of field. The magnitude of corresponding torque $= \mu_m B\sin\theta$. Hence, the total work done in displacing the atomic dipole to the position making an angle with the direction of $B$

$$W = \int_0^{\theta}\mu_m B\sin\theta d\theta = -\mu_m B\cos\theta$$

This work done is stored in the atomic dipole as its potential energy $(U)$

$\therefore$ Potential energy of atomic dipole

$$\boldsymbol{U = -\mu_m B\cos\theta}$$

Putting $x = \cos\theta$, so that $\sin\theta\, d\theta = -dx$,

we have

$$N = A\int_{+1}^{-1} -e^{qx}dx = -A\left[\frac{e^{qx}}{\alpha}\right]_{+1}^{-1} = \frac{A}{q}(e^{q} - e^{-q})$$

or,

$$A = \frac{qN}{e^{q} - e^{-q}} \qquad \cdots(6.7.2.5)$$

We know that the magnetic moment ($\mu_m$) of each magnetic dipole makes an angle $\theta$ with the direction of the external magnetic field ($\vec{B}$). So *the component of the magnetic moment of each dipole in the direction B is* $\mu_m \cos\theta$.

$\therefore$ The **magnetic moment of $dn$ number of dipoles** is $\mu_m \cos\theta\, dn$.

By symmetry, the sum of components of the magnetic moment at right angles to the field is zero. Thus, the total magnetic moment per unit volume of the substance i.e. **the intensity of magnetisation** $M$ of the material is given by

$$M = \int_0^{\pi} \mu_m \cos\theta\, dn = \int_0^{\pi} \mu_m \cos\theta A\, e^{q\cos\theta} \sin\theta\, d\theta$$

[Putting the value of $dn$ from equation (6.7.2.3)]

$$= A\mu_m \int_0^{\pi} e^{q\cos\theta} \sin\theta \cos\theta\, d\theta \qquad \cdots(6.7.2.6)$$

Putting $x = \cos\theta \quad \therefore \quad dx = -\sin\theta\, d\theta$

Again, when $\theta \to 0$, $x \to 1$ and $\theta \to \pi$, then $x \to -1$

Now, the equation (6.7.2.6) can be written as

$$M = -A\mu_m \int_1^{-1} x e^{qx} dx$$

$$= -A\mu_m\left[e^{q}\left(\frac{1}{q} - \frac{1}{q^2}\right) + e^{-q}\left(\frac{1}{q} + \frac{1}{q^2}\right)\right] \qquad \cdots(6.7.2.7)$$

$$= N\mu_m\left(\coth q - \frac{1}{q}\right) \quad \left[\because \quad N = A\left[\frac{e^{q}}{q} - \frac{e^{-q}}{q}\right] \text{ using equation 6.7.2.5}\right]$$

$$\cdots(6.7.2.8)$$

$\therefore$ $\boxed{M = M_s\left[\coth q - \frac{1}{q}\right]}$

where $M_S = N\mu_m$ is the **saturation value of the intensity of magnetisation or saturation magnetisation.** This saturation state occurs when *all the magnetic dipoles get aligned in the direction of magnetic field* $\vec{B}$.

The **function** $(\coth q - \frac{1}{q})$ is called the **Langevin function** and is denoted by $L(q)$.

So, the **intensity of magnetisation of the paramagnetic material** is obtained from equation (6.7.2.8) as,

$$\cdots(6.7.2.9)$$

$\boxed{M = M_s L(q)}$

where $M_s = N\mu_m$.

The variation of $L(q)\left(=\frac{M}{M_s}\right)$ with $q\left(=\frac{\mu_m B}{kT}\right)$ is shown in Fig. 6.

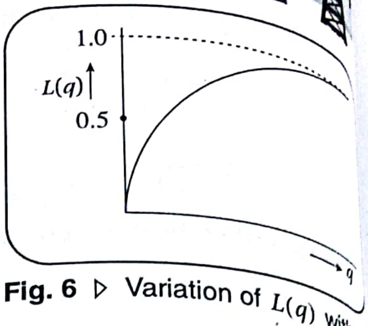



**Fig. 6** ▷ Variation of $L(q)$ with $q$

From the figure, the following *two special cases may be occured.*

**Case 1** **When the temperature ($T$) is high and magnetic field is weak** (i.e. $q$ is small); **Curie's law :**

When $q$ is small, then

$$L(q) = \left(\coth q - \frac{1}{q}\right) \approx \frac{q}{3} \quad \left[\because \text{ for small value of } q,\ \coth q = \frac{1}{q} + \frac{q}{3} + \frac{q^2}{45} + \cdots \approx \frac{1}{q} + \frac{q}{3}\right]$$

Thus, $$M = M_s L(q) = \frac{N\mu_m q}{3}$$

Now by putting the values of $q = \frac{\mu_m B}{kT}$, we get the intensity of magnetisation of a paramagnetic material,

$$\boxed{M = \frac{N\mu_m^2 B}{3kT}} \quad \cdots(6.7.2.10a)$$

Now, by putting $\vec{B} = \mu_0 \vec{H}$[3], we can write the above equation in vector form as

$$\boxed{\vec{M} = \frac{N\mu_m^2 \mu_0}{3kT}\vec{H}} \quad \cdots(6.7.2.10b)$$

This equation indicates :

❶ *The intensity of magnetisation* $(\vec{M})$ *of a paramagnetic material is proportional to applied magnetic field* $(\vec{B})$

i.e., $\vec{M} \propto \vec{H}$

❷ *The paramagnetic substance acquires* **magnetisation $(\vec{M})$ in the direction of applied magnetic field $(\vec{B})$.**

**Susceptibility:** The **susceptibility of paramagnetic material at its high temperature** (or in a weak magnetic field) is

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

or, $$\chi = \frac{N\mu_m^2 \mu_0 H}{3kT\,H}$$

---

❸ We know, magnetic induction $B = \mu_0(H + M)$. Since M is very small for paramagnetic materials, we can write $B = \mu_0 H$.

$$\chi = \frac{N\mu_m^2\mu_0}{3kT} \quad \cdots (6.7.2.11a)$$

or,

$$\chi = \frac{C}{T} \quad \cdots (6.7.2.11b)$$

or,

where $C = \frac{N\mu_m^2\mu_0}{3k}$ is known as **Curie constant.** $\cdots (6.7.2.12)$

The equation (6.7.2.11b) indicates that the **susceptibility of paramagnetic substance is always positive.**

The expression (6.7.2.11) shows that

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

This relation is known as **Curie's law of paramagnetism**. Thus **Curie's law states** that the **susceptibility of a paramagnetic substance varies inversely with its absolute temperature.**

*Since, paramagnetic* **susceptibilities decreases with temperature,** *all paramagnetic materials* **become diamagnetic at high enough temperature.**

**Case 2** *When the temperature is low and the field is very strong* (i.e., $q$ **is large**); **Saturation state of magnetisation :**

For large value of $q$, $\coth q \to 1$

Under this condition Langevin's function,

$$L(q) = \left(\coth q - \frac{1}{q}\right) \to 1 \text{ and } M \to M_s$$

This indicates intensity of magnetisation gets its maximum (saturation) value $M_s$. This state is called **saturation state** [Fig. 6].

The saturation state occurs due to the fact that *at low temperature the thermal motions of the atoms of paramagnetic material are small and so all the magnetic dipoles are aligned in the direction of external strong magnetic field.*

Thus *at low temperature and in very strong magnetic field,* **paramagnetic substance acquires its saturation state.**

## 6.7.3 Failure of Langevin's Theory of Paramagnetism

In Langevin's theory of paramagnetism, it is assumed that the separations of magnetic dipoles *are sufficiently far apart* and *their mutual interactions are negligibly small.* So this theory **cannot be applicable for the substances those have large mutual inteactions among their magnetic dipoles**. This theory is also **failed to explain the complicated temperature dependency of susceptibility** of several paramagnetic substances. To remove this failures, **Weiss** had modified Langevin's theory of paramagnetism *with his molecular field theory.*

### 6.7.4 Curie-Weiss Law (or Weiss Molecular Field Theory)

In Langevin's theory of paramagnetism, the mutual interaction between the atomic magnetic dipoles is considered as very negligible. In order to explain the complicated temperature dependence of susceptibility of paramagnetic materials, **Weiss assumed** that **an internal molecular magnetising field** ($H_m$) **is generated** in a paramagnetic material **due to mutual interaction** among the atomic magnetic dipoles.

