Magnetic Properties of Materials

Introduction: Three important facts with respect to magnetic materials which require explanations are :
(i) Some materials are magnetic even without the application of any magnetic field and become more magnetic when a weak magnetic field is applied to them.
(ii) Many other materials lose their initial strong magnetism when heated above a certain critical temperature and completely weakly magnetized.
(iii) Some materials show magnetic response in a direction opposite to that of any externally applied field.

The magnetic effects in magnetic materials are due to atomic magnetic dipoles in the materials. These dipoles result from the effective current loops of electrons in atomic orbits, from effects of electron spin and from the magnetic moments of atomic nuclei.

1. What are the characteristics of magnetic materials?

(i) Magnetic substances like iron, cobalt, nickel are attracted by a magnet.
(ii) Like poles of magnets repel each other and unlike poles attract each other.
(iii) Magnetic monopole does not exist. They always exist in pairs.

2. What is magnetic permeability?

In an unmagnified bar of a magnetic materials is placed in a uniform magnetic field, it gets magnetized by induction and gets a polarity.

The lines of magnetized bar opposes the lines of original field outside the magnet and favour inside the magnet.
As a result, the magnetic field strength ($\vec{H}$) is increased inside the bar and decreased outside it. Similarly the magnetic flux density ($\vec{B}$) is directly proportional to the magnetic field strength ($\vec{H}$), i.e.

$$\vec{B} \propto \vec{H}$$
$$\vec{B} = \mu\vec{H},$$

where, μ is a constant of proportionality and is unknown as absolute permeability of the medium. If flux density is established in air or vacuum or in a non magnetic material, then the above equation may be written as,

$$\vec{B}_0 = \mu_0\vec{H}.$$

The ratio $\frac{\mu}{\mu_0}$ is known as relative permeability of the medium and is expressed by μ_r.

$$i.e. \mu_r = \frac{\mu}{\mu_r} = \frac{B}{B_0}.$$

The relative permeability of air or nonmagnetic material is unity, but for certain nickel-iron alloys, its value is as high as $\sim 10^5$.

3. What is magnetization?

The term magnetization may be defined as the process of converting a non magnetic bar into magnetic bar. The flux density,

$$\vec{B} = \mu\vec{H} = \mu_0\mu_r\vec{H}.$$

Again,

$$\vec{B} = \mu_0(\vec{H} + \vec{M})$$

4. What is magnetic susceptibility?

It is defined as the ratio of the intensity of magnetization ($\vec{M}$) at any point inside a material to the magnetic field ($\vec{H}$). i.e.

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

Definition: The property which determines how easily and up to what extent a specimen can be magnetized is referred to as the magnetic susceptibility of the material.

The material is supposed to be made of large number of tiny dipoles when the substance is placed in a magnetic field ($\vec{H}$), the tiny dipoles of the magnetic substance start orienting along the direction of applied field and thus contribute to the intensity of magnetization ($\vec{M}$).

5. Relation between Magnetic susceptibility and permeability?

We have the relation

$$\chi_m = \frac{\vec{M}}{\vec{H}}$$
$$\Rightarrow \vec{M} = \chi_m\vec{H}.$$

Again,

$$\vec{B} = \mu_0\left(\vec{H} + \vec{M}\right).$$

Combining the above two equations,

$$\vec{B} = \mu_0\left(\vec{H} + \chi_m\vec{H}\right)$$
$$\Rightarrow \mu\vec{H} = \mu_0(1 + \chi_m)\vec{H}$$
$$\Rightarrow \mu_0\mu_r\vec{H} = \mu_0(1 + \chi_m)\vec{H}$$
$$\Rightarrow \mu_r = 1 + \chi_m.$$

5. (a) Starting from the Ampere's law, show that, for linear media $\vec{B} = \mu\vec{H}$.

