MAGNETIC PROPERTIES OF SOLIDS

BSc. VI Sem-Paper6.1

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Syllabus: Define magnetic moment. Diamagnetism (explain origin)-Langevin classical theory, Para magnetism-Curie's law, Ferromagnetism, Hysteresis loop, Weiss theory (main features)

Magnetic materials are those which can be easily magnetized as they have permanent magnetic moment or induced magnetic moment in the presence of applied magnetic field .Magnetism arises from the magnetic dipole moments or simply magnetic moment of the magnetic materials.

The following are some of the important terms that are used in the study of magnetic materials

1. **Magnetic dipole:** It is a system consisting of two equal and opposite magnetic poles separated by a small distance 2l As shown below
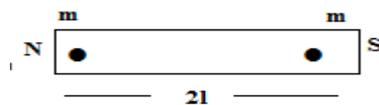
   m- is the Pole Strength. SI unit of **m** is ampere meter (Am)

1. Magnetic moment(M) : It is defined as the product of its pole strength and distance between the two poles ie M= mx2l

   SI unit of M is ampere meter^2 (Am^2)

   It is also given by M = Ix A, I is the current through a loop of area A

2. Magnetic induction or magnetic flux density(B): The number of magnetic lines of induction inside a magnetized substance crossing unit area normal to their direction is known as magnetic induction or Magnetic flux density

   S.I unit of B is weber/m^2 or tesla(T)

3. Intensity of magnetization(I) :   It is defined as the ratio of magnetic dipole moment developed per unit volume ,when a sample of magnetic material is subjected to a magnetizing field

   Ie, I= M/V   or I=m/A

   S.I unit of I is A/m

4. Magnetic permeability(μ): Magnetic permeability of a substance is defined as the ratio of magnetic induction to the magnetizing field ,

   ie, μ= B/H

    Magnetic Permeability is the ability of a material to allow the magnetic lines of force through it

   Further $\mu = \mu_0$ x μ_r

   $\mu_0 = 4\pi$ x 10^{-7} H/m – it is the permeability of free space

   μ_r is the relative permeability

μ is the Absolute permeability

5. <u>Magnetic susceptibility(χ)</u> : It is defined as the ratio of intensity of magnetization to magnetizing field

ie, χ = I/H

χ has no unit , it is just a number , χ is also called volume susceptibility

the relation between μ_r and χ is $\mu_r = 1 + \chi$

Classification of magnetic materials:

Magnetic substances are those which are attracted by a magnet. They can be classified as diamagnetic, paramagnetic and ferromagnetic substances .Ferromagnetic substances are strongly attracted by a magnet while paramagnetic substances are weakly attracted by a magnet, But diamagnetic substances are repelled by a magnet .The behavior of magnetic substances can be explained on the basis of electron theory

The matter is made up of atoms, each atom has a positively charged nucleus at its center and around the nucleus negatively charged electrons revolve in various orbits. The revolving electron behaves like a magnetic dipole, which has some magnetic movement .This magnetic moment arises due to orbital motion and spin motion. The contribution to the magnetic moment due to orbital revolution is negligibly small .Hence most of the magnetic moment is produced due to electrons spin .The magnetic moment vectors are oriented in different directions in an atom.

In diamagnetic substance the vector sum of magnetic moments is zero

The property of diamagnetism is generally found in those substances whose atoms or molecules have even number of electrons which form pairs. In the electron pairs, the direction of spin of one electron is opposite to that of the other. In this way the magnetic moment of one electron is neutralized by that of the other and the net magnetic moment is zero

In paramagnetic substances the vector sum of magnetic moment is not zero, so the atoms or molecules of a paramagnetic substance possesses a permanent magnetic moment. The property of Para magnetism is found in the substances whose atoms or molecules have single electrons and their orbitals oriented in a random way such that the permanent magnetic moment is greater than zero.

