UNIT V (B)

MAGNETIC PROPERTIES

5.9 INTRODUCTION TO MAGNETIC PROPERTIES

Magnetic materials are the materials which can be easily magnetised since they have permanent magnetic moment or induced magnetic moment in the presence of applied magnetic field. i.e. they are capable of creating self magnetic field in the presence of external magnetic field. There are nearly eleven types of magnetic materials. Some of them are diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic and ferrimagnetic etc. ***Magnetism arises from the magnetic moment or magnetic dipole of the magnetic materials.***

Magnetic dipole is a system consisting of two equal and opposite magnetic poles separated by a small distance. In the case of a magnetic dipole or a bar magnet, the **magnetic moment** associated with that is the product of its pole strength and magnetic length.

$$\text{i.e., } M = 2\ell \text{ m ampere m}^2$$

where 'm' is the poles strength and '2ℓ' is the distance between north pole and south pole of the magnet.

Magnetic dipoles are the substances in which due to internal atomic currents the substance as a whole possesses a magnetic dipole moment. When an electric current 'i' ampere flows round a circular wire of one turn and area 'a' square metre, it is said to have a **magnetic dipole moment** 'M' = ia ampere m². This magnetic dipole moment or simply magnetic moment is a vector quantity. Its direction is normal to the plane of the loop to the right if the current is clockwise. The magnetic dipole moment of a current is responsible for magnetic field around the wire.

5.10 ORIGIN OF MAGNETIC MOMENT IN MAGNETIC MATERIALS

The magnetic moment in a material originates from the orbital motion and spinning motion of electrons in an atom.

When a magnetic moment is obtained through the motion of electrons in various orbits of an atom, then it is called **orbital magnetic moment** whose magnitude is always small.

In an atom, generally every two electrons will form a pair such that they have opposite spins. Thus the resultant spin magnetic moment is zero. But in magnetic materials like iron, cobolt, nickel, etc. there are **unpaired electrons** in the 3d orbital. This unpaired electron's spin magnetic moment interacts the adjacent atom's unpaired electron spin magnetic moment to align in a parallel manner resulting enormous **spin magnetic moment**. Thus these unpaired electron spins are responsible for ferro and paramagnetic behaviour of materials. The value of spin magnetic moment is very large when we compare it with orbital magnetic moment.

5.11 MAGNETIC QUANTITIES

First let us see the important terms involved in the magnetism.

(i) Magnetic induction (B) in any material is the number of lines of magnetic force passing perpendicularly through unit area. Unit : weber / m^2 (or) tesla. It is also equal to the magnetic force experienced by an unit north pole placed in that magnetic field.

(ii) Intensity of magnetization (I) of a sample of a material is the magnetic moment per unit volume. Unit : ampere m^{-1}

(iii) Magnetic field intensity (H) is the ratio between the magnetic induction and the permeability of the medium in which the magnetic field exists.

$$\text{i.e., } H = \frac{B}{\mu} \text{ ampere } m^{-1}.$$

(iv) Magnetic permeability (μ) of any material is the ratio of the magnetic induction in the sample to the applied magnetic field intensity.

$$\text{i.e., } \mu = \frac{B}{H} \text{ henry } m^{-1}$$

Thus it measures the amount of produced magnetic induction in the sample per unit magnetic field intensity .

(v) Magnetic susceptibility (χ) of a material is the ratio between the intensity of magnetisation produced in the sample and the intensity of the applied magnetic field.

$$\text{i.e., } \chi = \frac{I}{H}.$$

It has no unit. Thus it measures the amount of magnetisation produced in the sample during the application of magnetic field.

(vi) Relation between μ and χ

Now $B = \mu H$.

This equation can be written in other way as

$$B = \mu_o (I + H)$$

where μ_o is the permeability of free space.

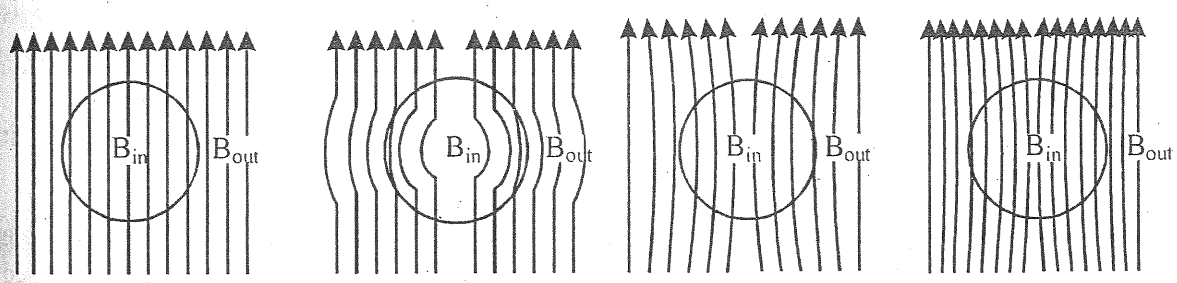
The relative permeability $\mu_r = \frac{\mu}{\mu_o} = \frac{B/H}{B/(H+I)} = 1 + \frac{I}{H} = 1 + \chi$

where χ is the susceptibility of the medium. The relative permeability has no unit. The magnetic materials must have high permeability so that large fluxes may be produced.

5.12 DIFFERENT TYPES OF MAGNETIC MATERIALS

(a) Diamagnetic materials and their properties

1. The diamagnetism is the phenomenon by which the induced magnetic moment is always in the opposite direction of the applied magnetic field.
2. The magnetic material having negative susceptibility is called a diamagnetic material.
3. Further for the diamagnetic materials, each atom has no permanent magnetic moment.
4. The number of orientations of electronic orbits in an atom of the diamagnetic material is such that the vector sum of magnetic moments is zero. The external field will cause a rotation action on the individual electronic orbits. This produces an induced magnetic moment which is in the direction opposite to the field and hence tends to decrease the magnetic induction present in the specimen (figure 5.12(b)).