Ampere's law is given by,

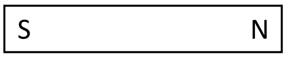
$$\oint \vec{B}.\overrightarrow{dl} = \mu_0 I \text{ (Integral form)}$$
$$\Rightarrow \iint (\vec{\nabla} \times \vec{B}).\overrightarrow{da} = \mu_0 \iint \vec{J}.\overrightarrow{da} \text{ (Applying Stokes' theorem)}$$
$$\Rightarrow \vec{\nabla} \times \vec{B} = \mu_0\vec{J} \text{ (Differential form).}$$

The bound current within a material is given by, $\vec{J}_b = \vec{\nabla} \times \vec{M}$; where, $\vec{M}$ is the magnetization of the material . The field produced due to the magnetization of the material is just the field produced by this bound current.

The free current ($\vec{J}_f$) might flow through the wires embedded in the magnetized substance or if the substance is a conductor itself. The total current is written as,

$$\vec{J} = \vec{J}_f + \vec{J}_b$$
$$\therefore \vec{\nabla} \times \vec{B} = \mu_0(\vec{J}_f + \vec{J}_b) = \mu_0(\vec{J}_f + \vec{\nabla} \times \vec{M})$$
$$\Rightarrow \vec{\nabla} \times \frac{1}{\mu_0}\vec{B} = \vec{J}_f + \vec{\nabla} \times \vec{M}$$
$$\Rightarrow \vec{\nabla} \times \left(\frac{1}{\mu_0}\vec{B} - \vec{M}\right) = \vec{J}_f$$
Now, the intensity of magnetic field is defined as,
$$\vec{H} = \frac{1}{\mu_0}\vec{B} - \vec{M}$$
$$\Rightarrow \vec{B} = \mu_0(\vec{H} + \vec{M}) = \mu_0(\vec{H} + \chi\vec{H}) = \mu_0(1 + \chi)\vec{H}$$
$$\vec{B} = \mu_0\mu_r\vec{H} = \mu\vec{H}$$

6. What do you mean be magnetic dipole and dipole moment?



Magnetic dipole: A bar magnet of finite separation between the two poles of it is called a magnetic dipole.

Let m be the pole strength and $2l$ be the separation between poles of a bar magnet, then dipole moment is
$$\vec{\mu}_m = 2l\vec{m}.$$
Here, $\vec{\mu}_m$ is a vector directed from the north to the South Pole.

7. Discuss the atomic theory of magnetic dipole moment and define Bohr Magnetron.

Let's consider the simplest model of hydrogen atom in which one electron moves the proton, say on a circular loop of radius r.
The moving electron is equivalent to a current loop. If v is the velocity of the electron, it will make $\frac{v}{2\pi r} = \frac{\omega}{2\pi}$ revolutions per second and it is equivalent to a current, $I = -\frac{e\omega}{2\pi}$.
The circular current loop is equivalent to a magnetic dipole and the magnetic moment due to this orbiting electron is
$$\mu_{el} = IA = \left(-\frac{e\omega}{2\pi}\right)\pi r^2 = -\frac{e\omega r^2}{2}.$$
The angular momentum associated with the electronic motion is given by $m\omega r^2$. Hence, we can relate the magnetic dipole moment and the angular momentum as,
$$\mu_{el} = \left(-\frac{e}{2m}\right) \times angular\ momentum.$$
The $-ve$ sign indicates that the dipole moment points in a direction opposite to a vector representing the vector angular momentum. A substance therefore possesses permanent magnetic dipoles if the electron of its constituent atom has a net non-vanishing angular momentum.
The ratio of the magnetic dipole moment of the electron due to its orbital motion and the angular momentum of the orbital motion of the electron represented by γ.
$$\gamma = \frac{Magnetic\ moment}{Angular\ momentum} = \frac{\mu_{el}}{m\omega r^2} = \frac{e}{2m}.$$
This (γ) is known as orbital gyromatic ratio.

According to the quantum theory, the angular momentum of an electron in the orbit is determined by the orbital quantum number l which is restricted to the set of values

$l = 0,1,2,3 \ldots\ldots\ldots\ldots\ldots. (n-1).\ n = Principal\ quantum\ number.$
The angular momentum of electrons associated with a particular value of l is given by $l\left(\frac{h}{2\pi}\right)$.
Therefore, the permanent dipole moment is given by,

$$\mu_{el} = -\left(\frac{e}{2m}\right)\left(\frac{lh}{2\pi}\right) = -\frac{ehl}{4\pi m} = -\mu_B l.$$

The quantity $\mu_B = \frac{eh}{4\pi m} = \frac{e\hbar}{2m}$ is an atomic unit called Bohr magnetron and has a value of $9.27 \times 10^{-24} amp/m^2$, and this represents the magnetic moment of elementary permanent dipole.