In Ferromagnetic materials all the orbits of single electrons are oriented in a symmetric manner such that the atom as a whole possesses a Large magnetic moment

Langevin theory of Diamagnetism:

Consider an electron of mass m rotating about the nucleus [charge Ze] in a circular orbit of radius 'r'. Let w_0 be the angular velocity of the electron. The force acting on the electron is given by

$$F_0 = m\omega_0^2 r = \frac{Z e^2}{4\pi\varepsilon_0 r^2} \quad \Rightarrow \quad \omega_0^2 = \frac{Z e^2}{4\pi\varepsilon_0 m r^3}$$
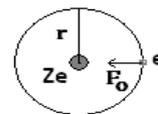
$$\omega_0 = \sqrt{\frac{Z e^2}{4\pi\varepsilon_0 m r^3}} \quad \text{- - - (1)}$$

The magnetic moment associated with an electronic orbit is given by,

$$\overrightarrow{m} = current \times area \ of \ the \ loop = \left(\frac{e\ \omega_0}{2\pi}\right) \times \pi\ r^2 = \frac{e\ \omega_0\ r^2}{2}$$
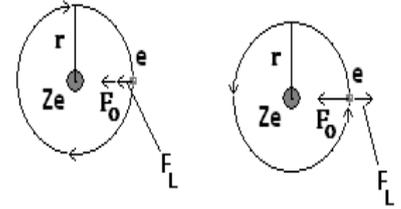
(Because, I = q /T = e /(2π/ω₀) = e ω₀/2π)

Let a magnetic field **B** is applied perpendicular to the orbit and into the page. Due to this an additional force **F_L** called Lorentz force acts on the electron given by,

$$F_L = -e\left(\overrightarrow{v} \times \overrightarrow{B}\right) = -e\,B\,r\,\omega \quad \text{- - - (2)}$$

The condition for stable equilibrium is given by,

$$m\omega^2 r = \frac{Z\,e^2}{4\pi\varepsilon_0 r^2} - e\,B\,r\,\omega = \frac{Z\,e^2 \times mr}{4\pi\varepsilon_0 mr^3} - e\,B\,r\,\omega = \omega_0^2\,mr - e\,B\,r\,\omega$$

[Because from equation(1)]

Dividing by *mr*, we get, $\omega^2 = \omega_0^2 - \frac{e\,B\,\omega}{m} \quad \Rightarrow \quad \omega^2 + \frac{e\,B\,\omega}{m} - \omega_0^2 = 0 - - - (3)$

Solving the quadratic equation, we get, $\omega = \dfrac{-\frac{eB}{m} \pm \sqrt{\left(\frac{eB}{m}\right)^2 + 4\omega_0^2}}{2} = \pm\sqrt{\omega_0^2 + \left(\frac{eB}{2m}\right)^2} - \frac{eB}{2m} \quad \text{- - - (4)}$

Neglecting $\frac{eB}{m}$ compared to ω_0, we get, $\omega = \pm\,\omega_0 - \frac{eB}{2m} \quad \text{- - - (5)}$

Thus the angular frequency of the electron in its orbit changes with the application of an external magnetic field. Therefore, the result of establishing a field of flux density B is to set up a precessional motion of the electron orbit with an angular velocity $-\dfrac{e\overrightarrow{B}}{2m}$.

This is known as Larmor theorem.

Thus the change in frequency of revolution of the electron $= \delta n = \dfrac{-e\overrightarrow{B}/2m}{2\pi} = -\dfrac{e\overrightarrow{B}}{4\pi m} \quad \text{- - - (6)}$

The corresponding change in magnetic moment of the electron is given by,

$$\Delta m = current \times area = (ch\arg e \times frequency) \times area = e \times -\left(\frac{e\overrightarrow{B}}{4\pi m}\right) \times \pi\,r^2 = -\frac{\overrightarrow{B}\,e^2 r^2}{4m} \quad \text{- - - (7)}$$

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

$$\left(\Delta m\right)_{atom} = -\frac{\overrightarrow{B}\,e^2 \sum r^2}{4m}$$

If there are N atoms per unit volume, then the magnetization M is given by,

$$M = N\left(\Delta m\right)_{atom} = -\frac{N\overrightarrow{B}\,e^2 \sum r^2}{4m} \quad \text{- - - (8)}$$

All the electron orbits are not oriented normal to the field. Hence r^2 in equation should be replaced by the average of the square of the projection of the orbit radii for various electrons in a plane perpendicular to $\overrightarrow{B}$. Hence $\sum r^2$ should be replaced by $\frac{2}{3}\langle r^2 \rangle \times Z$. Therefore,

$$M = -\frac{NZ \vec{B} e^2 \langle r^2 \rangle}{6m} = -\frac{NZ(\mu H)e^2 \langle r^2 \rangle}{6m} \quad \text{- - - (9)}$$