$B_{in}=B_{out}$	$B_{in}<B_{out}$	$B_{in}>B_{out}$	$B_{in}>>B_{out}$
(a) Normal material	(b) Diamagnetic material	(c) Paramagnetic material	(d) Ferromagnetic material

Figure 5.12 Behaviour of magnetic materials in the presence of magnetic field

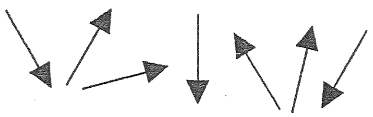
Figure 5.12(a) shows the ordinary material which has no repulsion or attraction for the magnetic flux lines when it is placed in an uniform magnetic field. But in figure 5.12(b), there is repulsion of magnetic flux from the centre of the material indicating the diamagnetic behaviour of the magnetic material.

5. Diamagnetic materials repel magnetic lines of force.
6. There are no permanent dipoles; consequently magnetic effects are very small.

7. Generally the value of diamagnetic susceptibility is independent of temperature and applied magnetic field strength.

   Examples : Organic materials, light elements, Alkali earths, Bismuth, Niobium and its compounds in the superconducting state, etc.

(b) Paramagnetic materials and their properties

1. The paramagnetism is the phenomenon by which the orientations of magnetic moments are largely dependent on temperature and applied field. If the applied magnetic energy is greater than the thermal energy, the magnetic moment of the material is finite and large.
2. The number of orientations of orbital and spin magnetic moments be such that the vector sum of magnetic moments is not zero and there is a resultant magnetic moment in each atom even in the absence of applied field.
3. If we apply the external magnetic field, there is an enormous magnetic moment along the field direction and the magnetic induction will increase.
4. Paramagnetic materials attract magnetic lines of force (Figure 8.1(c)).
5. They possess permanent magnetic dipoles.
6. The value of the paramagnetic susceptibility is independent of the applied magnetic field and depends greatly on temperature such that $\chi = \frac{C}{T-\theta}$ where C is the curie constant and θ is the curie temperature.
7. When the temperature T is less than the curie temperature of the material, it is converted into diamagnetic.
8. These materials are used in Lasers and Masers where one can create the required energy levels for transition. Paramagnetic property of oxygen is used in the nuclear magnetic resonance imaging instrument which is used to diagnose the brain tumor or blood clot in the brain.
9. **Spin alignment :** 

   Examples : Alkali metals (Na, K), transition metals, chromium and yttrium.

(c) Ferromagnetic material and their properties

1. Ferromagnetism is a phenomenon by which spontaneous magnetisation occurs when $T \leq \theta$ and so even in the absence of applied filed, the magnetic moments are enormous. Here θ is the curie temperature of the material.

2. Ferromagnetism arises when the exchange energy is favourable for spin alignment.
3. If a material acquires a relatively high magnetization in a weak field, then it is ferromagnetic.
4. Magnitude of Susceptibility is very large and positive.
5. When temperature is greater than curie temperature 'θ' then it is converted into paramagnetic.
6. When temperature is less than 'θ', the material is in ferromagnetic state and χ is very large due to spontaneous magnetization.
7. Due to the large internal field, the permanent dipoles are strongly aligned in the same direction and consequently a large spontaneous magnetization results even in the absence of an applied field.
8. They attract the lines of force very strongly (Figure 8.1(d)).
9. They exhibit magnetization even when the magnetizing field is removed. i.e. they exhibit magnetic hysteresis.
10. During heating they lose their magnetization slowly.
11. **Spin alignment :**

Examples : Fe, Ni, Co.

(d) Antiferromagnetic materials and their properties

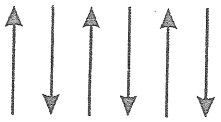
1. This refers to spin alignment in an antiparallel manner in neighbouring magnetic ions resulting in zero net magnetization.
2. Magnitude of susceptibility is small and positive. At T = 0, the net spin magnetic moment of an A - site atoms is equal and opposite to the net spin magnetic moment of B-site atoms. Therefore $I_A = I_B$ (or) $\chi = 0$. But as the temperature increases, I_A and I_B vary in a slightly different manner. This will lead to a positive and small value of susceptibility for these materials. The susceptibility varies with temperature as shown in figure 8.2. Here I_A and I_B are the intensity of magnetization in A sites and B sites respectively.
3. Temperature dependence of susceptibility : When $T > T_N$ (Neel temperature),

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

4. The opposite alignment of adjacent magnetic moments in a solid is produced by an (unfavourable) exchange interaction.

5. Initially susceptibility increases slightly as the temperature increases and beyond Neel temperature the susceptibility decreases with the temperature.

6. Neel temperature is the temperature at which susceptibility of the material is maximum.

7. **Spin alignment :** 

Examples : FeO (ferrous oxide), MnO (manganese oxide), Cr_2O_3 (chromium oxide) and salts of transition elements.

(e) Ferrimagnetic materials and their properties

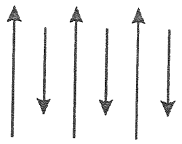
1. It is a special case of antiferromagnetic in which antiparallel moments are of different magnitudes and a large magnetization arises.

2. Magnitude of susceptibility is very large and positive.

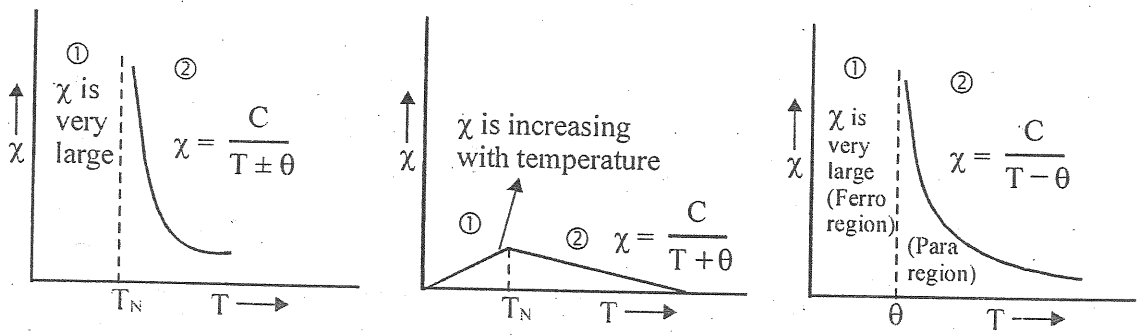
3. Temperature dependence of susceptibility : At $T > T_N$, $\chi = \dfrac{C}{T \pm \theta}$

4. These are composed of two or more sets of different transition metal ions. There are different number of ions in each set. Due to that, unlike antiferromagnetics, there is a net large magnetization.