8. Quantum theory of magnetism:
The magnetic behaviour of atoms, molecules, solids etc. is actually related to the orbital and spin motion of electrons. The motion of the electrons are govern by three well known quantum numbers, namely- (i) Principal quantum number (n) with values 1,2,3,4 ......; (ii) Orbital quantum number (l) with values 0,1,2,3, ... $(n-1)$ and magnetic quantum number (m_l) with values $-l, -l+1, -l+2, \ldots -1, 0, 1, 2, \ldots, l-1, l$. Here, n determines the energy of an electron, and l gives the magnitude of the angular momentum vector $\vec{L}$. Orientation of $\vec{L}$ is determined by m_l.
The magnitude of the electron's orbital angular momentum, $\vec{L}$ is quantized and the value is given by,

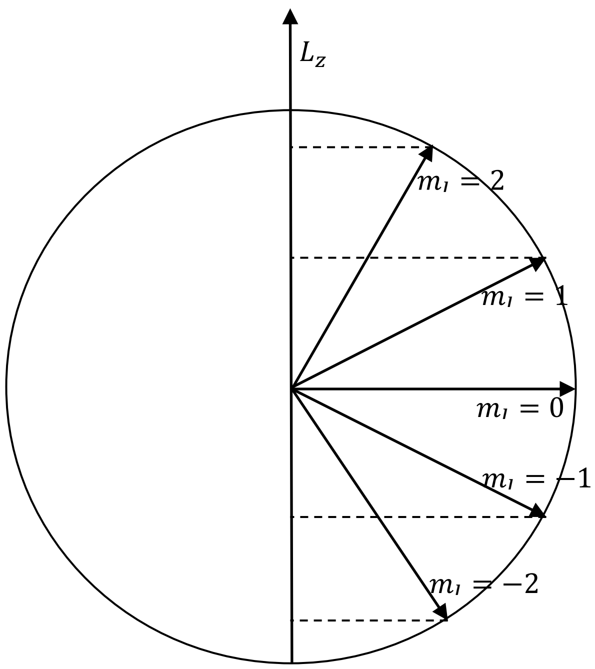
$$L = \sqrt{l(l+1)}\hbar.$$

The orbitals are designated by s, p, d, f for $l = 0, 1, 2, 3$ etc. The directions of $\vec{L}$ is also quantized with respect to an external field. This fact is often referred to as space quantization. If the magnetic field direction be along the Z axis, the component of $\vec{L}$ in this direction is

$$L_z = m_l\hbar.$$

The possible values of m_l for a given for a given value of l range from $-l$ through 0 to $+l$, in a magnetic field is $(2l+1)$. If θ is the angle between $\vec{L}$ and the magnetic field direction, which may be taken as Z direction, then,

$$cos\theta = \frac{L_z}{L} = \frac{m_l\hbar}{\sqrt{l(l+1)}\hbar} = \frac{m_l}{\sqrt{l(l+1)}}.$$



Space quantization of orbital angular momentum

An electron also possesses spin angular momentum represented by vector $\vec{S}$, whose magnitude is quantized in terms of $\hbar$, such that,

$$S = \sqrt{s(s+1)}\hbar.$$

With $s = \frac{1}{2}$ is the spin quantum number. Thus, $S = \sqrt{\frac{3}{2}}\hbar$.