This internal molecular field ($H_m$) is proportional to the intensity of magnetisation ($M$)

i.e. $H_m \propto M$

or, $H_m = \lambda M$ ...(6.7.4.1)

where $\lambda$ is molecular field coefficient or **Weiss constant.**

Therefore, the net effective field ($H_n$) is the sum of external magnetic field ($H$) and internal molecular field ($H_m$) within the magnetic substance and is expressed as,

$$H_n = H + H_m$$

$$= H + \lambda M \qquad \text{...(6.7.4.2)}$$

From Langevin's theory, the **intensity of magnetisation** ($M$) of a paramagnetic material with $N$ number of dipoles per unit volume **at high temperature** is

$$\vec{M} = \frac{N\mu_m^2\mu_0}{3kT}\vec{H}_n \quad \text{[from equation (6.7.2.10b)]}$$

or, $$M = \frac{N\mu_m^2\mu_0(H+\lambda M)}{3kT} \quad \text{or,} \quad M\left[1 - \frac{N\mu_m^2\mu_0\lambda}{3kT}\right] = \frac{N\mu_m^2\mu_0 H}{3kT}$$

or, $$M = \frac{N\mu_m^2\mu_0 H}{3kT - N\mu_m^2\mu_0\lambda}$$

Hence, the **magnetic susceptibility** of a paramagnetic material,

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

or, $$\chi = \frac{N\mu_m^2\mu_0}{3kT - N\mu_m^2\mu_0\lambda}$$

or, $$\chi = \frac{N\mu_m^2\mu_0/3k}{T - \left(\frac{N\mu_m^2\mu_0\lambda}{3k}\right)}$$

or, $$\boldsymbol{\chi = \frac{C}{T-\theta}} \qquad \text{...(6.7.4.3)}$$

where $C = \frac{N\mu_m^2\mu_0}{3k}$ = **Curie constant** and $\theta = \frac{N\mu_m^2\mu_0\lambda}{3k}$ = **paramagnetic Curie point** or **Curie temperature.**

This relation [equation (6.7.4.3)] is called the **Curie-Weiss law.**

## 6.7.5 Physical Interpretation of Curie-Weiss Law

If the **absolute temperature** $(T)$ of the paramagnetic substance is **below the Curie temperature** $(\theta)$, the **susceptibility** of the paramagnetic material **becomes negative.** *Thus the paramagnetic materials* **would behave like diamagnetic substance below the Curie temperature** (i.e. for $T < \theta$)

Hence, *the Curie-Wiess law is applicable for a paramagnetic substance, only when its temperature is above the Curie temperature* i.e., for $T > \theta$. For most of the paramagnetic materials, Curie temperature is quite low and so a situation for which $T < \theta$ is rare.

**Paramagnetic Curie temperature: The temperature below which a paramagnetic substance would behave like a diamagnetic substance is called paramagnetic Curie temperature.**

**PROBLEM 1** **The susceptibility of a paramagnetic material at 330 K is $3.6 \times 10^{-4}$. Calculate the temperature of the material at which its susceptibility is $1.8 \times 10^{-4}$.**

**Solution** From Curie law, we get $\frac{\chi_1}{\chi_2} = \frac{T_2}{T_1}$

Here $\chi_1 = 3.6 \times 10^{-4}$, $T_1 = 330\text{K}$, $\chi_2 = 1.8 \times 10^{-4}$

$$\therefore \quad T_2 = \frac{\chi_1}{\chi_2}T_1 = \frac{3.6 \times 10^{-4}}{1.8 \times 10^{-4}} \times 330\text{K} = 660\text{K}$$

$\therefore$ The temperature of the material is 660K.

**PROBLEM 2** **The magnetic moment per molecule of a paramagnetic material is 2 Bohr magneton. If the molecular weight and density of this material are 165.5 kg and 4210 kg/m$^3$ respectively at 27°C temperature find (i) the number of molecules or dipoles per unit volume, (ii) the magnetic moment of each molecule, (iii) susceptibility and (iv) intensity of magnetisation produced in it due to a magnetic field of $3 \times 10^5 \text{A} \cdot \text{m}^{-1}$. The permeability of free space is $4\pi \times 10^{-7}\ \text{H} \cdot \text{m}^{-1}$.**

**Solution** Here, the density of the material, $d = 4210\ \text{kg/m}^3$

molecular weight, $M_0 = 165.5$ kg

Temperature of the material, $T = (27 + 273)\text{K} = 300\text{K}$

**i** The number of molecules (or dipoles) per unit volume,

$$N = \frac{\text{total weight per unit volume}}{\text{molecular weight}}$$

$$= \frac{\text{density of the material} \times \text{Avogadro's number}}{\text{molecular weight}}$$

$$= \frac{4210 \times 6.02 \times 10^{23}}{165.5} = 1.53 \times 10^{25} \text{ per m}^3$$

**ii** The magnetic moment of each molecule

$\mu_m = 2\mu_B$

[2 comes before $\mu_B$ as the magnetic moment per molecule is 2 Bohr magneton]

$$= 2\frac{eh}{4\pi m} = 2\left(\frac{1.6 \times 10^{-19} \times 6.6 \times 10^{-34}}{4 \times 3.14 \times 9.1 \times 10^{-31}}\right) = 2 \times 9.24 \times 10^{-24}$$

$$= 18.48 \times 10^{-24} \text{ A} \cdot \text{m}^2$$

**iii** Susceptibility

$$\chi = \frac{N\mu_m^2\mu_0}{3kT} = \frac{(1.53 \times 10^{25})(18.48 \times 10^{-24})^2(4\pi \times 10^{-7})}{3(1.38 \times 10^{-23})(300)}$$

$$= 5.29 \times 10^{-7}$$

**iv** Intensity of magnetisation

$M = \chi H$, where $H = 3 \times 10^5 \text{ A} \cdot \text{m}^{-1}$

$\therefore \quad M = 5.29 \times 10^{-7} \times 3 \times 10^5$

$= 0.1587 \text{ A} \cdot \text{m}^{-1}$

**PROBLEM 3** **If the number of atoms per $m^3$ of a paramagnetic substance is $5 \times 10^{25}$. Find (i) the Curie constant and (ii) the susceptibility of the material at room temperature considering the magnetic moment for each atom is 1 Bohr magneton. The permittivity of free space $\mu_0 = 4\pi \times 10^{-7}$ H/m.**

**Solution** We know, the susceptibility of a paramagnetic material, $\chi = \frac{C}{T}$

where, $C$ = Curie constant $= \frac{N\mu_m^2\mu_0}{3k}$

Now, $N$ = number of atoms per $\text{m}^3 = 5 \times 10^{25}$

$\mu_m$ = induced dipole moment

$= 1 \times \mu_B = 9.24 \times 10^{-24} \text{ A} \cdot \text{m}^2$

**i** Curie constant,

$$C = \frac{N\mu_m^2\mu_0}{3k} = \frac{5 \times 10^{25}(9.24 \times 10^{-24})^2(4\pi \times 10^{-27})}{3 \times (1.38 \times 10^{-23})}$$

$$= 1295 \times 10^{-27} \text{ K}$$

**ii** Susceptibility,

$$\therefore \quad \chi = \frac{C}{T} = \frac{1295}{300} \times 10^{-27} = 4.3 \times 10^{-27}$$

## 6.8 FERROMAGNETIC MATERIALS

**The substances which when placed in a magnetic field are strongly magnetised in the direction of applied magnetic field are called ferromagnetic materials.**

*Examples:* Iron (Fe), cobalt (Co), nickel (Ni) and their alloys.

*The susceptibility of a ferromagnetic substance is not a constant but a function of applied magnetising force H as well as of its absolute temperature* ($T$). But the susceptibility of such materials is positive and very large. The susceptibility of this material decreases with temperature and about a certain temperature the material loses its ferromagnetic character and behaves as a paramagnetic material. This temperature is called **ferromagnetic Curie temperature** ($\theta_f$).

Thus, *the ferromagnetic materials* **behave as a paramagnetic material above the ferromagnetic Curie temperature** and **behave as ferromagnetic materials below the temperature** ($\theta_f$).