Where, μ is the permeability of the material. The volume susceptibility of the material is given by,

$$\chi = \frac{M}{H} = \frac{-NZ\mu H e^2 \langle r^2 \rangle}{6mH} = \frac{-NZ\mu e^2 \langle r^2 \rangle}{6m} = \frac{-\mu e^2}{6m} NZ \langle r^2 \rangle \quad \text{- - - (10)}$$

Equation (10) shows that magnetic susceptibility is independent of both the field strength and temperature. This is in good agreement with Curie's experimental results.

Langevin theory of Paramagnetism:

Langevin assumed that each atom has a permanent magnetic moment 'm'. The only force acting on the atom is that due to the external magnetic field **B**. Then the magnetic potential energy of the atomic dipole is given by,

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

According to classical statistics, the number of atoms having potential energy U is given by,

$$n = K^` \exp\left(\frac{-U}{kT}\right) = K^` \exp\left(\frac{mB \cos \theta}{kT}\right)$$

The number of atoms having potential energy between U and U + dU inclined at an angle between $\theta \, \& \, (\theta + d\theta)$ is given by,

$$dn = K^` \exp\left(\frac{mB \cos \theta}{kT}\right)\left(-\frac{mB}{kT} \sin \theta \, d\theta\right) = -C \exp\left(\frac{mB \cos \theta}{kT}\right) \sin \theta \, d\theta$$

Where k is Boltzmann constant and T is the absolute temperature. Putting $\frac{mB}{kT} = \alpha$, we get,

$$dn = -C \, e^{\alpha \cos \theta} \sin \theta \, d\theta \quad \text{- - - (1)}$$

The total number of atomic magnets in unit volume of the paramagnetic material is given by,

$$n = \int_0^\pi dn = \int_0^\pi C e^{\alpha \cos \theta} \left(-\sin \theta \, d\theta\right) \quad \text{- - - (2)}$$

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

$$n = \int_{+1}^{-1} C e^{\alpha x} dx = C \int_{+1}^{-1} e^{\alpha x} dx = C \frac{\left(e^{\alpha x}\right)_{+1}^{1}}{\alpha} = C \frac{e^{-\alpha} - e^{+\alpha}}{\alpha}$$

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

The component of each dipole moment parallel to B is *m* cos θ. The total magnetic moment of all the n atoms contained in unit volume of the gas is the magnetization M. It is given by,

$$M = \int_0^\pi m \cos\theta \, dn = \int_0^\pi m \cos\theta \, C \, e^{\alpha\cos\theta}(-\sin\theta \, d\theta)\text{- - -}(4)$$

Put $\cos\theta = x$, then $-\sin\theta \, d\theta = dx$. With this we can write equation (4) as follows.

$$M = \int_{+1}^{-1} m \, x C \, e^{\alpha x} dx = Cm \int_{+1}^{-1} x \, e^{\alpha x} dx$$

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

$$M = \int_{+1}^{-1} m \, x \left(\frac{-n\alpha}{e^x - e^{-x}}\right) e^{\alpha x} dx = \frac{\alpha \, mn}{e^x - e^{-x}} \int_{-1}^{+1} x \, e^{\alpha x} dx \qquad \left| = mn\left[\coth\alpha - \frac{1}{\alpha}\right] \right.$$

Where, $L(\alpha) = \left[\coth\alpha - \dfrac{1}{\alpha}\right]$ is called Langevin function.

Case (i): At low temperature [or large magnetic field] $L(\alpha) \to 1$. Hence M = mn. So the saturation is reached and all the atomic dipoles are parallel to the field **B**.