The space quantization of electron spin is described by the spin magnetic quantum number m_s which can take values $+\frac{1}{2}$ and $-\frac{1}{2}$. The component s_z of the spin angular momentum of an electron along a magnetic field in Z direction is determined by spin magnetic quantum number, so that,

$$S_z = m_s\hbar = \pm\frac{1}{2}\hbar.$$

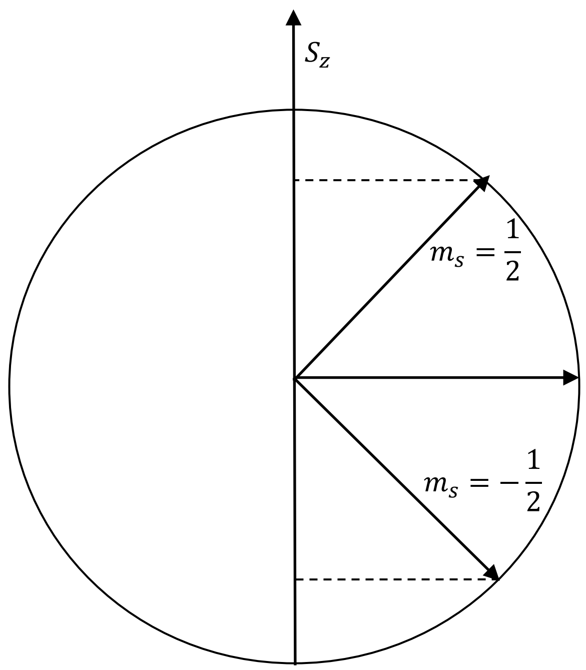
The gyromatic ratio, characteristic of the electron spin is almost twice that of electron orbital motion. Taking the ration equal to 2, the spin magnetic moment $\vec{\mu}_s$ of an electron is related to its spin angular momentum $\vec{S}$ by,

$$\vec{\mu}_s = \left(\frac{e}{m}\right)\vec{S}$$

$$\mu_{sz} = \frac{e\hbar}{2m}.$$

The constant $\frac{e\hbar}{2m}$ is the Bohr magnetron. The orientation of spin space with respect to Z axis (magnetic field direction) are determined by the relation

$$cos\varphi = \frac{S_z}{S} = \frac{m_s\hbar}{\sqrt{s(s+1)}\hbar} = \frac{m_s}{\sqrt{s(s+1)}}.$$



Two possible orientations of spin angular momentum

9. Theory of magnetism in electrons:

The electrons of an atom move round the nucleus in some specific orbits. The motion of the electrons in an orbit can be considered as small current loops. The magnetic moment of a current loop is,

$$M_L = iA = i\pi r^2.$$

For electrons,

$$M_L = -\frac{e}{T}(\pi r^2) = -\frac{e}{\frac{2\pi r}{v}}\pi r^2 = -\frac{evr}{2}.$$

The angular momentum of the electron is,

$$L = I\omega = mr^2\frac{v}{r} = mvr.$$

$$\therefore rv = \frac{L}{m}.$$

Putting this equation in the above equation,

$$M_L = -\left(\frac{e}{2m}\right)L = -\left(\frac{e}{2m}\right)\sqrt{l(l+1)}\hbar.$$

Since quantum mechanically, $L = \sqrt{l(l+1)}\hbar$.

The negative sign indicates that M_L and L are in opposite directions. The quantity $\frac{e\hbar}{2m}$ is a constant and known as Bohr Magnetron (μ_B).

$$\therefore\ |M_L| = \mu_B\sqrt{l(l+1)}.$$

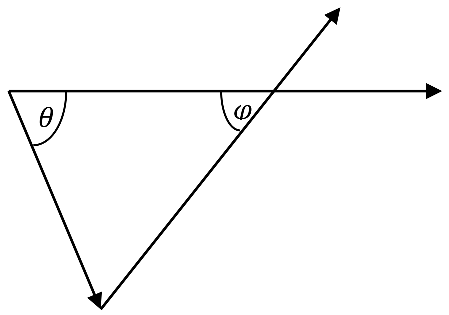
Similarly, magnetic moment corresponding to the spin of the electron is,

$$M_s = 2\mu_B S = 2\mu_B\sqrt{s(s+1)}.$$

The net angular momentum of the atom corresponding to $\vec{L}$ and $\vec{S}$ is,

$$\vec{J} = \vec{L} + \vec{S}.$$

The effective magnetic moment is obtained by summing the components M_L and M_s along $\vec{J}$.



