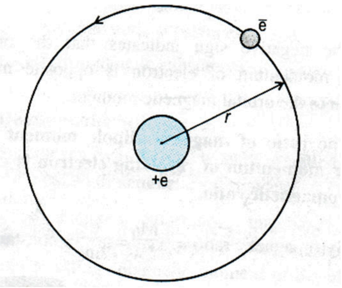
# MAGNETISM PART 1

**MAGNETIC DIPOLE MOMENT OF A REVOLVING ELECTRON**:

An atom consists of a positively charged heavy nucleus around which negatively charged electrons are revolving in a circular orbit.

Let r be the radius of revolution of the electron and v its orbital velocity. Then, magnitude of magnetic moment



$M_o = IA = \frac{Q}{T}\pi r^2 = \frac{e}{2\pi r/v} . \pi r^2 = \boxed{\frac{evr}{2}}$

Direction if from South to North (this case into the paper)

$M_o = \frac{evr}{2} = \frac{e}{2m} . mvr = \frac{e}{2m} . L_o$ (where Lo=orbital angular momentum)

$\vec{M_o} = -\frac{e}{2m} . \vec{L_o}$ (m=mass of electron)

The negative sign indicates that the orbital angular momentum is oppositely directed to the orbital magnetic moment.

NOTE: Gyromagnetic ratio = $\frac{Mo}{Lo} = \frac{e}{2m} = 8.8 \times 10^{10}$ C/kg

NOTE: The circular orbit of the electron produces an orbital magnetic moment. In addition, an electron has spin magnetic moment.

NOTE: $L = mvr = nh/2\pi$. Therefore, $M = (e/2m).L = \frac{enh}{4\pi m}$

This is called Bohr Magneton.

For n=1, Bohr Magneton = $9.274 \times 10^{-24}$ A/m².

**MAGNETIZATION:**

The net magnetic dipole moment per unit volume is called as the magnetization ($\vec{Mz}$) of the sample.

Magnetization ($\vec{Mz}$) = $\frac{\text{Net magnetic moment}}{\text{Volume}} = \frac{M_{net}}{\text{Volume}}$

SI unit: A/m  Dimensions: $[M^0L^{-1}T^0I^1]$

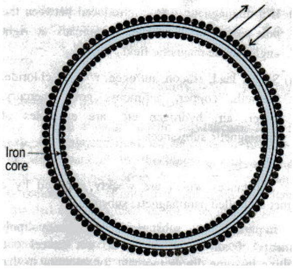
NOTE: Complete alignment of the atomic dipole moment is called saturation of the sample.

- ***Magnetization of Paramagnetic substance (Curie's Law)***
  Magnetization of a paramagnetic sample is directly proportional to the external magnetic field and inversely proportional to the absolute temperature.
  Mz α Bext and Mz α 1/T
  Therefore, Mz α Bext / T

  $Mz = C \times \frac{Bext}{T} = \frac{C\mu_oH}{T}$. Thus $\chi = \frac{Mz}{H} = 1-\mu_r = \frac{C\mu_o}{T}$ . Thus $\boldsymbol{\chi \propto \frac{1}{T}}$

  This is known as Curie's Law and C is called Curie constant.

- ***Magnetization of Ferromagnetic substance***.
  Consider a Toroid with an iron core. Let the toroid coil have n turns per unit length and carries a current I.
  The magnetic field inside the coil would be
  $B_O = \mu_O$ n I where
  $\mu_O$=permeability of vacuum

  However with the iron core the magnetic field inside the coil would be $B = B_O + B_M$ (where BM = magnetic field due to core)
  $B_M = \mu_O M_Z$ and $B_O = \mu_O H$ , where H=magnetic intensity=nI
  SI unit of H: A/m  Dimension : $[M^0L^{-1}T^0I^1]$