Ferromagnetic Curie temperature: **The temperature above which the ferromagnetic material behaves as a paramagnetic material and below which behaves as ferromagnetic material is called ferromagnetic Curie temperature.**

### 6.8.1 Explanation of Ferromagnetism on the Basis of Domain Theory

The atom of a ferromagnetic materials also **possesses nonzero magnetic moment** due to **spin motion of the unpaired electrons** of the atom. Weiss postulated that the atomic dipole of an atom strongly interacts to the neighbouring atom by a **quantum mechanical interaction called exchange interaction**. Due to this exchange interaction, a large number of atomic dipoles spontaneously align themselves in the same direction over a small volume of the material. Hence each domain is magnetised to the saturation stage. Thus, **the ferromagnetic materials exhibit spontaneous magnetisation, even in the absence of an external field**. The small volumes of uniform magnetisation of a ferromagnetic material **are called domains.** Thus, **the domain is a small volume of the material that consists of a large number of atomic dipoles held together by forces of exchange interaction.** Every *domain* is **magnetically saturated** *due to the alignment of all the magnetic dipoles in the same* direction. The direction of magnetisation in different domains is different.

Although domains are extremely small in size ($\approx 10^{-8}$ to $10^{-12}$ cubic metre), yet each domain contains a large number of atomic magnetic dipoles. The boundary region between two domains is called a **domain wall**. The magnetic domains within the material are so arranged that the direction of magnetisation varies from domain to domain and form closed chains such that the magnetic effect of one another is nullified [Fig. 7a]. The sample is then said to be in a **demagnetised state.**

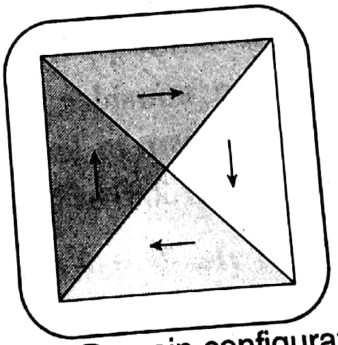


**Fig. 7a** ▷ Domain configuration of a ferromagnetic substance

**Magnetisation:** When an external magnetic field is applied to the ferromagnetic material, the substance becomes magnetized. This **magnetisation is observed** due to (i) the **displacement of boundaries of domains** [Fig. 7b], when the *applied field is* **weak** and (ii) the **rotation of domains in the direction of magnetising field,** when the *applied field is strong.*

The *transition metals, like Fe, Co and Ni exhibit magnetisation even when the magnetising field is removed.*

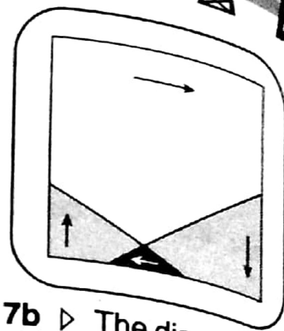


Fig. 7b ▷ The displacement of the boundaries of the domain

### 6.8.1.1 Spin Alignment

In ferromagnetic materials, the **magnetic dipoles are arranged parallel to each other.** The spin arrangement of the unpaired electrons of the atom is shown in Fig. 8.

This is observed due to the *existence of a strong exchange interaction between the atomic magnetic dipoles.*

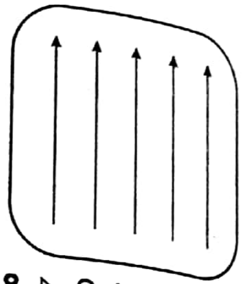


Fig. 8 ▷ Spin alignment of ferromagnetic materials

## 6.8.2 Spontaneous Magnetisation and Weiss Theory (or Molecular Field Theory on Ferromagnetism)

When magnetising field is removed from the ferromagnetic substance, it also exhibits magnetisation. Pierre **Weiss** in 1907, **postulated** the existence of an **internal molecular field ($H_i$) to explain the spontaneous magnetisation of a ferromagnetic material.** This internal molecular field (or Weiss molecular field) is responsible for the alignment of magnetic dipoles even when the magnetising field is removed.

Weiss suggested that the internal molecular field ($H_i$) **is proportional** to the **magnetisation** ($M$) of the material,

i.e. $$H_i \propto M$$

or, $$H_i = \gamma M \quad \cdots (6.8.2.1)$$

where $\gamma$ is the **molecular field constant** or **Weiss constant**. Thus, the net magnetic field $H_n$ acting on magnetic dipole is

$$H_n = (H + H_i) = H + \gamma M \quad \cdots (6.8.2.2)$$

where $H$ is the applied external magnetic field acting on the ferromagnetic material.

If we consider, the Weiss internal field and then apply Langevin's theory of paramagnetism to ferromagnetism, we can write the expression for magnetisation from equation (6.7.2.9) as

$$M = N\mu_m L(q)$$

or, $$M = M_s L(q) \quad \cdots (6.8.2.3)$$

where $M_s = N\mu_m$ **is the saturation value of intensity of magnetisation,** $N$ is the number of spins per unit volume of the ferromagnetic material, $\mu_m$ is magnetic moment of each magnetic dipole and $L(q) = (\coth q - \frac{1}{q})$ which is called **Langevin function** with

$$q = \frac{\mu_m B}{kT}$$

**At very high temperature** $(T > \theta_f)$ and for a *weak magnetic field* (i.e. $q$ is small), $L(q) \approx \frac{q}{3}$. Thus the magnetisation of the specimen is given from equation (6.8.2.3) by puting $B = \mu_0 H_n$

$$M = N\mu_m \frac{q}{3} = \frac{N\mu_m^2 \mu_0}{3kT} H_n$$

or, $$M = N\frac{\mu_m}{3}\left[\frac{\mu_m \mu_0 (H + VM)}{kT}\right]$$

or, $$M = \frac{N\mu_m^2 \mu_0 (H + \gamma M)}{3kT}$$

or, $$M\left[1 - \frac{\mu_0 N \mu_m^2 \gamma}{3kT}\right] = \frac{\mu_0 N \mu_m^2 H}{3kT} \qquad \cdots(6.8.2.4)$$

Considering $\boldsymbol{C = \frac{\mu_0 N \mu_m^2}{3k}}$ = **Curie constant** and $\boldsymbol{\theta_f = \frac{\mu_0 N \mu_m^2 \gamma}{3k}}$ = **Curie temperature of ferromagnetic material**, the equation (6.8.2.4) becomes

$$M\left[1 - \frac{\theta_f}{T}\right] = C\frac{H}{\theta_f}$$

or, $$\boldsymbol{M = \frac{CH}{T - \theta_f}} \qquad \cdots(6.8.2.5)$$

Hence, the magnetic susceptibility of a ferromagnetic material

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

or, $$\boldsymbol{\chi = \frac{C}{T - \theta_f}} \qquad \cdots(6.8.2.6)$$

*Thus, the susceptibility of a ferromagnetic substance above its Curie temperature is inversely proportional to the excess temperature above the Curie temperature.* It is called **Curie-Weiss law of ferromagnetic material**. This relation is identical in form with the Curie-Weiss law of paramagnetism.

When $\boldsymbol{T > \theta_f}$ (Curie temperature), the magnetic susceptibility decreases with increase in temperature. In this condition, a **ferromagnetic substance slowly loses its ferromagnetic character as the temperature is reduced**. At *Curie temperature, the susceptibility is so small that the* **ferromagnetic substance becomes paramagnetic**. This is because *the thermal agitation of ferromagnetic material above the Curie temperature is so* *great that the internal field is not sufficient to maintain alignment of magnetic dipole moments.*

**Special Note**

A plot of reciprocal of magnetic susceptibility ($\chi$) with temperature ($T \geq \theta_f$) is a straight line [Fig. 9a]. We can calculate the magnetic moments of various dipoles by measuring $\chi$ at different temperatures.

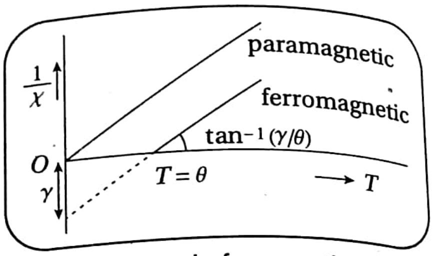



**Fig. 9a** ▷ Reciprocal of magnetic susceptibility as a function of temperature for ferromagnetic and paramagnetic materials for $T > \theta_f$

On the basis of the above relation (6.8.2.13), we can also make the following two conclusions—

1. If $T = \theta_f$ (Curie temperature), the **magnetic susceptibility** ($\chi$) becomes infinite. This shows that the existence of nonvanishing value of $M$, even though the magnetising field $H = 0$. *The existence of magnetisation in a ferromagnetic material even in the absence of magnetic field is called* **spontaneous magnetisation.**

2. If $T < \theta_f$, $\chi = -ve$. In this situation, the Curie-Weiss law is not applicable. Because **ferromagnetic substance then gets magnetised** even in the absence of external magnetising field.