The resultant magnetic moment is

$$M = \mu_L cos\theta + \mu_s cos\varphi.$$

From the figure,

$$S^2 = L^2 + J^2 - 2JLcos\theta$$

$$\Rightarrow cos\theta = \frac{L^2 + J^2 - S^2}{2JL}.$$

Similarly,

$$cos\varphi = \frac{S^2 + J^2 - L^2}{2JS}.$$

$$\therefore M = \mu_B \left(L.\frac{L^2 + J^2 - S^2}{2JL} + 2S.\frac{S^2 + J^2 - L^2}{2JS} \right)$$

$$= \frac{\mu_B}{J} \left(\frac{L^2 + J^2 - S^2}{2} + S^2 + J^2 - L^2 \right)$$

$$= \frac{\mu_B}{J} \left(J^2 + \frac{J^2 + S^2 - L^2}{2} \right)$$

$$= \mu_B J \left(1 + \frac{J^2 + S^2 - L^2}{2J^2} \right)$$

In terms of quantum numbers,

$$M = \mu_B \sqrt{j(j+1)} \left(1 + \frac{j(j+1) + s(s+1) - l(l+1)}{2j(j+1)} \right)$$

$$= g\mu_B \sqrt{j(j+1)}.$$

Where,

$$g = 1 + \frac{j(j+1) + s(s+1) - l(l+1)}{2j(j+1)}$$

and g is called the Lande g factor.

10. Based on the magnetic properties, how the materials are classified? Write their differences.

Materials are classified into three basic categories,

(i) Diamagnetic material, (ii) Paramagnetic material, (iii) Ferromagnetic material; besides there are two more categories (iv) Anti-ferromagnetic material and (v) Ferrimagnetic material.

Diamagnetic	Paramagnetic	Ferromagnetic
(i) Weakly repelled by the magnetic field. (ii) Magnetic susceptibility does not depend on temperature. (iii) Magnetic susceptibility is negative.	(i) Weakly attracted by the magnetic field. (ii) Magnetic susceptibility depends on the temperature. (iii) Magnetic susceptibility is positive.	(i) Strongly attracted by the magnetic field. (ii) Magnetic susceptibility depends on the temperature. (iii) Magnetic susceptibility is positive.

11. Write down a note on classical theory of diamagnetism.

Consider a circular orbit of radius r in which an electron revolves with an angular velocity ω_0 around the nucleus of charge Ze. Then,

$$F_0 = \frac{mv^2}{r} = \frac{Ze^2}{4\pi\epsilon_0 r^2}$$

$$\Rightarrow m\omega_0^2 r = \frac{Ze^2}{4\pi\epsilon_0 r^2}$$

$$\Rightarrow \omega_0^2 = \frac{Ze^2}{4\pi\epsilon_0 m r^3}$$

$$\omega_0 = \sqrt{\frac{Ze^2}{4\pi\epsilon_0 m r^3}}$$

The orbital magnetic moment of the electron is

$$\mu_L = iA = -\frac{e}{T}\pi r^2 = -\frac{e\omega_0 r^2}{2}.$$

If an external magnetic field is applied to the atom, then the Lorentz force acting on the electron is,

$$F_L = -Bev = -Be\omega r.$$

Now the equation of motion is,

$$m\omega^2 r = \frac{Ze^2}{4\pi\epsilon_0 r^2} - Be\omega r$$

$$\Rightarrow \omega^2 = \frac{Ze^2}{4\pi\epsilon_0 m r^3} - \frac{eB\omega}{m}$$

$$\Rightarrow \omega^2 + \frac{eB}{m}\omega - \omega_0^2 = 0$$

$$\Rightarrow \omega = -\frac{eB}{2m} \pm \sqrt{\omega_0^2 + \left(\frac{eB}{2m}\right)^2}$$

$$\Rightarrow \omega \approx -\frac{eB}{2m} \pm \omega_0^2; if\ \frac{eB}{2m} \ll \omega_0.$$

Therefore the change in frequency of the electron is

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

$$\Rightarrow 2\pi\Delta\nu = \frac{eB}{2m}$$

$$\Rightarrow \Delta\nu = \frac{eB}{4\pi m}.$$

Therefore, the corresponding change in the magnetic moment of the electron is,

$$\Delta\mu_L = \Delta iA = -e\Delta\nu\pi r^2 = -\frac{e\pi r^2(eB)}{4\pi m} = -\frac{e^2 r^2 B}{4m}.$$