Thus, $B=\mu_O(H + M_Z)$ where $M_Z=\chi H$ and χ: magnetic susceptibility

Thus, $B=\mu_O(1+\chi)H = \mu_O\mu_rH = \mu H$ ,

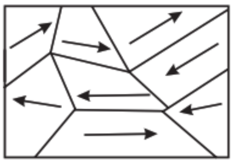
where $\mu_r = 1+\chi$ = relative magnetic permeability & is dimensionless quantity

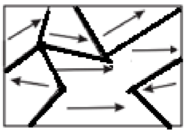
NOTE: $\mu = \mu_O\mu_r = \mu_O(1 + \chi)$

**FERROMAGNETISM on basis of DOMAIN THEORY:**

Ferromagnetism is explained bases on domain theory proposed by Weiss. According to domain theory, a ferromagnetic material contains large number of small regions or domains (about 1mm, with $10^{11}$ atoms). In this region all magnetic moments are aligned in the same direction.

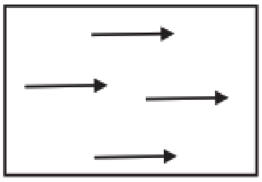
In the absence of any external magnetic field, the different domains are oriented at random, so that the magnetic fields of the domains cancel each other and substance does not show magnetic properties.





When externally applied magnetic field is weak, the individual atomic magnets tend to align parallel to the direction of the external field. The domain wall thus shifts in the direction of the applied field. With the removal of the external magnetic field, the boundaries return to their original positions and the material loses its magnetism.

When the external applied magnetic field is strong, the dipole moments of the non-aligned domains abruptly rotate in the direction of the applied field. This process is referred as flipping or domain rotation. The removal of the external field does not set the domain boundaries back to the original position; hence the material gets permanent magnetic properties. (The degree of magnetization also depends on the temperature of the substance).



**CURIE TEMPERATURE (Tc):**

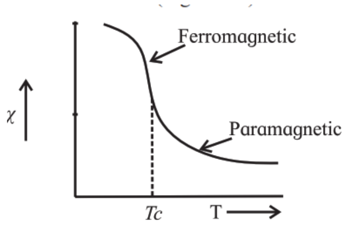
It is observed that when ferromagnetic substance is heated, its magnetization decreases with increase in temperature. At a particular temperature it looses its magnetization completely. This temperature at which the domain structure is destroyed and ferromagnetic substance looses its magnetism is called ***curie temperature***.

At higher temperature, the exchange coupling between the atomic magnets in each domain breaks completely and all the atomic dipoles get randomly oriented.

Above the curie temperature, ferromagnetic substance is converted into a paramagnetic substance.

The curie temperature is different for different ferromagnetic materials. e.g. IRON is 1043K.

$\chi = \frac{C}{T-T_C}$, where C is a constant and T > $T_C$



**Hysteresis.** When a ferromagnetic sample is placed in a magnetising field, the sample gets magnetised by induction. As the magnetising field intensity $H$ varies, the magnetic induction $B$ does not vary linearly with $H$, *i.e.* the permeability $\mu (= B/H)$ is not constant but varies with $H$. In fact, it also depends on the past history of the sample.

Fig. 5.56 shows the variation of magnetic induction $B$ with magnetising field intensity $H$. Point $O$ represents the initial unmagnetised state of a ferromagnetic sample. As the magnetising field intensity $H$ increases, the magnetic induction $B$ first gradually increases and then attains a constant value. In other words, the magnetic induction $B$ *saturates* at a certain value $+H_{max}$.

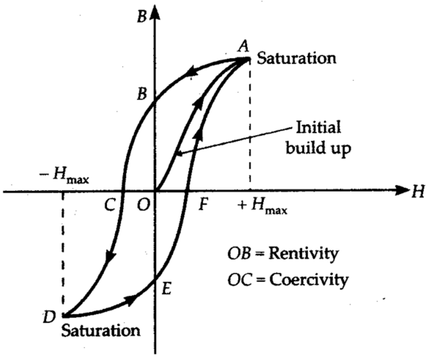
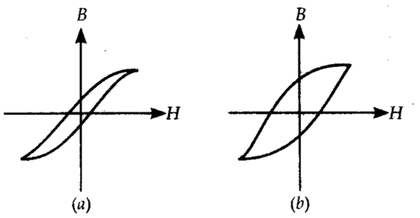