Thus, ferromagnetic curie temperature is **the temperature above which the ferromagnetic material behaves as a paramagnetic material and below which behaves as ferromagnetic material is called ferromagnetic Curie temperature.**

**PROBLEM 1** **The saturation value of intensity of magnetisation of iron is $1.75 \times 10^6$ ampere/meter. Each iron atom has a magnetic moment of two Bohr magnetons. If the Curie temperature of iron is 1043 kg, find the value of (i) the Weiss constant and (ii) the Curie constant.**

**Solution** Here,

$M_s$ = saturation magnetisation of iron = $1.75 \times 10^6$ A/m

$\mu_0$ = permeability of free space = $4\pi \times 10^{-7}$ H/m

$k$ = Boltzmann constant = $1.38 \times 10^{-23}$ J/K

$\mu_m$ = magnetic moment for each magnetic dipole

= 2 Bohr magnetons = $2 \times 9.27 \times 10^{-24}$ A · m$^2$

$\theta_f$ = Curie temperature of ferromagnetic materials

= 1043 K

$N$ = total number of atoms (i.e. spin motion) per unit volume $= \dfrac{M_s}{\mu_m}$

(i) We know, Curie temperature

$$\theta_f = \frac{\mu_0 N \mu_m^2 \gamma}{3k}$$

or, $$\gamma = \frac{3k\theta_f}{\mu_0 N \mu_m^2} = \frac{3k\theta_f}{\mu_0 M_s \mu_m}$$

$$= \frac{3(1.38 \times 10^{-23}) \times 1043}{(4\pi \times 10^{-7}) \times (1.75 \times 10^6) \times (2 \times 9.27 \times 10^{-24})}$$

$$= 1059$$

∴ The Weiss constant, $\gamma = 1059$.

(ii) Curie constant

$$C = \frac{N\mu_0\mu_m^2}{3k} = \frac{M_s\mu_0\mu_m}{3k} \quad [\because M_s = N\mu_m]$$

$$= \frac{(1.75 \times 10^6) \times (4\pi \times 10^{-7}) \times (2 \times 9.27 \times 10^{-24})}{3 \times (1.38 \times 10^{-23})}$$

$$= 9848\text{K}$$

**PROBLEM 2** **A ferromagnetic substance has a body centered cubic structure with its edge of length $2.68 \times 10^{-10}$ Å. The saturation value of intensity of magnetisation of it is $1.62 \times 10^6$ A/m. Calculate its average number of Bohr magnetons contributing to the saturation magnetisation per atom.**

**Solution** For a body centered cubic cell there are 2 atoms per cubic cell.

The volume of each cubic cell $(V) = (2.68 \times 10^{-10})^3 \text{ m}^3$

∴ The total number of atoms per unit volume

$$N = \frac{2}{V} = \frac{2}{(2.68 \times 10^{-10})^3} \text{ m}^{-3}$$

$$= 1.03 \times 10^{29} \text{ m}^{-3}$$

Again, the saturation magnetisation

$$M_s = 1.75 \times 10^6 \text{ ampere/metre}$$

∴ The dipole moment of each atom

$$\mu_m = \frac{M_s}{N} = \frac{1.75 \times 10^6}{1.03 \times 10^{29}} \text{ Bohr magnetons}$$

$$= (1.69 \times 10^{-23}) \times 9.27 \times 10^{-24} \text{ A} \cdot \text{m}^2$$

$$= 15.66 \times 10^{-47} \text{ A} \cdot \text{m}^2$$

### 6.8.2.1 Temperature dependence of spontaneous magnetisation

The temperature dependence of spontaneous magnetisation is shown in Fig. 9b.

When the temperature $T = 0$, $\frac{M}{M_s} = 1$. This implies **spontaneous magnetisation** $(M)$ is **maximum.** Here, $M_s$ indicates *saturation magnetisation.*

When $T = \theta_f$ (Curie temperature), $\frac{M}{M_s} = 0$. This implies spontaneous magnetisation **vanishes.**

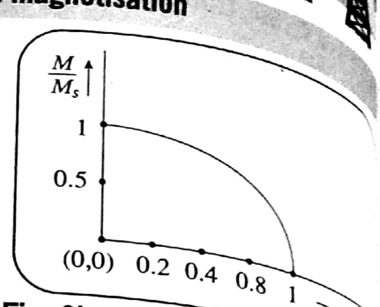



**Fig. 9b** ▷ The variation of the relative spontaneous magnetisation as a function of temperature

Thus, **when the temperature of a ferromagnetic material is increased from 0K, the spontaneous magnetisation decreases** and **reaches zero value at Curie temperature.**

## 6.8.3 Hysteresis: Nonlinear Relationship between $\vec{B}$ and $\vec{H}$

**Hysteresis is the phenomenon of lagging of magnetic induction (*B*)** [or intensity of magnetisation $(M)$] **behind the magnetising field (*H*) of a ferromagnetic material when the specimen is at a temperature below its critical temperature.** It is a typical property of a ferromagnetic material. A specimen of ferromagnetic material can be magnetised by using it as the core of a solenoid and passing a current through the solenoid. When the current is gradually increased, the magnetising field also increases. Now we can explain *B*-*H* curve as follows.

Suppose a piece of ferromagnetic material (say iron) is magnetised slowly. As magnetising field (*H*) **is increased** (due to increase in current), at first the **magnetic induction *B* begins to increase** slowly, then more rapidly. At last the magnetic induction gets a saturated value $B_s$ along the path *OA* and becoming independent of *H* [Fig. 10]. This curve is known as **initial magnetisation curve**. Here $H_m$ represents the corresponding value of the magnetising field for which the magnetic induction $(B)$ reaches the saturated value $(B_s)$.

If ***H* is now decreased** slowly, the magnetic induction **(*B*) decreases** but does not follow the initial magnetisation curve and **lags behind magnetising field** $(H)$. *When H is decreased from $H_m$ to zero,* the magnetic induction does not become zero but has **a finite value $(B_r)$ at *C***. Thus, *OC* represents the **retentivity of the material under study**

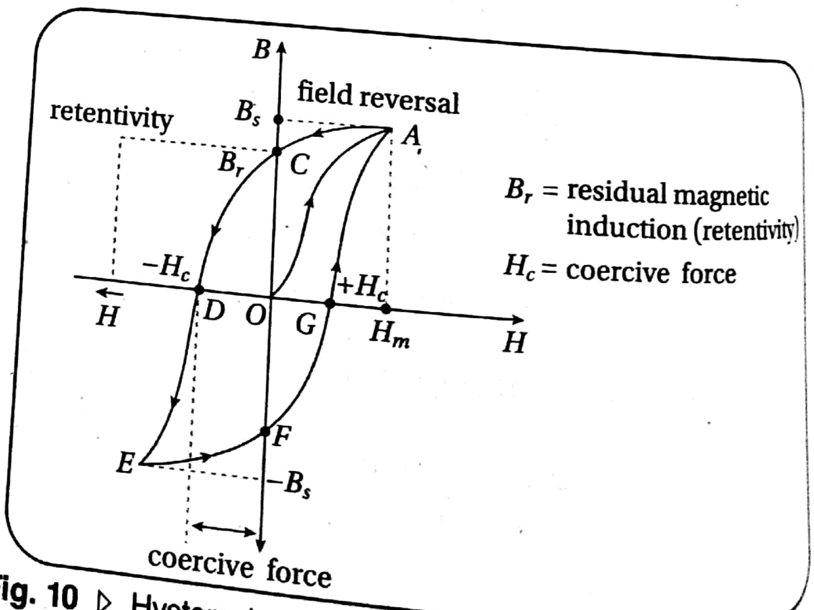



**Fig. 10** ▷ Hysteresis curve (*B*-*N* curve) of ferrimagnetic materials

(as residual magnetism is defined as the *magnitude of magnetic induction of the magnetic material*, even when the magnetising field is reduced to zero). This indicates that **ferromagnetic material remains magnetised** even in the **absence of an external magnetising field ($H$). The existence of $B_r$** is one of the factors which determine whether a material can be used as a permanent magnet or not.