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

$$\Delta\mu_L = -\frac{e^2 B}{4m}\sum_{i=1}^{z} r_i^2.$$

Where, the summation extends over all the orbital electrons (z) in the atom, since the core electrons have different radii, we may write,

$$\sum_{i=1}^{z} r_i^2 = z\langle r^2\rangle.$$

Where, $|\langle r^2\rangle|^{\frac{1}{2}}$ is the average radius of the orbitals. If the orbitals lie in xy plane, then

$$\langle r^2\rangle = \langle x^2\rangle + \langle y^2\rangle.$$

If $\langle r_0^2\rangle$ represents the average distance of the electrons from the nucleus,

$$\langle r_0^2\rangle = \langle x^2\rangle + \langle y^2\rangle + \langle z^2\rangle.$$

When the atom has spherical symmetry,

$$\langle x^2\rangle = \langle y^2\rangle = \langle z^2\rangle$$

$\therefore \langle r^2\rangle = 2\langle x^2\rangle$ and $\langle r_0^2\rangle = 3\langle x^2\rangle$; $\therefore\ \frac{\langle r^2\rangle}{\langle r_0^2\rangle} = \frac{2}{3}$.

Therefore,

$$\Delta\mu_L = -\frac{e^2 Bz}{4m}.\frac{2}{3}\langle r_0^2\rangle.$$

If N be the number of atoms per unit volume, then the magnetization is given by,

$$M = N\Delta\mu_L = -\frac{\mu_0 Hze^2 N\langle r_0^2\rangle}{6m}.$$

$$\Rightarrow \chi = \frac{M}{H} = -\frac{\mu_0 ze^2 N\langle r_0^2\rangle}{6m}.$$

Observations: (i) χ is independent of temperature.
(ii) χ is negative.

12. Discuss on classical theory of paramagnetism.

For the analysis of variation of the susceptibility of a paramagnetic spin system with temperature, the following assumption have been made.
(i) Only the effect electron spin magnetic moment is considered.
(ii) Individual spin moment can accept only two possible components along the field direction +1 or -1 Bohr magnetron, i.e. spin moments in the presence in the presence of field are either parallel or anti-parallel with the field.
(iii) The interaction between individual spin system is negligible, so that, the field at any point in the spin system is the applied field.

On the basis of equipartition of energy, the number of molecules whose potential E is proportional to $e^{-\frac{E}{kT}}$, where k is the Boltzmann constant and T is the absolute temperature.

Let N be the number of molecules in unit volume. If dN is the number of molecules having inclinations θ and $\theta + d\theta$ and energy value E, then

$$dN \propto e^{-\frac{E}{kT}} sin\theta d\theta$$

$$\Rightarrow dN \propto e^{-\frac{E}{kT}} sin\theta d\theta$$

The torque on the dipole is ,

$$\tau = mB(2lsin\theta) = \mu_m Bsin\theta$$

Where, $\mu_m = 2ml$ is the dipole moment of the dipole.
Therefore, the potential energy of the dipole is given by,

$$E = \int_{90°}^{\theta} \tau d\theta = \int_{90°}^{\theta} \mu_m Bsin\theta d\theta = -\mu_m Bcos\theta$$

Therefore,

$$dN = C\left(e^{\frac{\mu_m Bcos\theta}{k_B T}}\right)sin\theta d\theta,$$

Let $a = \frac{\mu_m B}{k_B T}$, then

$$dN = Ce^{acos\theta}sin\theta d\theta$$

Therefore, the total number of molecules (N) having inclinations between 0 to π is given by,

$$N = \int_0^{\pi} C\left(e^{acos\theta}\right)sin\theta d\theta.$$

Let, $x = cos\theta, \Rightarrow dx = -sin\theta d\theta,$

$$\therefore N = \int_{1}^{-1} C(e^{ax})(-dx) = C \int_{-1}^{1} (e^{ax})dx = C\frac{e^a - e^{-a}}{a}$$

$$\Rightarrow C = \frac{aN}{e^a - e^{-a}}.$$

Therefore, the resolved components of all the dipole moments inclined at an angle θ will be,

$$dM = dN\mu_m cos\theta.$$

Hence the total dipole moment due to all N molecules lying between 0 to π contained in unit volume gives intensity of magnetization,

$$M = \int dM = \int_{0}^{\pi} dN\mu_m cos\theta = \int_{0}^{\pi} \mu_m cos\theta C e^{acos\theta} d\theta.$$

