MAGNETIC PROPERTIES OF MATERIALS

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Response of substance of magnetic field:

A magnetic field can be described by either magnetic induction B (or magnetic flux density) or the field strength H. In vacuum, they are related by the equation

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

where $\mu_0 = 4\pi \times 10^{-7}\ H - m^{-1}$ and is called the permeability of the free space (vacuum).

When a substance is placed in a magnetic field, it gets magnetized and hence a magnetization M(defined as the magnetic moment per unit volume, i.e. $M = \mu_m / \Delta V$) is produced in it. The magnetic induction inside the substance is given by

$$B = \mu_0 H + \mu_0 M = \mu_0 \left(H + M\right) \qquad \text{... (2)}$$

where the first term on the right side of equation (2) is due to external field and the second term is due to the magnetization. For an isotropic medium, M and H are parallel vectors and are related to each other according to the relation

$$M = \chi H \qquad \text{... (3)}$$

where χ is the susceptibility of the medium and is a scalar quantity. Substituting the value of M from equation (3) into equation (2), we have

$$B = \mu_0 \left(1 + \chi\right) H = \mu H \qquad \text{... (4)}$$

where $\mu = \mu_0 \left(1 + \chi\right)$ ... (5)

is known as the permeability of the medium. It is often more convenient to use the relative permeability μ_r, which is defined as

$$\mu_r = \frac{\mu}{\mu_0} = \left(1 + \chi\right) \qquad \text{... (6)}$$

Magnetic susceptibility is defined as $\chi = \frac{M}{H}$.

Classification of magnetic materials:

Magnetic materials can be classified into different categories according to their χ values and the way in which these vary with the magnetic field strength and temperature. They are: (i) Diamagnetic, (ii) Paramagnetic, (iii) Ferromagnetic, (iv) Antiferromagnetic and (v) Ferrimagnetic.

The Diamagnetic property is the result of an induced magnetic moment. This arises when an atom is placed in a magnetic field. The motion of orbital electrons of the atom (analogous to a current flowing in a circuit) gets modified in such a way that weak magnetic moment opposing the field is induced. Also, if χ is negative in equation (3), the direction of magnetization M is opposite to that of the field H. If M and H behave linearly then $\chi = \frac{M}{H}$ (for diamagnetic material)

A diamagnetic solid has a tendency to repel the magnetic lines of force due to an external applied field (Figure). A superconductor which repels all the lines of force, is an example of a perfect diamagnet.

Diamagnetic substances include inert gases (helium, argon, etc), metals (bismuth, copper, zinc, gold, silver etc.), mercury, water, glass, marble and many other organic compounds. For a diamagnetic substance, the relative permeability μ_r (or the susceptitibility χ) is independent of temperature.

Unlike diamagnetism, paramagnetism and ferromagnetism are the results of intrinsic magnetic moment. Some atoms and ions do posses permanent magnetic moment. In the absence of an external field, these moments are randomly oriented with respect to one another because of thermal fluctuations and therefore the substance exhibits no net magnetic moment. However, when placed in a magnetic field, the moments tend to align along the direction of field, producing a net magnetization. When the atoms and ions are acted upon individually, with no mutual interaction between them, the effect is called paramagnetism. Since the moments line up in the direction of the field which help enhance the external field, the paramagnetic susceptibility is greater than zero. Further, because of small paramagnetic susceptibility a paramagnetic substance weakly attracts the lines of force. (Figure). As thermal energy randomizes the alignment of the dipoles, the paramagnetic susceptibility decreases with the increase of temperature.

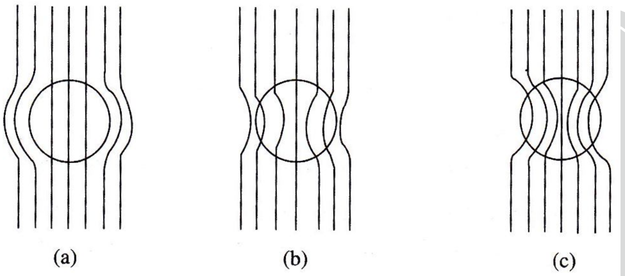

Figure: Behaviour of magnetic lines of force under applied magnetic field in (a) Diamagnet (b) Paramagneti and (c) Ferromagnet.

Paramagnetic substances include aluminium, platinum, potassium, manganese, the rare-earth elements, alkali and alkaline earth metals etc.

A ferromagnetic substance possesses permanent (spontaneous) magnetic moments even in the absence of an external magnetic field. Since, the ferromagnetic susceptibility is very large and positive, so that a ferromagnetic substance strongly attracts the lines of force (Figure). Ferromagnetism exists only below a certain temperature T_c, above which the substance becomes paramagnetic.

If M and H are not linear then $\chi = \frac{\partial M}{\partial H}$ (for ferromagnetic material).

Ferromagnetic substances include iron, cobalt, nickel and a number of alloys.

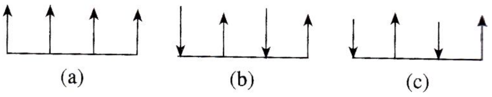

Figure: Magnetic arrangements in (a) Ferromagnet (b) Antiferromagnet and (c) Ferrimagnet

In fully magnetized state of a ferromagnet, all the dipoles are aligned in exactly the same direction (Figure). An antiferromagnetic substances has the dipoles with equal moments, but the alternate dipoles point in opposite directions (Figure). As a result, the moments balance each other and result in a zero net magnetization. Another commonly encountered substance is ferrimagnetic, the moments of which are shown in figure. In this case too, the neighbouring dipoles point in opposite directions but they are unequal. As a result, they do not completely balance each other and posses finite net magnetization.