*If now* the direction of magnetising field ($H$) **is reversed and increased in negative direction** (by reversing the current), magnetic induction **$B$ further decreases and then becomes zero at $D$** for the magnetising field $H = -H_c$. This value of reverse magnetising field $OD$ (i.e. $-H_c$) for which the **residual magnetism becomes zero** is called **coercivity of the substance.**

*If the magnetising field* (**$H$**) *is further increased in negative direction, the magnetic induction* ($B$) *increases and reaches a saturated value in reverse direction (point $E$).*

*On reversing and increasing the field* ($H$) again, the magnetic induction ($B$) *follows the curve EFGA* similar to *ACDE*, yielding a negative retentivity ($-B_r$) and a positive coercivity $+H_c$. As a result, a closed curve *ACDEFGA* is obtained for a complete cycle of magnetisation. This *closed B-H curve is known as hysteresis loop.*

**Special Note**

**Coercivity:** The value of **reverse magnetising field** for which the **residual magnetism becomes zero** is called **coercivity** of the substance.

**Retentivity:** The value of the magnetic induction which remains even when the magnetising field in the material is reduced to zero is called retentivity of the substance.

**Hysteresis loop:** The graph showing how magnetic induction ($B$) increases with magnetising field ($H$) from zero to a maximum in one direction and then back through zero to a maximum in the opposite direction and finally returns back again zero to the first maximum is called a hysteresis loop.

## 6.8.4 Energy Loss Due to Hysteresis

*During a complete cycle of magnetisation,* a **definite amount energy is spent in aligning the domains of the specimen in the direction of applied magnetic field.** But when a reverse magnetic field is applied on the material (i.e., during demagnetisation process), the absorbed energy is not completely recovered. The rest energy in the material is lost in the form of heat energy. This loss of energy during the cycle of magnetisation of the specimen is called hysteresis loss.

**Hysteresis loss: The energy loss that occurs during the magnetisation and demagnetisation processes of a ferromagnetic body through a complete cycle of magnetisation is called Hysteresis loss.** *This loss of energy is represented by the area enclosed by the hysteresis loop.*

**Hysteresis loss due to B-H curve:** We know the magnetic induction ($B$) and the intensity of magnetisation ($M$) is related by

$$B = \mu_0(H+M) \quad \therefore \quad dB = \mu_0(dH + dM) \quad \text{or,} \quad dB = \mu_0 dH + \mu_0 dM$$

Multiplying both sides by $H$ and integrating over a complete cycle, we get

$$\oint H\,dB = \mu_0 \oint H\,dH + \mu_0 \oint H\,dM \qquad \cdots (6.8.4.1)$$

Now, the value of $\oint H\,dH = 0$, because the **curve between $H$ against $H$ is a straight line and will not enclose any area** for a complete cycle of magnetisation. So, the equation 6.8.4.1 becomes

$$\mu_0 \oint H\,dM = \oint H\,dB \qquad \cdots (6.8.4.2)$$

But $\mu_0 \oint H\,dM$ is the *loss of energy per unit volume* per cycle of hysteresis and $\oint H dB$ is the area of $B$-$H$ hysteresis loop.

***Thus, the loss of energy per unit volume per cycle of hysteresis***

$$= \oint H dB = \textit{area of } B\text{-}H \textit{ curve.}$$

### 6.8.5 Importance of Hysteresis Curve

The hysteresis curve of a ferromagnetic material provides us very useful **information about the properties of a material.** It helps us to select a particular material for a particular technical purpose. They are as follows :

1. **The shape and size of the hysteresis curve** of a ferromagnetic material is a characteristic of the magnetic material. It **provides information regarding retentivity, coercivity, permeability,** susceptibility and energy loss per cycle of magnetisation.
2. It helps **to select a material** that should be used **for making permanent magnet, electromagnet or core of transformers and dynamos.**

Now we will discuss what type of materials are suitable for permanent magnets or electromagnets etc.

**For Permanent magnets:** The material for the permanent magnet should have the following properties:

1. **High coercivity** (so that a greater demagnetising force is required to destroy the residual magnetic induction).
2. **Fairly large value of retentivity.**
3. **Large hysteresis loss** (so that the energy stored in the material may be large).

All these essential properties are **present in steel. So steel is the best suitable material to make a permanent magnet.** (Materials suitable for making permanent magnets are cobalt steel, chromium steel and tungsten steel).

**For electromagnet or core of transformers or dynamos:** The material for the electromagnet should have the following properties:

1. **High initial permeability** (so that the material can acquire a high value of magnetic induction even for low magnetising field).
2. **The area of hysteresis loop** of the material **should be small** (so that the dissipation of energy is small). This will avoid heating.
3. **High susceptibility** for low field.
4. **Small hysteresis loss.**

All these essential properties are **present in soft iron.** The $B$-$H$ curve of soft iron is steep and small in area in comparison to steel. This **indicates soft iron can be magnetised quickly.**

As soft iron has **high susceptibility (i.e. very small coercivity)** and very small area of hysteresis loop, it is an **ideal material for making electromagnets**.

Further in soft iron, the **hysteresis loss** is very small **to reduce the dissipation of energy and it has high specific resistance to reduce the eddy current losses**. So, *soft iron is suitable material for transformer cores, telephone diaphragm and chokes.*

**Special Note**

*The area of hysteresis loop is large for steel.* But this loss is not supposed to be as a defect. Because, a permanent magnet has never to be taken through a cycle of magnetisation.

## 6.8.6 Properties of Ferromagnetic Substances

Their properties are similar to the properties of paramagnetic substances, but the effect is much more intense. Their properties are as below:

1. It has **permanent magnetic dipoles.**
2. The **relative permeability** is of the order **of few thousands.**
3. It is **strongly attracted by a magnet.**
4. The magnetic **susceptibility decreases with increase in temperature**. It has a particular characteristic temperature (ferromagnetic Curie temperature) below which it behaves as ferromagnetic material and above which it behave as a paramagnetic substance.
5. It shows **positive but high magnetic susceptibility** (approximately in the order of $10^6$).
6. When a rod of ferromagnetic material is **suspended in a magnetic field**, it quickly **aligns itself in the direction of external field**. (i.e. behaves like a paramagnetic substance).
7. If a ferromagnetic substance is placed **in a nonuniform field, it is attracted towards the stronger field** (i.e. behaves like a paramagnetic substance).
8. **Spin alignment** of adjacent dipoles is **parallel** to each other along the same direction.
9. They **exhibit hysteresis.**
10. They consist a number of **small regions which are spontaneously magnetised.** These small regions are called **domains.**

**PROBLEM 1**

**The mass of iron core of a transformer is 150 kg. The density of the iron is $6.2\times10^3$ kg/m$^3$ and specific heat 100 cal $\cdot$ kg$^{-1}$ $\cdot$ °C$^{-1}$, The energy loss of iron per cubic meter per cycle is $10^4$ joule when it is subjected to an alternating field of frequency 50 Hz. Find**

**i) the number of ac cycles per minute, ii) the area of *B-H* loop,**
**iii) the energy loss in the core per minute and**
**iv) the rise of temperature of the specimen per minute.**

**Solution**

i) The frequency of alternating field = 50 Hz = 50 cycles/second

$\therefore$ The number of ac cycles per minute = $50\times60$ = 3000 cycles/minute

The energy loss in the core per cubic meter per cycle $= 10^4$ J

**ii** $\therefore$ Area of $B$-$H$ loop $= 10^4\ \mathrm{J/m^3}$

**iii** The volume of the iron core

$$V = \frac{\text{mass of the iron core}}{\text{density of iron}} = \frac{150}{6.2 \times 10^3} = 24.19 \times 10^{-3}\ \mathrm{m^3}$$

$\therefore$ The energy loss i.e., heat generated in the entire core per minute

$= (\text{area } B\text{-}H \text{ loop}) \times (\text{volume of the core}) \times (\text{number of ac cycles per minute})$

$= 10^4 \times 24.19 \times 10^{-3} \times 3000\ \mathrm{J} = 72.57 \times 10^4\ \mathrm{J}$

$= \dfrac{72.57 \times 10^4}{4.2}\ \mathrm{cal} = 17.27 \times 10^4\ \mathrm{cal}$

**iv** Specific heat of iron, $s = 100\ \mathrm{cal \cdot kg^{-1} \cdot {}^\circ C^{-1}}$

Mass of iron core, $m = 150$ kg

If $\theta$ is the rise in temperature per minute of the iron core then,

$$ms\theta = 10.94 \times 10^4 \quad \text{or,} \quad 150 \times 100 \times \theta = 10.94 \times 10^4$$

$$\text{or,} \quad \theta = \frac{10.94}{150 \times 100} \times 10^4 = 7.29^\circ\mathrm{C}$$