5. These are also called ferrites.

6. **Spin alignment :** 

Examples : Ferrous Ferrite and Nickel ferrite

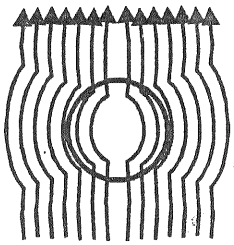
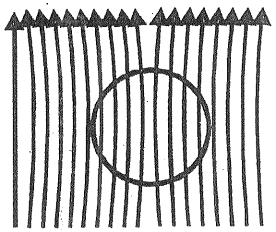
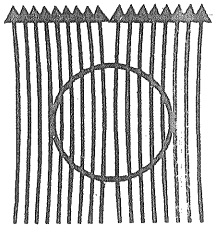


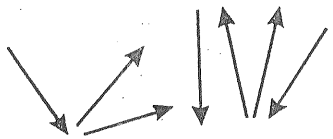
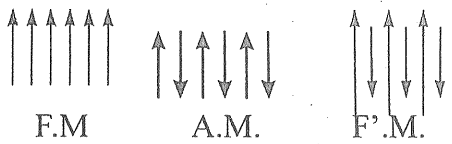
Ferrimagnetic material **Anti - Ferromagnetic material** **Ferromagnetic material**

Figure 5.13 Variation of the susceptibility with temperature in different magnetic materials

Figure 5.13 shows the variation of susceptibility with temperature for ferri, antiferro and ferromagnetic materials.

Table 5.1 Distinction between dia, para and ferromagnetic materials

	Diamagnetic material	Paramagnetic material	Ferromagnetic material
1. Definition	It is a material in which there is no permanent dipole moment (or) magnetic moment in each atom. The induced magnetic moment produced in these materials during theapplication of the external magnetic field decreases the magnetic induction present in the specimen.	It is a material in which there is permanent dipole moment (or) magnetic moment in each atom. The induced magnetic moment produced in these materials during the application of the external magnetic field increases the magnetic induction present in the specimen.	It is a material in which there is enormous permanent dipole moment (or) magnetic moment in each atom. The induced magnetic moment produced during the application of the exteranl magnetic field is very large and it increases the magnetic induction present in the specimen.
2. Susceptibility and its temperature dependence	It is always negative and it is independent of the temperature and strength of applied magnetic field also.	It is always positive and small and it is inversely proportional to absolute temperature of the material.	It is always positive and large and it depends upon temperature in a complex manner.
3. Behaviour of material in the presence of magnetic field.	 In a normal material $B_{in} = B_{out}$. But in a diamagnetic material, the magnetic lines of force are repelled away from the centre of the material and hence $B_{out} > B_{in}$.	 The magnetic lines of force are attracted towards the centre of the material and hence $B_{in} > B_{out}$.	 The magnetic lines of force are highly attracted towards the centre of the material and hence $B_{in} >> B_{out}$

4. Spin alignment (or) magnetic moment alignment	No spin (or) magnetic moment	 All spins (or) magnetic moments are randomly oriented.	 All spins (or) magnetic moments are orderly oriented. Antiferro magnetic materials (A.M.) and ferrimagnetic materials (F'.M.) are the special cases of ferromagnetic materials (F.M.) on the basis of spin alignmemt.
5. Origin	Arises from the Larmor precession of the electronic orbits in the presence of applied magnetic field.	Arises from the magnetic moments orientation along the external magnetic field direction and magnetic moments orientation is largely determined by tempera ture and applied magnetic field.	Arises from the spontaneous magnetization due to local molecular magnetic field which arises from exchange interaction between unpaired electrons of adjacent atoms in the crystal lattice.
6. Magnetic phase transition	At very low temperatures (≈1K) the superconductors are perfect diamagnetic. When we increase its temperature beyond its critical temperature diamagnetism suddenly disappears and then it behaves like a normal material.	When the temperature of material is less than its curie temperature it is converted into diamagnetic substance. But paramagnetic curie temperature is very low (100K)	When the temperature of material is greater than its curie temperature it is converted into paramagnetic. The ferromagnetic curie temperature is very high.
7. Examples	Hydrogen, Bismuth and super-conducting materials like Niobium and its components.	Aluminium, Platinum, crown glass and Iron (or) Nickel salt solutions.	**Ferromagnetic materials :** Iron, Nickel and Cobalt. **Antiferromagnetic materials:** Ferrous oxide, Zinc ferrite and Manganese oxide. **Ferrimagnetic materials:** *Nickel ferrite, Manganese ferrite and Ferrous ferrite*

5.13 CLASSICAL THEORY OF DIAMAGNETISM (Langevin theory)

An atom is made up of central positive nucleus and number of electrons revolving around it in discrete orbits. This will result in the production of magnetic field perpendicular to the plane of the orbit. Thus the electronic orbits are associated with a magnetic moment. Most of the orbital planes are not parallel to each other and sense of rotation is not essentially the same. Hence the vector sum of magnetic moments is zero and so there is no resultant magnetic moment for each atom.

But in the presence of external magnetic field it causes a rotation action on the individual electronic orbits. This action produces an induced magnetic moment which according to Lenz's Law will be in direction opposite to the field and hence tend to decrease the magnetic induction. This action is called ***dismagnetic action*** and the substances belonging to this action are called ***diamagnetic substances***.

Theory : Consider a circular orbit of radius 'r_o' in which an electron revolves with an angular velocity 'ω_o'. This constitutes a current of magnitude $\frac{e\omega_o}{2\pi}$ where $\frac{\omega_o}{2\pi}$ is the frequency and e is the electronic charge.