If magnetisation M is anti-parallel to applied magnetic field then it is diamagnetic and if M is parallel to applied magnetic field then paramagnetic or ferromagnetic.

Atomic theory of magnetism:

There are three principle sources of magnetic moment in an atom.

(*i*) Orbital motion of electrons

(*ii*) Spin motion of electrons

(*iii*) Induced magnetic moment due to change in the orbital motion of electron on the application of external magnetic field.

In an atom, there is a nucleus about which electrons do orbital motion and produce current and this constitute a magnetic dipole.

$$I = \frac{e}{T} = \frac{ev}{2\pi R}$$

Magnetic moment $\mu_m = I \cdot A = \frac{ev}{2\pi R}\pi R^2$

$$\Rightarrow \boxed{\mu_m = \frac{evR}{2}}$$

This μ_m is due to orbital motion of electron

Direction of μ_m will be decided by motion of electron.

For orbital motion of electrons, $\frac{\mu_l}{L} = \frac{e}{2m}$

Spin motions of electrons, $\frac{\mu_s}{S} = \frac{2e}{2m}$

Both orbital and spin motions of electron give paramagnetic contribution.

In an atom, we know that the electrons revolve around the nucleus in different circular orbits. Analogous to this situation let us consider an electron of mass m, having an electronic charge ($-e$) moving in a circular orbit of radius 'r' with a velocity v (angular velocity ω) as shown in (Figure) From the basic knowledge of current electricity, we know that a moving electron constitutes an electric current, i.e.

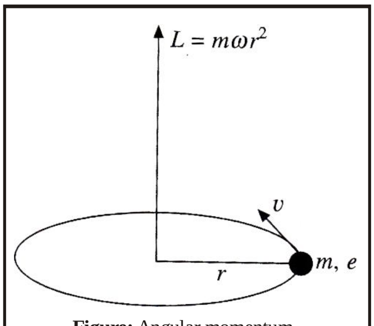

Figure: Angular momentum of an orbitting electron

$$I = \frac{dq}{dt} \text{ and } Ids = \frac{dq}{dt}ds = dq\frac{ds}{dt} = -ev \qquad \text{... (7)}$$

where $dq = -e$ and $v = \frac{ds}{dt}$, the linear velocity. But for a circular orbit, $ds = 2\pi r$ and $v = \omega r$, so that

$$I \times 2\pi r = -e\omega r \qquad \Rightarrow \quad I = -\frac{e\omega}{2\pi} \qquad \text{... (8)}$$

From electromagnetic theory, it is well known that the magnetic field produced by a current, *I* flowing in a stationary loop of cross sectional area *A* at right angles to the plane of the current loop is identical with that produced by a magnetic dipole when measured at large distance (as compared to the radius of the loop). The magnitude of the magnetic moment produced by (the circular motion of the electron) a dipole is

$$\mu_m = I.A \qquad \text{... (9)}$$

For a circular orbit $A = \pi r^2$, also substituting the value of I from equation (8) into equation (9), we obtain

$$\mu_m = -\frac{e\omega}{2\pi} \times \pi r^2$$

$$\Rightarrow \qquad \mu_m = -\frac{e\omega r^2}{2} = -\frac{em\omega r^2}{2m} = -\left(\frac{e}{2m}\right)L \qquad \text{... (10)}$$

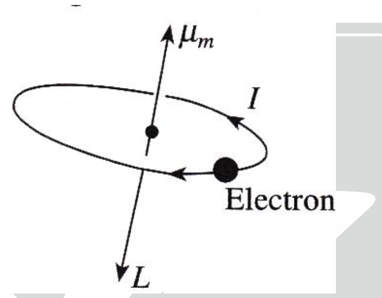

Figure: The magnetic dipole moment and the angular momentum associated with a current loop

where $L = m\omega r^2$ is the orbital angular momentum of electron and is normal to the plane of the orbit. The minus sign in equation (10) indicates that the magnetic moment μ_m is antiparallel to the angular momentum L (above figure). This equation is valid only for motion of electron and not for spin of the electron or nucleus.

The origin of permanent magnetic moments:

Permanent magnetic moments can arise from the following three different sources.

1. The orbital magnetic moment of the electrons.
2. The spin magnetic moment of the electrons, and
3. The spin magnetic moment of the nucleus.

1. The orbital magnetic moment of the electrons:

Based on the classical consideration of atomic theory of magnetism, we obtained an expression of magnetic moment (μ_m). However, quantum consideration tells us that the angular momentum vector can take only specific orientation in space when the atom is placed in an external magnetic field. Therefore, with the help of equation (10), we obtain

$$\mu_m = -\left(\frac{e}{2m}\right)L_{\ell,B} = -\left(\frac{e}{2m}\right)m_\ell \hbar = -\left(\frac{eh}{4\pi m}\right)m_\ell$$

$$\Rightarrow \qquad \mu_m = -m_\ell \mu_B \qquad \text{... (11)}$$

where $\mu_B = \frac{eh}{4\pi m} = 9.27 \times 10^{-24}\ A - m^2$, and is called the Bohr magneton. It is the quantum of orbital magnetic moment and is accepted as one unit for measuring the magnetic moments of atomic systems.