**PROBLEM 2** **The hysteresis loop of a transformer has an area 2500 erg/cm³. Calculate the loss of energy per hour at 50 Hz frequency. Density of iron is 7.5 g · cm⁻³ and weight is 10 kg.** [Kan. U. 1995]

**Solution** The volume of iron $= \dfrac{\text{mass of iron}}{\text{density of iron}} = \dfrac{10 \times 10^3}{7.5}\ \mathrm{cm^3}$

The area of hysteresis loop of a transformer $= 2500\ \mathrm{erg/cm^3}$

So, the energy loss per unit volume per cycle $= 2500$ ergs

Thus the loss of energy per unit volume per hour

$= 2500 \times (50 \times 60 \times 60)$ ergs

Thus the total loss of energy per hour

$$= 2500 \times (50 \times 60 \times 60) \times \left(\frac{10 \times 10^3}{7.5}\right) \text{ ergs} = 6 \times 10^{11} \text{ ergs}$$

**PROBLEM 3** **The area of $B$-$H$ curve of a ferromagnetic material is 905.76 J/m³. Find the energy loss per second and hysteresis power loss when the specimen of volume $10^{-4}$ m³ is subjected to an alternating magnetic field of frequency 40 Hz.**

**Solution** Area of $B$-$H$ curve

$= 905.76\ \mathrm{J/m^3}$

$\therefore$ The loss of energy per cycle per m³ $= 905.76$ J

The volume of ferromagnetic material

$V = 10^{-4}\ \mathrm{m^3}$

The frequency of alternating field = 40 cycles/s

The total loss of energy per second throughout the material $= 905.76 \times (10^{-4}) \times 40$ J

∴ The hysteresis power loss = 3.62 W

**Special Note**

The different shapes of the lines of forces due to different magnetic substances in homogeneous magnetic field ($\vec{B}$) are shown in Fig. 11.

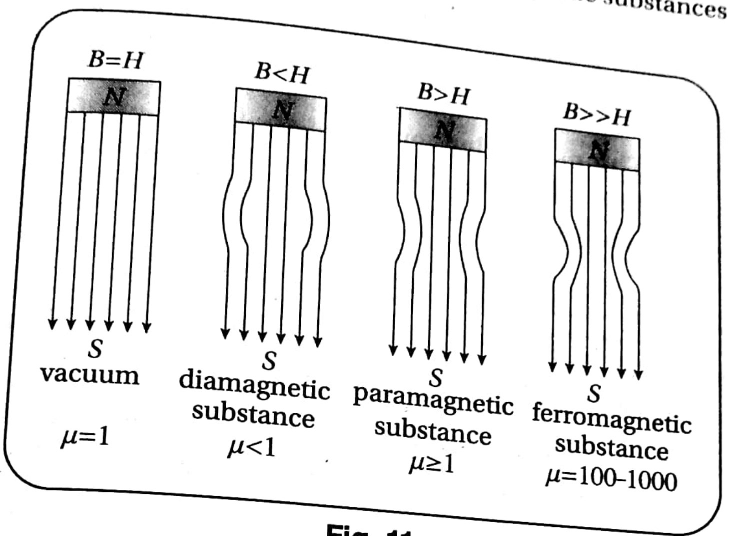



Fig. 11

## 6.9 ANTIFERROMAGNETIC MATERIALS

In ferromagnetic materials, the magnetic dipoles due to spin motion of the unpaired electrons of the atom are aligned parallel to each other along the same direction by the quantum mechanical exchange forces between the adjacent dipoles of it. But in certain materials in which the **distance between interacting atoms is small**, the exchange forces produce a **tendency for antiparallel** alignment of adjacent dipole of neighboring atoms so that the **net magnetisation** of the material **is zero**. This type of material is known as antiferromagnetic material.

**When the magnitudes of all the antiparallel aligned magnetic dipoles [Fig. 12] of a material are equal and the resultant magnetisation becomes zero, the material is called antiferromagnetic material or antiferromagnetics.**

*Examples:* MnO (manganese oxide), $Cr_2O_3$ (chromium oxide), FeO (ferous oxide) etc.

Such systems were first investigated theoretically by *Neel and Bitter.*

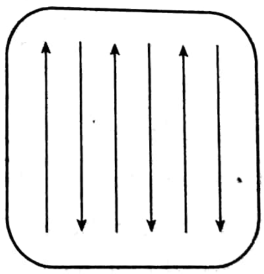


Fig. 12 ▷ Spin alignment of antiferromagnetic material

### 6.9.1 Temperature Dependence of Susceptibility

**With the increase of temperature of an antiferromagnetic material, the susceptibility of it increases and then reaches a maximum value at a particular temperature.** This temperature is called **Neel temperature** ($T_N$) of an antiferromagnetic material. The variation of susceptibility of an antiferromagnetic material with temperature is shown in Fig. 13. It shows that **above Neel temperature, the susceptibility of the material decreases with temperature. Above the Neel temperature, the susceptibility of the material** follows the equation

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

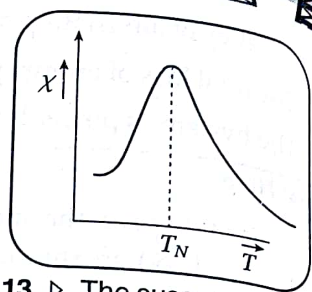



**Fig. 13** ▷ The susceptibility versus temperature curve for $MnF_2$

where $\theta$ is the **Curie temperature.**

**Neel temperature: The particular temperature for an antiferromagnetic material at which the susceptibility becomes maximum and after which its susceptibility decreases is called antiferromagnetic Neel temperature.**

### 6.9.2 Properties of Antiferromagnetic Substances

1. The exchange forces between the adjacent dipoles of this material produce a **tendency for antiparallel alignment of dipole.**
2. Since the adjacent dipoles with equal spin magnetic moments in antiferromagnetic are **aligned antiparallel** to each other, the **net magnetisation becomes zero.**
3. With the *increase of temperature, the susceptibility of it increases* and **at Neel temperature susceptibility reaches maximum.**
4. **Above the Neel temperature,** the **susceptibility decreases with temperature** following the equation

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

## 6.10 FERRITE OR FERRIMAGNETIC MATERIAL

**Ferrite is a special type of antiferromagnetic material in which antiparallel aligned dipoles [Fig. 14] with different magnitudes produce a large net magnetisation.** It possesses a **large magnetisation even for a small external** applied field.

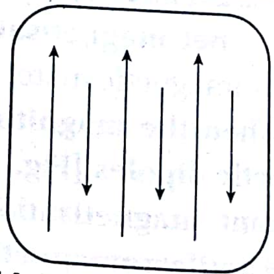


**Fig. 14** ▷ Spin alignment or dipole arrangements of ferrites or ferrimagnetic materials

**Temperature dependance:** The **magnetic moment** of ferrite **dissappears above** a particular temperature, called **Curie temperature. Above Curie temperature, ferrite behaves like a paramagnetic material** (due to random orientations of the individual magnetic moments by the thermal energy)

***Examples:*** The usual chemical formula for ferrite is $Me^{2+}Fe_2^{3+}O_4^{2-}$ where $Me^{2+}$ is a **divalent metal** like $Mn^{2+}$, $Fe^{2+}$, $Zn^{2+}$, $Ni^{2+}$, $Mg^{2+}$, $Co^{2+}$. Ferrites are composed of two or more sets of different transition metal ions.

**Manganese ferrite, nickel ferrite, cadmium ferrite** etc. are the common **examples of ferrites.**

### 6.10.1 Properties of Ferrimagnetic Substances

- The magnetic dipoles with different spin magnetic moments of the ferrites are aligned antiparallel to each other. So, they **have a large magnetisation** even for a small external magnetic field.
- They possess a **net magnetic** moment.
- They behave as paramagnetic and ferromagnetic materials respectively above and below Curie temperature.
- They have a **negligible electrical conductivity.**
- They have **low hysteresis loss.**
- They have **high magnetic permeability.**

### 6.10.2 Differences between Ferrites and Ferromagnetic Materials

- **Ferrites have** a very **low electrical conductivity** as compared to ferromagnetic materials.
- **Ferrites** have a **higher permeability and lower hysteresis loss** as compared to ferromagnets.