Case (ii): Under normal condition α is very small. Then $L(\alpha) = \left[\coth\alpha - \dfrac{1}{\alpha}\right] = \dfrac{mB}{3kT}$

$$\therefore \quad M = mn \times \frac{mB}{3kT} = \frac{nm^2 B}{3kT} = \frac{nm^2 \mu_0 H}{3kT} \qquad \text{Thus} \qquad \text{the} \qquad \text{magnetic}$$

susceptibility is given by,

$$\chi = \frac{M}{H} = \frac{\mu_0 n \, m^2}{3kT} = \frac{C}{T} \text{- - - -}(6)$$

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

Failure of Langevin theory:

(i) Langevin theory fails to explain more complicated dependence of susceptibility on temperature exhibited by several paramagnetic substances such as highly compressed and cooled gases, very concentrated solutions of salts.

(ii) Langevin theory could not account for the intimate relation between para and ferromagnetism.

Weiss modification of Langevin theory:

Langevin theory applies strictly to gases, where the molecules are sufficiently far apart so that the mutual interactions between molecules are negligible. In liquids and solids interaction between molecules is large resulting in a deviation from Curie law. Weiss modified the theory and derived a modified equation for susceptibility of paramagnetic materials in the following form: $\chi = \dfrac{C}{T-\theta} \text{- - -}(7)$

In equation (7), θ is known as Curie temperature and is characteristics of the substance. Equation (7) holds only at temperatures T > θ. At T = θ, the transition from paramagnetic to ferromagnetic material takes place. At T < θ substance behaves like ferromagnetic substance and at T > θ, the material become paramagnetic substance.

Ferromagnetism :

Ferromagnetic substances are strongly magnetic . A ferromagnetic material has a spontaneous magnetic moment even in zero applied field . The atoms or molecules of paramagnetic materials have a net intrinsic magnetic dipole moment which is primarily due to the spin of the electrons. The interaction between the neighboring atomic dipoles is very strong . It is called spin exchange interaction and is present even in the absence of an external magnetic field .

Weiss Theory of ferromagnetism :

Weiss made the following hypothesis for ferromagnetism

1.   A specimen of ferromagnetic material contains a number of small regions called domains which are spontaneously magnetized . The magnitude of spontaneous magnetization of the specimen as a whole is determined by the vector sum of the magnetic moments of individual domains

2.   The spontaneous magnetization of each domain is due to the presence of an exchange field B_E .which tends to produce a parallel alignment of the atomic dipoles . B_E is proportional to the magnetization I of each domain ie, $B_E = \beta I$ ……..(1)

Where β is a constant called the Weiss field constant and is independent of temperature.

B_E is also called Weiss field .

The effective magnetic field on an atom or ion become

$B_{eff} = B + B_E = B + \beta I$ ………(2)

Using classical theory and with the above hypothesis,Weiss obtained the following expression

 ie $T = \sigma_o^2 \rho / 3RM$, σ_o -- Saturation values of gram molecular moment
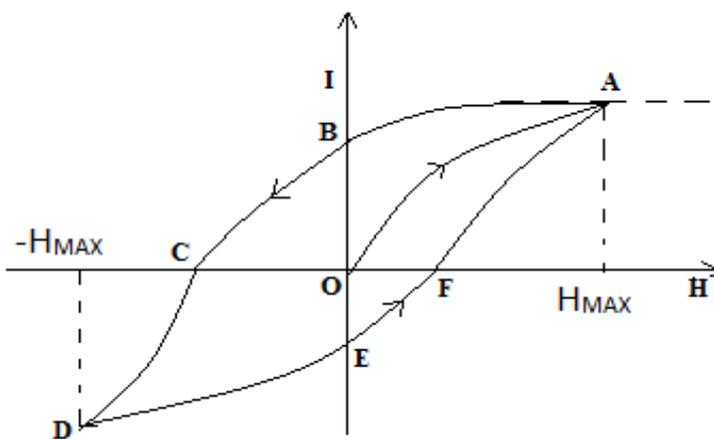
ρ - density of the substance

M- Molecular weight

ρ - is the Weiss field constant

T is the Absolute temperature of the substance .