Therefore the magnetic moment associated with this electron,

$\mu_e = iA = \frac{e\omega_o \pi r_o^2}{2\pi} = \frac{1}{2} e\omega_o r_o^2$ where A = area of cross section of the circular orbit. The angular momentum of the electron due to rotation of the electron of mass 'm' = $m \omega_o r_o^2 = L$. Hence $\mu_e = \frac{1}{2} eL/m$. From Bohr's theory, $L = n \hbar$ where n is an integral number. Therefore, 'μ_e' the magnetic moment of the electron is multiple of $\frac{e\hbar}{2m}$. i.e., $\mu_e = \frac{ne\hbar}{2m}$ where $\frac{e\hbar}{2m}$ is called Bohr Magneton. Here $\hbar = h/2\pi$ where h is the Planck's constant.

Thus a Bohr magneton is used as a practical unit for electron's magnetic moment. One Bohr magneton $= \frac{e\hbar}{2m} = 9.27 \times 10^{-24}$ ***A–m²***.

The total magnetic moment of the atom will be given by the vector sum of the moments of each orbit.

According to Larmor, the external field causes the 'Precession' of the orbits and the velocity of the precision is given by $\omega = \frac{-eB}{2m}$.

This produces a variation in the magnetic moment of the electron. The variation in the magnetic moment is given by

$$\Delta\mu_e = \mu_e \text{ (final)} - \mu_e \text{ (initial)}$$

This produces a variation in the magnetic moment of the electron. The variation in the magnetic moment is given by

$$\Delta\mu_e = \mu_e \text{ (final)} - \mu_e \text{ (initial)}$$

$$\therefore \Delta\mu_e = \frac{er_o^2}{2}((\omega+\omega_o)-\omega_o) = \frac{er_o^2\,\omega}{2} = \frac{-e^2 Br_o^2}{4m}$$

The negative sign shows that an increasing magnetic field tends to induce currents which produce a field opposite in direction to the applied field.

The above expression is only for an electronic orbit. Since complex atoms have more electrons, the r_o^2 term is replaced by $\sum_n \bar{r}_o^2$ by an appropriate average value since all the orbits are neither equal nor circular.

$$\therefore \Delta\mu_A = \frac{-e^2 B}{4m}\sum \bar{r}_o^2$$

In a plane, $\bar{r}_o^2 = \bar{r}_x^2 + \bar{r}_y^2$

For a spherically symmetric atom,

$$r_x^2 = r_y^2 = r_z^2 = \frac{1}{3}r^2$$

$$\therefore \bar{r}_o^2 = \frac{2}{3}\bar{r}^2$$

where the bars indicate the average value for all the electrons. The magnetic moment per kilogram atom $\Delta\mu = \frac{-Ne^2 B}{4m}\frac{2}{3}\sum \bar{r}^2$ where N is the Avagardo number. If the atom possesses no intrinsic moment, the kilogram atomic susceptibility,

$$\chi = \frac{\Delta\mu}{H} = \frac{-\mu_o Ne^2}{6m}\sum \bar{r}^2$$

Results

1. The diamagnetic susceptibility arises from the Larmor precession of the electronic orbits and it is determined by the charge distribution in the atom. It is independent of temperature.

2. The diamagnetism is the inherent property of all atoms and molecules. Only if the atom possesses an initial magnetic moment then it behaves as para or ferromagnetic.

Drawbacks

1. In most of the diamagnetic materials the susceptibility varies with temperature at very low temperatures. But according to classical theory it is independent of temperature.

2. Further the value of the susceptibility depends upon the physical nature of the material. But it is not indicated in this theory.

5.14 LANGEVIN THEORY OF PARAMAGNETISM

1. Langevin considered a paramagnetic gas in which each atom or molecule possesses a permanent magnetic moment. These magnetic moments are arising from a particular combination of orbital and spin magnetic moments of the electrons.

2. These magnetic moments, in the absence of any external field, point in random directions so that there is no resultant magnetic moment for paramagnetic material eventhough each atom or molecule possesses intrinsic permanent magnetic moment. This happens because the interaction energy between the dipoles is smaller than the thermal energy given by kT where k is Boltzmann's constant and 'T' is the temperature of the material in kelvin.

3. When an external field is applied the individual atomic magnetic moments tend to line up along the field direction and individual atomic moments produce a net magnetization, counteracting the thermal agitation. When the atoms and ions are acted upon individually with no mutual interaction between them, the effect is called ***paramagnetism.***

4. Paramagnetism depends upon the magnetic moment of ions or atoms. So the state of magnetization will be determined by the applied magnetic field and the thermal agitation (i.e., temperature).

5. The probability that a dipole inclined at an angle to the field direction in thermal equilibrium is proportional to exp (μ B cos θ/kT) by Maxwell-Boltzmann distribution.

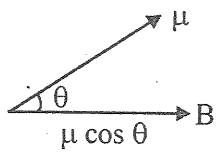


Figure 5.14(a) Orientation of magnetic moment with respect to applied field

6. If 'n_0' is the total number of dipoles, then the number of dipoles, 'n' inclined at an angle θ with the field direction is given by $n = n_0 \exp(\mu B \cos\theta/kT)$ (figure 5.14(a)).

7. Average magnetic moment $\bar{\mu}$ in the field direction is given by the sum of the resolved components of magnetic moments of all the dipoles in the field direction divided by the total number of dipoles.

$$\text{i.e. } \bar{\mu} = \frac{\int \mu \cos\theta \, dn}{\int dn}$$

where $dn = -n_0 \exp(\mu B \cos\theta / kT) \sin\theta \, d\theta \, (\mu B/kT)$

$$\therefore \bar{\mu} = \frac{-n_0 \int \mu \cos\theta \exp(\mu B \cos\theta/kT) \sin\theta \, d\theta}{-n_0 \int \exp(\mu B \cos\theta/kT) \sin\theta \, d\theta}$$

Putting the limits for θ and keeping $\alpha = \mu B/kT$,

$$\bar{\mu} = \frac{\int_0^{\pi} \mu \cos\theta \exp(\alpha \cos\theta) \sin\theta \, d\theta}{\int_0^{\pi} \exp(\alpha \cos\theta) \sin\theta \, d\theta}$$

Put $\cos\theta = x$

$\therefore -\sin\theta \, d\theta = dx$

$$\bar{\mu} = \frac{\int_{-1}^{1} \mu x \exp(\alpha x) \, dx}{\int_{-1}^{1} \exp(\alpha x) \, dx}$$

Evaluating the integrals in the above equation for $\bar{\mu}$, we get

$$\bar{\mu} = \mu \frac{\alpha}{\left(e^{\alpha} - e^{-\alpha}\right)} \left[\frac{1}{\alpha}\left(e^{\alpha} + e^{-\alpha}\right) - \left(\frac{e^{\alpha} - e^{-\alpha}}{\alpha^2}\right)\right]$$

$$\therefore \bar{\mu} = \mu \left\{\frac{e^{\alpha} + e^{-\alpha}}{e^{\alpha} - e^{-\alpha}} - \frac{1}{\alpha}\right\} = \mu \left\{\coth\alpha - \frac{1}{\alpha}\right\}$$

$\therefore \bar{\mu} = \mu L(\alpha)$ where $L(\alpha)$ is called Langevin function.