### 6.10.3 Uses of Ferrite Materials

There are several applications of ferrites due to their *low electrical conductivity, lower hysteresis loss and higher permeability*. Here are few important applications:

1. **Soft ferrites** are used in **transformer cores** and in **ac inductor cores.**

   **Reason :** In transformer cores or in ac inductor cores, the material goes through complete cycle of magnetisation continuously. The material therefore, must have a **low hysteresis loss** to have less dissipation of energy and hence a small heating of the material (otherwise the insulation of winding may break). The materials also should have a **high permeability** (to obtain a large flux density at low external field) and a low electrical conductivity (to reduce eddy current loss i.e. low eddy current loss). Manganese zinc ferrite and nickel zinc ferrite are the materials satisfly the above conditions. So these materials are used **in high frequency transformer cores,** in **ac inductor cores, in radio** and **communication devices.**

2. **Hard ferrites** [e.g. Barium ferrite and strontium ferrite] are more suitable to **make permanent magnets** that are used in loudspeakers and wiper motors.

   **Reason:** The essential requirements for a material for making a permanent magnet are high coercive force and high resistivity. The high coercive force gives the material an ability to be used where there are **strong demagnetising field.**

3. **Ferrites are used in digital memory devices in computers.**

   **Reason:** The hysteresis curve of a ferrimagnetic material is nearly in the form of a rectangle [Fig. 15].

   It is observed from the curve that the ferrite exhibits in any one of the saturated states of magnetic induction

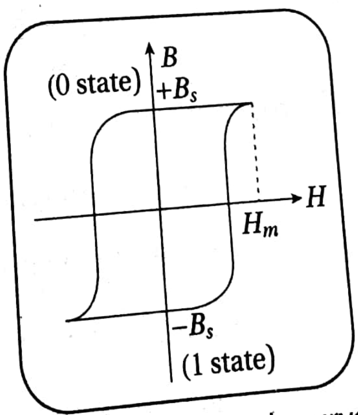



**Fig. 15** ▷ Hysteresis curve of a ferrimagnetic material

i.e. either $+B_s$ or $-B_s$. The above two states of ferrites are similar to that of binary digits 0 and 1.

The reversal of the external magnetic field can remagnetise instantaneously the material to the same strength as before in the reverse direction.

**Special Note**

**Soft magnetic material and hard magnetic material:**

**Soft magnetic material:** The material that can be easily magnetised even when placed in a weak magnetic field is called soft magnetic material. Some essential properties are mentioned below.

① It has **low coercivity** and **low retentivity**. ② It has **larger permeability**.
③ It has a **smaller hysteresis curve**. ④ It has **reversible domain wall movement**.

The soft magnetic materials are so used for making **electromagnets**.

**Hard magnetic material:** The material, (which is magnetised by a strong magnetic field) can retain its magnetisation even when the applied field is turned off, is called hard magnetic material. The hard magnetic material has some essential properties as mentioned below.

① It has **high coercivity and high retentivity**. ② It has **low permeability**.
③ It has a **large hysteresis curve**. ④ It has irreversible domain wall movement.

The hard magnetic materials are so used for making **permanent magnets**.

**ROBLEM**

**1 A rare earth element behaves like a ferromagnetic material below 16°C with 7.1 Bohr magneton per atom. If the atomic weight of the element is 157.26 and its density is $7.8 \times 10^3$ kg/m$^3$, calculate the saturation value of intensity of magnetisation.**

**lution** The density of the rare earth element, $\rho = 7800$ kg/m$^3$

e atomic weight of the element, $A = 157.26$

w, the total number of atoms per unit volume

$$N = \frac{\rho N_A}{A}, \quad \text{where } N_A = \text{Avogadro's number.}$$

stituting the values of $\rho$, $N_A$ and $A$, we get

$$N = \frac{7800 \times 6.023 \times 10^{23}}{157.26} = 298.836 \times 10^{26} \text{ atoms/m}^3$$

magnetic moment for each atom

$= 7.1$ Bohr magneton

The saturation value of intensity of magnetisation

$= 298.836 \times 10^{23} \times 7.1$ Bohr magneton

$= 298.836 \times 10^{23} \times 7.1 \times 9.27 \times 10^{-24}$ ampere/metre

$= 1966.849$ ampere/metre

*Special Note*

**Total number of atoms per unit volume :**

The number of atoms in $m$ gram of substance of atomic weight $A$ and volume $V$ is

$$n = \frac{mN_A}{A},\ N_A = \text{Avogadro's number}$$

$\therefore$ The number of atoms per unit volume

$$N = \frac{n}{V} = \frac{m}{V}\frac{N_A}{A} = \frac{\rho N_A}{A} \quad \text{where } \rho = \frac{m}{v}$$

# EXERCISE

## MULTIPLE CHOICE QUESTIONS

1. **Material which shows negative susceptibility is**
   Ⓐ paramagnetic Ⓑ diamagnetic Ⓒ ferrite **Ans. Ⓑ**
2. **Material which has no permanent dipoles is**
   Ⓐ ferromagnetic Ⓑ paramagnetic Ⓒ diamagnetic **Ans. Ⓒ**
3. **The magnetic dipole moment of a perfect diamagnetic material is**
   Ⓐ 0 Ⓑ −1 Ⓒ 1 **Ans. Ⓐ**
4. **The materials that are weakly repelled by magnets are**
   Ⓐ paramagnetic Ⓑ diamagnetic Ⓒ antiferromagnetic **Ans. Ⓑ**
5. **Relative permeablility ($\mu_r$) is related to the magnetic susceptibility ($\chi$) by**
   Ⓐ $\mu_r = \chi - 1$ Ⓑ $\mu_r = (\chi + 1)\mu_0$ Ⓒ $\mu_r = \frac{1-\chi}{\chi}$ **Ans. Ⓑ**
6. **Magnetic permeability ($\mu$), magnetic susceptibility ($\chi$) is realated as**
   Ⓐ $\mu = \mu_0(1+\chi)$ Ⓑ $\mu = \mu_0(1-\chi)$ Ⓒ $\mu = \frac{1-\chi}{\mu_0}$ **Ans. Ⓐ**
7. **If the magnetic field intensity of a material is $10^5$ A/m and its susceptibility is $2.3 \times 10^{-5}$, the value of its intensity of magnetisation is**
   Ⓐ 1.5 A/m Ⓑ 2.3 A/m Ⓒ 3.07 A/m **Ans. Ⓑ**
8. **The susceptibility of a paramagnetic material at 330 K is $3.6 \times 10^{-4}$. Its susceptibility at 660 K is**
   Ⓐ $1.8 \times 10^{-4}$ Ⓑ $1.8 \times 10^{-14}$ Ⓒ $2.93 \times 10^{-14}$ **Ans. Ⓑ**
9. **Gold is a**
   Ⓐ paramagnetic material
   Ⓑ diamagnetic material Ⓒ ferromagnetic material **Ans. Ⓐ**
10. **The susceptibility ($\chi$) of a paramagnetic material in a weak magnetic field**
    Ⓐ $\chi = \frac{C}{T}$ Ⓑ $\chi = CT$ Ⓒ $\chi = \frac{T}{C}$
    **where $C$ is known as Curie constant.** **Ans. Ⓐ**

11. **The Weiss law for paramagnetism is**

Ⓐ $\chi = \frac{C}{T}$ Ⓑ $\chi = \frac{C}{T-\theta}$ Ⓒ $\chi = \frac{C}{T+\theta}$

**where $C$ is Curie constant and $\theta$ is Curie temperature.** Ans. Ⓐ

12. **The Curie Weiss law for paramagnetism is**

Ⓐ $\chi = \frac{C}{T}$ Ⓑ $\chi = \frac{C}{T+\theta}$ Ⓒ $\chi = \frac{C}{T-\theta}$ Ans. Ⓒ

13. **Below Curie temperature, a paramagnetic material behaves like a**

Ⓐ diamagnetic substance Ⓑ ferromagnetic substance

Ⓒ antiferromagnetic substance Ans. Ⓑ

14. **The complicated temperature dependance susceptibility of paramagnetic materials is explained by**

Ⓐ Weiss theory Ⓑ Langevin's theory Ⓒ None of these Ans. Ⓐ

15. **The value of one Bohr magneton is**

Ⓐ $9.1 \times 10^{-31}$ A · m² Ⓑ $9.27 \times 10^{-24}$ A · m² Ⓒ $9.12 \times 10^{-19}$ A · m² Ans. Ⓑ