HYSTERSIS:

 The phenomenon of lagging of intensity of magnetization (I) behind magnetizing field(H) when a ferromagnetic substance is subjected to a magnetizing field is called

Hysteresis

A graph obtained by plotting I against H is called Hysteresis Curve

Consider an un magnetized iron bar, let it be subjected to a gradually increasing field H .Initially when I= 0 , H= 0 , as H gradually increases, I also increases and reaches to a saturated value at maximum field(H_m) as shown in the figure. In the figure OA is called initial magnetization curve. As the value of H decreases from H_m to zero, the specimen does not pass through its previous path but I decreases at lower rate and follows the path AB. When H is reduced to zero but still I has certain value equal to OB. This magnetism left behind in the specimen when magnetizing field is reduced to zero is called residual magnetism. This property is called retentivity

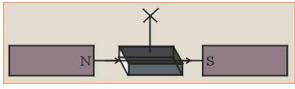Retentivity is the ability of ferromagnetic substance to retain intensity of magnetization when the field is zero.

When the magnetic field is applied in the reverse direction, *I* decreases and becomes zero at a particular value of H, the corresponding value of H at which I become zero is called Cohersive field

The reverse magnetizing field applied to ferromagnetic substance for which I becomes zero is called coercive field .This property is called coercivity.
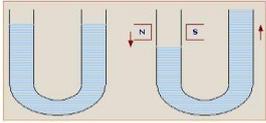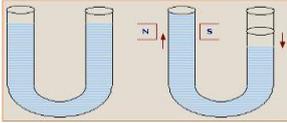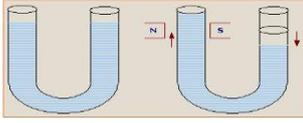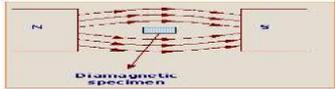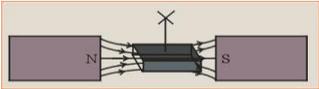
When the ferromagnetic substance is subjected to a cycle of magnetization, a loop is obtained as shown in the figure. This loop is called Hysteresis loop. The area under Hysteresis loop is a measure of the amount of energy lost by the specimen per unit volume per cycle of magnetization.

A soft ferro magnetic material has a narrow Hysteresis loop and the energy loss is minimum. Such soft magnetic materials are useful for the course of transformers, motors etc.

Distinction between dia, para & ferromagnetic materials:

No.	Diamagnetic material	Paramagnetic material	Ferromagnetic material
1	A diamagnetic rod suspended in a uniform magnetic field sets its longest axis perpendicular to field.	A paramagnetic rod suspended in a uniform magnetic field sets its longest axis parallel to field.	A ferromagnetic rod suspended in a uniform magnetic field sets its longest axis parallel to field.
2	In a non uniform magnetic field, these materials move from stronger to weaker field.	In a non uniform magnetic field, these materials move from weaker to stronger field.	In a non uniform magnetic field, these materials move from weaker to stronger field.
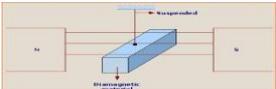
3	A diamagnetic liquid in a U shaped tube subjected to magnetic field is depressed in the limb	A paramagnetic liquid in a U shaped tube subjected to magnetic field is elevated in the limb	A Ferromagnetic liquid in a U shaped tube subjected to magnetic field is elevated in the limb
4	These materials do not permit the magnetic lines of induction to pass through them.	These materials permit the magnetic lines of induction to pass through them	These materials readily permit the magnetic lines of induction to pass through them.
5	$\mu_r < 1$ and $\chi < 0$	$\mu_r > 1$ and $\chi > 0$	$\mu_r >> 1$ and $\chi >> 0$
6	Substance loses its magnetization as soon as the magnetizing field is removed.	Substance loses its magnetization as soon as the magnetizing field is removed.	Substance retains its magnetization as soon as the magnetizing field is removed.
7	Examples:Bismuth, antimony, copper, gold, quartz, mercury, water, alcohol, air, hydrogen etc.	Examples:Aluminum, platinum,chromium, manganese, copper sulphate, oxygen etc.	Examples: Iron, cobalt, nickel and number of alloys.
8	Diamagnetic susceptibility is negative and independent of field and temperature.	Paramagnetic susceptibility is positive and dependent on the strength of the field and also on the temperature. Below curie temperature it transforms into ferromagnetic material. $$\chi = \frac{C}{T}$$ It is Curie's law	Ferromagnetic susceptibility is positive and dependents on the temperature.Abovecurie temperature it transforms in to paramagnetic material. $$\chi = \frac{C}{T - \theta}$$ It is Curie-Weiss law

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