Case - 1

Consider $\mu B >> kT$ (or) α is very large. In such a case T is very small (or) B is large.

$$\therefore |L(\alpha)|_{\alpha\to\infty} = \left|\coth\alpha - \frac{1}{\alpha}\right|_{\alpha\to\infty}$$

$$= \left|\frac{e^{\alpha}+e^{-\alpha}}{e^{\alpha}-e^{-\alpha}} - \frac{1}{\alpha}\right|_{\alpha\to\infty} = \left|\frac{1+e^{-2\alpha}}{1-e^{-2\alpha}} - \frac{1}{\alpha}\right|_{\alpha\to\infty} = 1$$

$$\therefore \bar{\mu} = \mu$$

If N is the number of dipoles/unit volume, then magnetization 'I' = N $\bar{\mu}$ = Nμ = I_s where I_s is the saturation value of magnetization.

Case - 2

Consider $\mu B << kT$ (or) α is very small. i.e., T is large (or) B is small.

$$|L(\alpha)|_{\alpha\to 0} \left|\frac{1}{\alpha}\left(1+\frac{\alpha^2}{2}\right) - \frac{1}{\alpha}\right|_{\alpha\to 0} = \frac{2\alpha}{6}$$

$$\therefore |L(\alpha)|_{\alpha\to 0} = \frac{\alpha}{3} = \frac{\mu B}{3kT}$$

So the intensity of magnetization $I = N\bar{\mu} = \frac{N\mu^2 B}{3kT} = \frac{N\mu^2\mu_o H}{3kT}$. ... (A)

Susceptibility $\chi = \frac{I}{H} = \frac{\mu_0 N\mu^2}{3kT} = \frac{C}{T}$ where C is called Curie constant and relation is called Curie's law or Curie - Langevin relation since Curie found experimentally this relation before Langevin's theoretical derivation.

Weiss postulated the internal molecular field to get a relationship between para and feromagnetism. This internal molecular field is represented by H_i, then $H_i = \lambda I$ where λ is molecular field coefficient or Weiss constant. Therefore the net effective field should be $H_e = (H+H_i)$ which is a vector sum of external applied field 'H' and internal molecular field 'H_i'.

Following the Langevin theory along with this effective field,

$$I = \frac{\mu_o\mu^2 NH_e}{3kT} = \frac{\mu_o\mu^2 N(H+\lambda I)}{3kT}$$ (Refer equation (A) in Langevin theory)

Rearranging the terms, we get

$$I\left(1-\frac{\mu_o \mu^2 N\lambda}{3kT}\right) = \frac{\mu_o \mu^2 NH}{3kT}$$

Let $C = \mu_o \mu^2 N/3k$ and $\theta = C\lambda$; we get $I\left(1-\frac{\theta}{T}\right) = \frac{CH}{T}$

$$\therefore \chi = \frac{I}{H} = \frac{C}{T\left(1-\frac{\theta}{T}\right)} = \frac{C}{T-\theta}$$

where C is called Curie constant and θ is called paramagnetic Curie point or Curie temperature. The equation is called Curie Weiss law. From that we can infer that below Curie temperature ($T < \theta$), susceptibility becomes negative; i.e., paramagnetics would become diamagnetics. However Curie temperature is quite low for most of the paramagnetic substances and so a situation for which $T < \theta$ is rare.

5.15 DOMAIN THEORY OF FERROMAGNETISM

(a). Magnetic domains

1. Weiss proposed this concept of Domains in 1907 to explain the hysteresis effects observed in Ferromagnetic materials as well as to explain the properties of Ferromagnetic materials.

2. A region in a ferromagnetic material where all the magnetic moments are aligned in the same direction is called a ***domain***. A magnetic domain is completely magnetised and has definite boundaries. So a ferromagnetic material is divided up into these small regions, called domains, each of which is at all times completely magnetized.

3. The direction of magnetization, however, varies from domain to domain and thus the net macroscopic magnetization is zero in a virgin specimen in the absence of external magnetic field.

4. But when the ferromagnetic material is in the magnetic field, in the initial stages of magnetization in the material, the domains having moments parallel to the magnetic field increases in area; in the final saturation stage, the other domains are rotated parallel to the field.

5. Similarly if we demagnetize the material the regular domain arrangement is changed and it is different from the original state. This creates the hysteresis in the ferromagnetic substances.

6. Each domain is grown by motion of domain walls and rotation of domain. A domain is formed by favourable spin-spin exchange interaction

5.16 HYSTERESIS

The hysteresis of ferromagnetic materials refers to the lag of magnetization or magnetic induction behind the magnetizing field. Thus the irreversible B-H characteristics of ferromagnetic materials is known as hysteresis.

A hysteresis loop 'ABCDEA' is a curve showing the change in magnetic induction of a ferromagnetic material to which an external field is applied as the intensity of this field is varied from H_s to $-H_s$ and back again.

Hysteresis loss is a loss of energy in taking a ferromagnetic body through a cycle of magnetization and this loss is represented by the area enclosed by the hysteresis loop.

When the magnetizing field is reduced to zero, the magnetic induction of the material does not come to zero, and this value of magnetic induction is called ***residual magnetism or retentivity***. Thus the retentivity of a specimen is defined as the magnetic induction retained by the specimen when the magnetizing field is reduced from saturation value to zero.