16. **One Bohr magneton $\mu_B$ is equal to**

Ⓐ $\frac{eh}{2m}$ Ⓑ $\frac{e\hbar}{2}$ Ⓒ $\frac{e\hbar}{2m}$ Ans. Ⓒ

17. **The materials that are strongly attracted by a magnet is**

Ⓐ paramagnetic material Ⓑ diamagnetic material

Ⓒ ferromagnetic material Ans. Ⓒ

18. **The susceptibility of a ferromagnetic material is**

Ⓐ constant Ⓑ a function of applied magnetic field

Ⓒ a function of applied magnetic field as well as its absolute temperature Ans. Ⓒ

19. **The spontaneous magnetisation is observed on**

Ⓐ ferromagnetic material Ⓑ paramagnetic material

Ⓒ diamagnetic material Ans. Ⓐ

20. **Above the ferromagnetic Curie temperature, the ferromagnetic substance behaves like**

Ⓐ antiferromagnetic substance Ⓑ paramagnetic substance

Ⓒ ferromagnetic substance Ans. Ⓑ

21. **Below the Curie temperature, the ferromagnetic substance behaves like**

Ⓐ antiferromagnetic substance Ⓑ ferrite

Ⓒ ferromagnetic substance Ans. Ⓒ

22. **The susceptibility ($\chi$) of paramagnetic material is**

Ⓐ $\chi = \frac{1}{T}$ Ⓑ $\chi = \frac{C}{T-\theta}$ Ⓒ $\chi = \frac{C}{T+\theta}$ Ans. Ⓐ

23. **The materials having the large hysteresis loss, high coercivity and retentivity is suitable for**

Ⓐ permanent magnet Ⓑ electromagnet Ⓒ none Ans. Ⓐ

24. **The material having the small hysteresis loss, high initial permeability is suitable for**

Ⓐ permanent magnet Ⓑ electromagnet Ⓒ none of these Ans. Ⓑ

25. **The dipoles are aligned antiparallel with equal magnitude in**

Ⓐ antiferromagnetic material Ⓑ ferromagnetic material

Ⓒ ferrimagnetic material **Ans. Ⓐ**

26. **The dipoles are aligned antiparallel with different magnitudes in**

Ⓐ ferromagnetic material Ⓑ ferrimagnetic material

Ⓒ antiferromagnetic material **Ans. Ⓑ**

27. **The spontaneous magnetisation for ferromagnetic material at Curie temperature is**

Ⓐ 1 Ⓑ 0 Ⓒ infinity **Ans. Ⓑ**

28. **The hysteresis curve for a ferrites is in the form of a**

Ⓐ rectangle Ⓑ ellipse Ⓒ parabola **Ans. Ⓐ**

29. **The susceptibility of antiferromagnetic material is**

Ⓐ $\chi = \frac{C}{T-\theta}$ Ⓑ $\chi = \frac{C}{T+\theta}$ Ⓒ none **Ans. Ⓑ**

**where $C$ is Curie constant and $\theta$ is the Curie temperature.**

30. **The transition of antiferromagnetism to paramagnetism takes place at**

Ⓐ Curie temperature Ⓑ Neel temperature Ⓒ Debye temperature **Ans. Ⓑ**

31. **The temperature below which a ferrimagnetic material shows ferromagnetism and above which it shows paramagnetism is known as**

Ⓐ Neel temperature Ⓑ inversion temperature

Ⓒ Curie temperature **Ans. Ⓒ**

## SHORT ANSWER TYPE QUESTIONS

1. What is magnetic induction? *[See article 6.1.5]*

   Establish a relation among the magnetic flux density $B$, the magnetic intensity $H$ and the intensity of magnetisation $M$. *[See article 6.1.8]*

2. Why does an atom possess magnetic dipole moment and behave as a magnetic dipole? *[See article 6.2]*

3. Prove that magnetic moment due to orbital motion of an electron must be an integral multiple of $\frac{e\hbar}{2m}$. How do you define a Bohr magneton? Give its numerical value.

   [H.P.U. 1996] *[See article 6.2.1]*

4. An electron revolves around a nucleus with frequency $4 \times 10^{15}$ Hz in an orbit of radius 0.53Å. Find the value of Bohr magneton. [Ans : $9.27 \times 10^{-27}$ J/T]

5. What is diamagnetic material? *[See article 6.6]*

   Why is diamagnetism, in contrast, almost independent of temperature?

**Hint:** The direction of magnetic moment of a diamagnetic material placed in a magnetic field is always opposite to the direction of the field. So it is not affected by the thermal motion of the dipoles.

6. What are the characteristics of paramagnetic substance? *[See article 6.7.1]*

   Give the physical interpretation of Curie-Weiss law. *[See article 6.7.5]*

7. Describe the ferromagnetism on the basis of domain theory. *[See article 6.8.1]*

8. [a] Explain the importance of hysteresis curve.
   [b] What type of material should be used for making transformer core and permanent magnet and why? [See article 6.8.5]
9. Distinguish between antiferromagnetic and ferrimagnetic materials. [See article 6.8.2. and article 6.9]
10. Discuss the temperature dependence of susceptibility of an antiferromagnetic material and hence define Neel temperature. [See article 6.8.1]

## LONG ANSWER TYPE QUESTIONS

1. [a] Define the terms magnetic susceptibility ($\chi$), magnetic permeability ($\mu$), magnetic induction ($B$), magnetising field ($H$) and intensity of magnetisation ($M$). [See article 6.1.1 to 6.1.7]
   [b] Derive the following relations
   (i) $\mu = \mu_0(1+\chi)$ [See article 6.1.8]
   (ii) $B = \mu_0(H+M)$ [See article 6.1.9]
2. [a] Explain how does an atom behave as magnetic dipole. Derive an expression for its magnetic dipole moment. [See article 6.2 and article 6.2.1]
   [b] An electron revolves around a nucleus with frequency $4 \times 10^{15}$ Hz in an orbit of radius 0.53 Å. Calculate (i) the magnetic moment of the orbital electron and (ii) the value of Bohr magneton.
3. [a] What is diamagnetic material? [See article 6.6]
   [b] Mention the properties of diamagnetic materials. [See article 6.6.1]
   [c] Deduce Langevin's formula for the molar diamagnetic susceptibility. [B.Urd. U. 1999]
   or, Prove that the diamagnetic susceptibility increases with the number of atoms per unit volume but is independent of the temperature of the material and the intensity of the external magnetic field. [See article 6.6.2]
4. [a] What is paramagnetic material? [See article 6.7]
   [b] Give the properties of paramagnetic material. [See article 6.7.1]
   [c] Derive Curie's law of paramagnetism from Langevin's theory. [CU 1984]
   or, Derive an expression showing the temperature dependence of paramagnetic susceptibility. [CU 1987] [See article 6.7.2]
   [d] Prove that at low temperature and in very strong magnetic field, paramagnetic substance acquires its saturation state. [See Case 2 of article 6.7.2]
5. [a] Distinguish among dia-, para-, and ferromagnetism.
   [b] Derive the Curie-Weiss law of paramagnetism and obtain an expression of Curie temperature. [See article 6.7.4]
   [c] Give the physical interpretation from the Curie-Weiss law. [See article 6.7.5]
6. [a] What is ferromagnetism?
   [b] Explain the phenomenon of spontaneous magnetism in magnetic materials. [See article 6.8.2]

[c] Calculate the loss of energy per unit volume per cycle of hysteresis of a ferromagnetic material. [See article 6.8.4]

7. [a] Discuss the characteristic features of a ferromagnetic materials.

[b] Derive the Curie-Weiss law of ferromagnetism and obtain an expression for the Curie temperature. [See article 6.8.2]

[c] 'Magnetic behaviour of magnetic substances decreases with increasing of temperature'—comment. [H.P.U. 1995] [See last part of article 6.8.2]

8. [a] What is hysteresis loop? [See first part of article 6.8.3]

[b] Explain the hysteresis loop observed in ferromagnetic material and also identify the retentivity and the coercivity of the material from the curve. [See article 6.8.3]

[c] Explain the importance of hysteresis curve. [See article 6.8.5]

9. [a] What is an antiferromagnetic material? [See article 6.9]

[b] Explain the antiparallel alignment of dipoles in antiferromagnetic material with suitable sketch. [See article 6.9]

or, Discuss the characteristic features of antiferromagnetic material.

[c] Discuss its temperature dependence of susceptibility and hence define Neel temperature. [See article 6.9.1]

10. [a] What are ferrites. Give two examples. [See article 6.10]

[b] Discuss the characteristic features of ferrites or ferri-magnetic materials. [See article 6.10.1]

[c] Give the differences between ferrites and ferromagnetic substances. [See article 6.10.2]

[d] Give the application of ferrimagnetic materials. [See article 6.10.3]