Let $x = cos\theta \Rightarrow dx = -cos\theta d\theta$.

$$\therefore M = C\mu_m \int_{1}^{-1} xe^{ax}(-dx) = \frac{\mu_m N}{e^a - e^{-a}} \int_{-1}^{1} xe^{ax}dx$$

$$= \frac{\mu_m N}{e^a - e^{-a}}\left\{[xe^{ax}] - \int_{-1}^{1} e^{ax}dx\right\}$$

$$= \frac{\mu_m N}{e^a - e^{-a}}\left\{(e^a + e^a) - \frac{(e^a - e^a)}{a}\right\}$$

$$= \mu_m N\left\{\frac{(e^a + e^a)}{e^a - e^{-a}} - \frac{1}{a}\right\} = \mu_m N L(a),$$

where, $L(a) = \left\{\frac{(e^a + e^a)}{e^a - e^{-a}} - \frac{1}{a}\right\}$ is known as Langevin's function.

In the above equation, $\mu_m N$ represents the dipole moment per unit volume when all the spins are turned into the direction of the applied magnetic field and hence it gives the saturation value of M say M_s . This M_s is a constant depending upon the nature of the gas.

Thus,

$$\frac{M}{M_s} = L(a) = \left(\coth(a) - \frac{1}{a}\right).$$

When $a\ (= \frac{\mu_m E}{k_B T})$ becomes large, that is, at very low temperature the function reaches a saturation corresponding to a maximum alignment of the dipoles along the field direction, i.e. at very high filed and low temperature.

So, at large a, $L(a) \to 1$, and so, $M = M_s = \mu_m N$.

The second characteristic of the curve is important for many practical purposes. That is for high temperature or small filed,

$a\ = \frac{\mu_m E}{k_B T} \ll 1$ and in such case,

$$L(a) = \left(\coth(a) - \frac{1}{a}\right) = \left\{\frac{(e^a + e^a)}{e^a - e^{-a}} - \frac{1}{a}\right\}$$

$$= \frac{\left(1 + a + \frac{a^2}{2!} + \frac{a^3}{3!} + \cdots\right) + \left(1 - a + \frac{a^2}{2!} - \frac{a^3}{3!} + \cdots\right)}{\left(1 + a + \frac{a^2}{2!} + \frac{a^3}{3!} + \cdots\right) - \left(1 - a + \frac{a^2}{2!} - \frac{a^3}{3!} + \cdots\right)} - \frac{1}{a}$$

$$= \frac{2 + 2\frac{a^2}{2!}}{2a + 2\frac{a^3}{3!}} - \frac{1}{a} = \frac{1 + \frac{a^2}{2} - 1 - \frac{a^2}{6}}{a(1 + \frac{a^2}{6})} = \frac{2a^2}{6a(1 + \frac{a^2}{6})} \approx \frac{a}{3}$$

Neglecting the higher powers of a.

$$\therefore \frac{M}{M_s} = L(a) \approx \frac{a}{3}.$$

The initial part of the curve (i.e. for small values of a) is sensibly linear and coincides with the tangent of the curve at the origin whose slope is $\frac{1}{3}$.

$$\therefore M = M_s\left(\frac{a}{3}\right) = \mu_m N \frac{\mu_m B}{3k_B T} = \frac{{\mu_m}^2 NB}{3k_B T} = \frac{{\mu_m}^2 N\mu_0 H}{3k_B T}.$$

Therefore, paramagnetic susceptibility is given by,

$$\chi = \frac{M}{H} = \frac{{\mu_m}^2 N\mu_0}{3k_B T} = \frac{C}{T}.$$

Where, C is a constant$\left(C = \frac{{\mu_m}^2 N\mu_0}{3k_B}\right)$. This is known as Curie's law.