**Fig. 5.56** Hysteresis loop for a ferromagnetic sample.

Now if the magnetising field intensity $H$ is gradually decreased to zero, $B$ decreases but along a new path $AB$. It is found that the magnetic induction $B$ does not become zero even when the magnetising field $H$ is zero, *i.e.*, the sample is not demagnetised even when the magnetising field has been removed. *The magnetic induction (= OB) left behind in the sample after the magnetising field has been removed is called* ***residual magnetism*** *or* ***retentivity*** or ***remanence***.

To reduce the magnetism to zero, the field $H$ is gradually increased in the *reverse* direction, the induction $B$ decreases and becomes zero at a value of $H = OC$. *The value of reverse magnetising field intensity H required for the residual magnetism of a sample to become zero is called* ***coercivity*** *of the sample.*



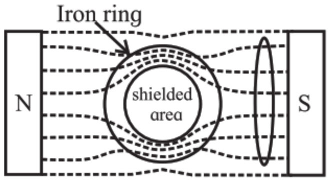
(*a*) (*b*)

**Fig. 5.57** Magnetic hysteresis loop for
(*a*) soft, (*b*) hard ferromagnetic material.

On further increasing $H$ in the reverse direction to a value $-H_{max}$, we reach the saturation point $D$ located symmetrically to point $A$. Now if $H$ is decreased gradually, the point $A$ is reached after going through the path $DEFA$.

The closed curve $ABCDEFA$ which represents a *cycle of magnetisation* of a ferromagnetic sample is called its ***hysteresis loop***. Throughout the cycle, the magnetic field $B$ lags behind the magnetising field intensity $H$, *i.e.*, the value of $B$ when $H$ is decreasing is always more than when $H$ is increasing. *The phenomenon of the lagging of magnetic induction behind the magnetising field is called* ***hysteresis***. In fact, the word hysteresis originates from a Greek word meaning '*delayed*'.

**Magnetic Shielding**

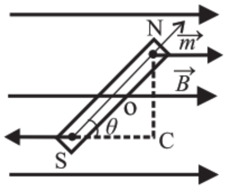


When a soft ferromagnetic material is put in a uniform magnetic field, large number of magnetic lines crowd up inside the material leaving a few outside. So not if we have a closed structure of this material, like a spherical shell of iron in magnetic field, very few lines of force will pass through the enclosed space (as shown). This effect is known as magnetic shielding. Some scientific experiments require the experiment to be protected from magnetic field in the laboratory. We can achieve this by completely surrounding this instrument by a soft ferromagnetic substance.