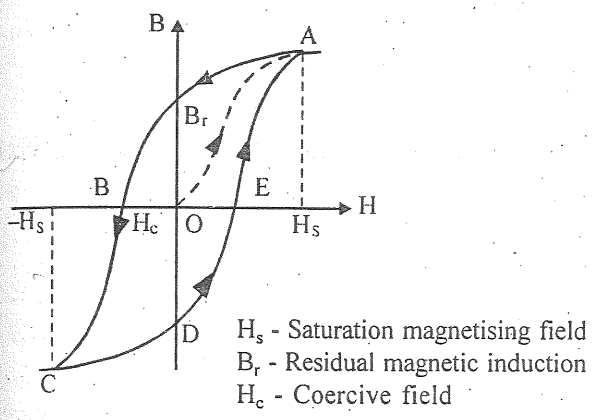


Figure 5.15(a) Hysteresis of ferromagnetic materials

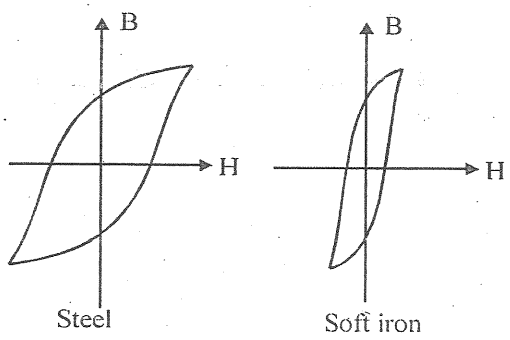


Figure 5.15(b) Hysteresis of steel and soft iron

Similarly ***coercive force or coercivity*** of a magnetic specimen is the magnitude of the demagnetizing field required to reduce the residual magnetism to zero. In the figure 5.15(a) the residual magnetic induction, coercive field and saturation of the magnetizing field are shown. Energy product (B_rH_c) of a magnetic material is the product of residual magnetic induction (B_r) and demagnetizing field strength (H_c).

A study of the hysteresis loop of different magnetic materials helps us to know their magnetic properties. For example let us see the hysteresis curves for soft iron and steel. From the loop we are able to get the following results.

1. The area of the loop for steel is greater than that of soft iron, showing a higher energy loss per cycle per m^3 for steel.

2. The B-H curve is steep for soft iron indicating quick magnetization. Further the magnetizing field necessary to saturate the soft iron is much smaller than that for steel. Further permeability and susceptibility are greater for soft iron.
3. A greater retentivity is appeared in the case of steel.
4. The coercivity is greater for steel than for soft iron (Figure 5.15(b). It shows that a greater demagnetizing force is required for steel to destroy the residual magnetic induction.

Therefore soft iron is used in electromagnets where a high value of magnetic induction is required. Further since the hysteresis loss is very small, it is also used in cores of transformers, dynamoes and telephone diaphragms. Steel is used in making permanent magnets because it will not be easily demagnetized.

(e) Explanation of hysteresis curve on the basis of domain theory

1. When a field is applied, domains where the magnetization is parallel or at a small angle with the field grow at the expense of those where the magnetization is antiparallel so that the boundary between domains is displaced.
2. Initially (OA) the magnetization of the substance as whole proceeds by small reversible boundary displacement but the steeper part (AB) of the magnetization curve is due to larger, irreversible displacements (figure 5.16).
3. Above the knee of the curve (BS) magnetization proceeds by rotation of the direction of magnetization of whole domains and such a process is rather difficult and the increase in magnetization is relatively slow.
4. When the applied field is reduced, there is a little change in the domain structure so that the magnetic induction or magnetization remains quite high, until high reverse fields are applied.
5. Further even when the external filed is zero, there is a residual magnetization in the specimen and that can be destroyed by applying a high reverse field.

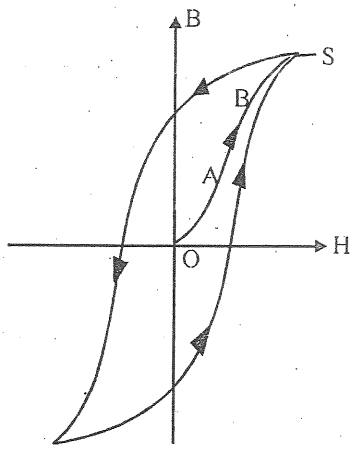


Figure 5.16 Explanation of hysteresis on the basis of domain theory

6. Thus the reversible and irreversible domain wall movements give rise to hysteresis in the ferromagnetic materials.

In the figure 5.16,

OA - Due to smaller reversible domain wall movement
AB - Due to larger irreversible domain wall movement
BS - Due to smaller irreversible domain rotation
S - Point of saturation

5.17 ANTIFERROMAGNETIC MATERIALS

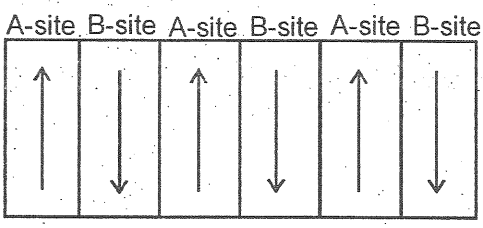
Antiferromagnetic materials are the magnetic materials in which the spin alignment of adjacent sites (A sites and B sites) is in an antiparallel manner and hence their intensity of magnetisation is equal and opposite resulting in zero net magnetisation at T = 0K.

Thus the susceptibility of antiferromagnetic materials at 0K is zero.

Above 0K, the alignment of spin magnetic moments in A sites and B sites are varying in a different manner. This will lead to a positive and small value of susceptibility for these materials. Alongwith the curie temperature, these materials have another critical temperature called Neel temperature at which the value of susceptibility is maximum. The variation of susceptibility with temperature is given in figure 5.13(b). Initially susceptibility increases slightly as the temperature increases and beyond Neel temperature, the susceptibility decreases witht the temperature such that $\chi = \frac{C}{T+\theta}$.

The opposite alignment of adjacent site spin magnetic moments in these materials is produced by an ***unfavourable exchange interaction.***

Spin alignment :



Examples: Fe O (ferrous oxide), Mn O(Manganese oxide), $Cr_2 O_3$ (Chromium oxide) and salts of transition elements.