13. Discuss Curie-Weiss theory of ferromagnetism.

Weiss introduce the concept of intermolecular field in order to explain the complicated type of dependence of susceptibility. In a real gas, the molecules are mutually in influenced by their magnetic moments and consequently, molecular field is developed. The field produced at any point by the neighbouring molecules is proportional to the intensity of magnetization and acting along it. Let this intermolecular field be H_i,

Now,

$$H_i = \lambda M,$$

Where, λ is the molecular field coefficient. Therefore the net effective filed should be,

$$H_{eff} = H + H_i.$$

From Lagevin's theory we know,

$$\chi = \frac{M}{H_{eff}} = \frac{C}{T}.$$

$$M = \frac{C}{T} H_{eff} = \frac{C}{T}(H + H_i) = \frac{C}{T}(H + \lambda M).$$

$$\Rightarrow MT = C(H + \lambda M)$$

$$\Rightarrow M(T - C\lambda) = CH$$

$$\Rightarrow M = \frac{CH}{(T - C\lambda)}.$$

Therefore, the susceptibility is given by,

$$\chi = \frac{M}{H} = \frac{C}{(T - C\lambda)} = \frac{C}{(T - \theta_c)}.$$

This is known as Curie-Weiss law, where $\theta_c$the ferromagnetic Curie temperature is.

14. What is hysteresis? Draw hysteresis loop for a ferromagnetic material and define coercively, retentively and saturation magnetization.

15. What is soft and hard magnets?

16. Draw $\frac{1}{\chi}$ versus T [Where, χ is the susceptibility of the material] for paramagnetic, ferromagnetic and anti-ferromagnetic materials on the same graph.

17. Discuss about Anti-ferromagnetism, ferrimagnetism and ferrites.

Ferromagnetism	Anti-ferromagnetism	Ferrimagnetism
1. All the spins are aligned parallel to each other and the individual spin magnetic moment has the same magnitude. $\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow$ 2. The ferromagnetic materials have spontaneous magnetization. 3. Negative susceptibility, independent of temperature. Ex: Fe, Co, Ni	1. All the spins are aligned anti-parallel to each other and the individual spin magnetic moment has the same magnitude. $\uparrow\downarrow\uparrow\downarrow\uparrow$ 2. The anti-ferromagnetic materials have zero spontaneous magnetization. 3. Positive susceptibility, $\chi = \frac{C}{T}$. Ex. Mn	1. All the spins are aligned anti-parallel to each other and the individual spin magnetic moment has has different magnitude. $\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow$ 2. The ferromagnetic materials have nonzero spontaneous magnetization. 3. 3. Positive susceptibility, $\chi = \frac{C}{(T-\theta_c)}$. Ex: Strontium ferrite, Barium ferrite, Cobalt ferrite etc.

18. What are ferrites?

A **ferrite** is a type of ceramic compound composed of iron oxide (Fe_2O_3) combined chemically with one or more additional metallic elements. They are both electrically nonconductive and ferrimagnetic, meaning they can be magnetized or attracted to a magnet. Ferrites can be divided into two families based on their magnetic coercivity, their resistance to being demagnetized. *Hard ferrites* have high coercivity, hence they are difficult to demagnetize. They are used to make magnets, for devices such as refrigerator magnets, loudspeakers and small electric motors. *Soft ferrites* have low coercivity. They are used in the electronics industry to make ferrite cores for inductors and transformers, and in various microwave components.

Applications:

- **Strontium ferrite**, $SrFe_{12}O_{19}$ ($SrO{\cdot}6Fe_2O_3$), used in small electric motors, micro-wave devices, recording media, magneto-optic media, telecommunication and electronic industry.
- **Barium ferrite**, $BaFe_{12}O_{19}$ ($BaO{\cdot}6Fe_2O_3$), a common material for permanent magnet applications. Barium ferrites are robust ceramics that are generally stable to moisture and corrosion-resistant. They are used in e.g. loudspeaker magnets and as a medium for magnetic recording, e.g. on magnetic stripe cards.
- **Cobalt ferrite**, $CoFe_2O_4$ ($CoO{\cdot}Fe_2O_3$), used in some media for magnetic recording.