# MAGNETISM PART 2

| | Property | Diamagnetic substances | Paramagnetic substances | Ferromagnetic substances |
|---|---|---|---|---|
| 1. | *Effect of magnets* | They are feebly repelled by magnets. | They are feebly attracted by magnets. | They are strongly attracted by magnets. |
| 2. | *In external magnetic field* | Acquire feeble magnetisation in the opposite direction of the magnetising field. | Acquire feeble magnetisation in the direction of the magnetising field. | Acquire strong magnetisation in the direction of the magnetising field. |
| 3. | *In a non-uniform magnetic field* | Tend to move slowly from stronger to weaker parts of the field. | Tend to move slowly from weaker to stronger parts of the field. | Tend to move quickly from weaker to stronger parts of the field. |
| 4. | *In a uniform magnetic field* | A freely suspended diamagnetic rod aligns itself perpendicular to the field. | A freely suspended paramagnetic rod aligns itself parallel to the field. | A freely suspended ferromagnetic rod aligns itself parallel to the field. |
| 5. | *Susceptibility value* ($\chi_m$) | Susceptibility is small and negative. $-1 \le \chi_m < 0$ | Susceptibility is small and positive. $0 < \chi_m < \varepsilon$, where ε is a small number | Susceptibility is very large and positive. $\chi_m > 1000$ |
| 6. | *Relative permeability value* ($\mu_r$) | Slightly less than 1<br>$0 \le \mu_r < 1$ | Slightly greater than 1<br>$1 < \mu_r < 1 + \varepsilon$ | Of the order of thousands<br>$\mu_r > 1000$ |
| 7. | *Permeability value* ($\mu$) | $\mu < \mu_0$ | $\mu > \mu_0$ | $\mu >> \mu_0$ |
| 8. | *Effect of temperature* | Susceptibility is independent of temperature. | Susceptibility varies inversely as temperature :<br>$\chi_m \propto \frac{1}{T}$. | Susceptibility decreases with temperature in a complex manner.<br>$\chi_m \propto \frac{1}{T - T_C} \ (T > T_C)$ |
| 9. | *Removal of magnetising field* | Magnetisation lasts as long as the magnetising field is applied. | As soon as the magnetising field is removed, magnetisation is lost. | Magnetisation is retained even after the magnetising field is removed. |
| 10. | *Variation of M with H* | *M* changes linearly with *H*. | *M* changes linearly with *H* and attains saturation at low temperature and in very strong fields. | *M* changes with *H* non-linearly and ultimately attains saturation. |
| 11. | *Hysteresis effect* | *B*-vector shows no hysteresis. | *B*-vector shows no hysteresis. | *B*-vector shows hysteresis. |
| 12. | *Physical state of the material* | Solid, liquid or gas. | Solid, liquid or gas. | Normally solids only. |
| 13. | *Examples* | Bi, Cu, Pb, Si, $N_2$(at STP), $H_2O$, NaCl | Al, Na, Ca, $O_2$(at STP), $CuCl_2$ | Fe, Ni, Co, Gd, $Fe_2O_3$, Alnico. |

**Torque, PE and Time Period of an oscillating magnetic dipole (SIMILAR TO Magnet Vibrating in a Uniform Magnetic file in Oscillation chapter):**



The forces exerted on the poles of a magnet form a couple, thus causing rotational motion.

τ = MB sin θ where

M=m.2l = magnetic dipole moment

B is the strength of the uniform magnetic field and θ is the angle between the magnetic axis and the field B

Magnetic potential energy $U = \int_0^\theta \tau.d\theta = \int_0^\theta MB\sin\theta.d\theta = -MB\cos\theta$

Case 1: θ = 0°, cos θ = 1, U = –MB

When $\vec{M}$ and $\vec{B}$ are parallel the PE is minimum and magnet is most stable

Case 2: θ = 90°, cos θ = 0, U = 0

This is when the bar magnet is perpendicular to the field

Case 3: θ = 180°, cos θ = –1, U = MB

When $\vec{M}$ and $\vec{B}$ are antiparallel the PE is maximum and magnet is most unstable

Now suppose this bar magnet is suspended then it will rotate with a toque τ and align itself and become stable. If we rotate this bar magnet in opposite direction by an angle dθ, then a restoring torque will be produces which with cause angular oscillations in the bar magnet.

$$\tau = I\alpha = I\frac{d^2\theta}{dt^2}, I = MI\ of\ bar\ magnet, \alpha = angular\ acceleration$$

Restoring torque = – MBsin θ

Equating the above we get

$$I\frac{d^2\theta}{dt^2} = -MBsin\theta$$

$$I\frac{d^2\theta}{dt^2} = -MB\theta, since\ \theta\ is\ small, thus\ \sin\theta \approx \theta$$

$$This\ \alpha = \frac{d^2\theta}{dt^2} = -\left(\frac{MB}{I}\right)\theta$$

Thus α is proportional to θ, hence

$$\omega^2 = \frac{MB}{I}, thus, \omega = \sqrt{\frac{MB}{I}}\ and\ T = \frac{2\pi}{\omega} = 2\pi\sqrt{I/_{MB}}$$