Theory of Antiferromagnetism

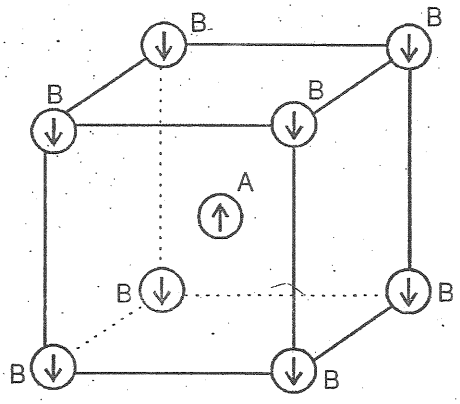


Figure 5.17 Body centred unit cell with spins of A atom oppositely directed to that of B atoms

Let us consider an antiferromagnetic crystal containing two types of atoms A and B distributed over two inter-locking lattices such that B atoms occupy the corner points of a body centred cubic lattice and A atoms occupy the body centres of these cubic lattices (Figure 5.17). Assume that the atom at A-site has its spin up and the arom at B-site has its spin down. All sites have a permanent magnetic dipole moment. Each A-site is surrounded by eight B-sites and each atom A has 8 nearest neighbours of B atom and vice versa. Let there be antiferromagnetic A-B interaction as well as A-A interaction and B-B interaction. If H_a and H_b are the net molecular magnetic fields at the A site and B site respectively, then

$$H_a = H - \alpha I_a - \beta I_b$$

$$H_b = H - \alpha I_b - \beta I_a$$

where H is the applied magnetic field; I_a and I_b are the intensity of magnetisation of the A and B lattices; α and β and the Weiss molecular field constants such that β is the A-B interaction constant and α is the A-A interaction or B-B interaction constant.

Let us consider three temperature regions.

Case I: $T > T_N$

i.e. when the temperature is above Neel temperature we are far away from saturation. Magnetisation of lattice A is given by

$$I_a = \left(N\mu^2 / 3kT \right) H_a$$

where N is the number of atoms per unit volume.

If we assume that the magnetic dipole moment on B sites is identical with those on A sites and there are equal number of A and B sites and equal number of atoms per unit volume in A and B sites, then we have

$$I_b = \left(N\mu^2 / 3kT \right) H_b$$

Let $I = I_a + I_b$

$$\therefore I = \left(\frac{N\mu^2}{3kT} \right) (H_a + H_b)$$

$$= \left(\frac{N\mu^2}{3kT} \right) (2H - (\alpha + \beta) I)$$

$$\therefore I \left[1 + \left(\frac{N\mu^2}{3kT} \right) (\alpha + \beta) \right] = \frac{2N\mu^2}{3kT} H$$

Taking $\theta = \frac{N\mu^2}{3k}(\alpha+\beta)$ = curie temperature and $C = \frac{2N\mu^2}{3k}$ = curie constant,

$$\chi = \frac{I}{H} = \frac{\frac{C}{T}}{1+\frac{\theta}{T}} = \frac{C}{T+\theta}$$

Case II : $T=T_N$

At the Neel temperature, still we are sufficiently far away from saturation effects.

Here the Neel temperature of the material increases when A-B interaction (β) is increased; it decreases when A-A interaction or B-B interaction (α) is increased.

$$\text{Hence } \frac{T_N}{\theta} = \frac{\beta-\alpha}{\beta+\alpha}$$

The above equation shows that $T_N < \theta$ indicates that α must be positive.

Case III : $T < T_N$

For simplicity, let us assume that there is only A-B interaction. i.e. $\alpha = 0$. As a result of crystalline anisotropy, there will be one or more of the natural spin directions along which the spins will tend to align. Therefore there are two cases of special interest. When the applied field is perpendicular to the natural spin direction,

$$\chi_\perp = \frac{1}{\beta}$$

Therefore, the susceptibility is independent of temperature.

When the applied field is parallel to the natural spin direction, at $T = 0$, $\chi_{\parallel} = 0$ and the susceptibility increases smoothly in a parabolic manner from zero at 0K to maximum at $T=T_N$ at which the spontaneous magnetisation vanishes and hence the value of susceptibility decreases with the rise of temperature.

5.18 FERRITES (Ferri magnetic materials)

(i) Structure and properties of ferrites

1. Ferrites are the modified structures of Iron with no carbon and are good examples of Ferrimagnetism in which the spins of adjacent ions in the presence of a magnetic field are in opposite senses and with different magnitudes.
2. They are made from ceramic ferro magnetic compounds.

3. Mechanically it has pure iron character. It has low tensile strength and it is a brittle, soft and non machinable one.

4. In these all valence electrons are tied up by ionic bonding and these are bad conductors with high resistivity of 10^{11} ohm metre.

5. Ferrites are manufactured by powder metallurgical process by mixing, compacting and then sintering at high temperatures followed by age hardening in magnetic fields.

6. These are mainly used in transformer cores, television scanning coils, memory devices and high speed switches.

7. The general formula is X Fe_2O_4 where X may be a metal as Mg, Mn or Zn.

8. These materials have low eddy current losses and low hysteresis losses at RF frequencies.

Normally there are two types of structures present in the ferrites.

Regular spinel

In the regular spinel, each trivalent metal ion occupies an octahedral site (B) and each divalent ion occupies a tetrahedral site (A) of FCC oxygen lattice.

Example : X^{2+} Fe_2^{3+} O_4 where X is divalent metal ion such as Mn, Cu, Ni, Mg, etc.

Inverse spinel

In the inverse spinel, trivalent metal ions occupy all tetrahedral sites (A) and half of octahedral sites (B) and the rest of octahedral sites (B) are occupied by divalent metal ions. **Example :** Fe^{3+} $(Fe^{2+}Fe^{3+})$ O_4 = Ferrous ferrite

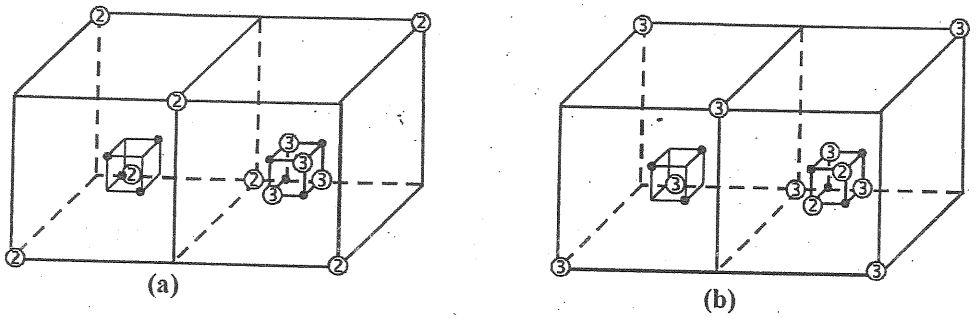


Figure 5.18 (a) Regular spinel structure (b) Inverse spinel structure

In figure 5.18(a), one circle enclosing the number ② is tetrahedrally surrounded by four O^{2-} or O^{--} ions indicated by solid dots and is called a tetrahedral site (site A). There are 8 tetrahedral sites in the unit cell of oxygen. The circle enclosing number ③ is surrounded octahedrally by six O^{2-} or O^{--} ions and is called an octahedral site (site B). There are 16 octahedral sites in the unit cell of oxygen. This type of arrangement belongs to regular spinel. In the inverse spinel (figure 5.18(b)) sites A are occupied by trivalent metal ions and half of sites B are occupied by trivalent metal ions and half of sites B are occupied by divalent metal ions.

(ii) Types of interaction present in the ferrites

Neel suggested that all the interactions in the ferrites are antiferromagnetic in sign. But that the A-B interaction is considerably stronger than the A-A or B-B interactions. If Nickel ferrite is truely ferromagnetic, then 12 Bohr magnetons should be present in that i.e., 7 Bohr magnetons in B site and 5 Bohr magnetons in A site. Since in A site there is ferric ion and in B site there are ferric and nickel ions due to inverse structure. But experimentally we observed that there are only 2.3 Bohr magnetons; so if we consider the interaction is antiferromagnetic along with Neel's suggestion, the net magnetic moment per molecule is the difference of 7 Bohr magnetons (B sites) and 5 Bohr magnetons (A sites). This is closely in agreement with experimental data. So nickel ferrite is a ferrimagnetic material.

In the case of zinc ferrite ($ZnFe_2O_4$) which has a normal or regular spinel structure, the A sites are entirely occupied by the non magnetic zinc ions and the ferric ions are in the B sites. Here A-B interactions are zero due to no magnetic moment in A sites. The ferric ions in B sites are aligned antiparallel through the antiferromagnetic B-B interaction. So B-B and A-A interaction are zero. So that zinc ferrite shows no magnetization and it is an antiferromagnetic material eventhough it is a ferrite.

(iii) Applications of ferrites

1. Ferrites are used to produce low frequency ultrasonic waves by magnetostriction principle. Further these are used in the electromechanical transducers.
2. Ferrite rods are used in radio receivers (particularly in medium wave coil) to increase the sensitivity and selectivity of receiver.
3. Ferrites like Nickel Zinc ferrites are used as cores in audio and T.V. transformers
4. Since for ferrites eddy current loss and hysteresis loss are small at microwave frequencies, these are widely used in non-reciprocal microwave devices like **gyrator** which is a two port unit transmitting power freely in two directions but with a differential phase shift of π radians between them, **circulator** which is a multiport unit providing sequential transmission of power between ports

but with finite phase shift between them and isolator which is a two port unit displaying differential attenuation. High resistivity with low hysteresis loss magnesium manganese ferrites are used in the above devices.

5. Based on nonlinear tensor permeability property, Ferrites can also be used in devices for power limiting and harmonic generation.

6. A ferromagnetic amplifier of microwave signals using ferrites can be designed utilizing spin precession of large amplitude as the coupling element. The use of ferrites in these parametric amplifiers provides very low noise figures.

7. Ferrites are also used in digital computers and date processing circuits. Normally here ferrites with rectangular hysteresis loops are used as magnetic storage elements.

i) Bistable elements

Ferrite core can be used as a Bistable element since after the passage of a saturation magnetizing current pulse, the remanent flux will be either $+\phi_r$ or $-\phi_r$ depending on the direction of the current pulse. In the absence of extraneous demagnetizing influences the core will hold this remanent flux indefinitely without further power consumption. It can therefore function as a storage for information in the binary code such that $-\phi_r$ and $+\phi_r$ may represent 'zero' and 'one' respectively. To read the stored information a negative current pulse of the same value of original current pulse for stored information may be passed through the primary or a further 'read out' winding. Since eddy currents are almost zero even under large and rapid flux reversals in ferrites these materials appear to be an obvious choice for switching cores in computers provided that they can be made to show the requisite rectangularity in their hysteresis loop.

Ferrox cube : It is one of the soft magnetic material and it is also a ferrite. It has square hysteresis loop. These have high permeability and high resistivity. They are used in switching circuits and in matrix storage and shift resisters of computers.

Example : Magnesium - Manganese Ferrite
(50% MgO + 50% MnO) – Fe_2O_3).

ii) Magnetic shift register

The function of a magnetic shift register or delay line is to accept and store information in binary code. The rectangular loop ferrite cores with low values of the switching coefficient and threshold field are used. We can construct magnetic shift register requiring two cores per stored digit or only one core per digit using rectifier circuits. Shift registers provide versatile facilities for

data storage and handling in computers. These can be used as frequency dividers. Large scale ready - access storage facilities can be provided conveniently by magnetic storage.

iii) Magnetic bubbles

Magnetic bubbles are also soft magnetic materials with magnetic domains of a few μ m in a diameter embedded in a matrix of a different spin orientation. These bubbles are the electronic analogue of the magnetic disc memories used in computers. The magnetic tape in the disc memory is moved mechanically whereas the bubbles in a bubble memory device are moved electrically at very high speeds. So the readout time or storing time is greatly reduced in bubble memory device.

8. The above applications are all based on the properties of soft ferrites. We have some hard ferrites which are used to make permanent magnets. Barium Ferrite ($BaO.6\ Fe_2O_3$) is one of the hard ferrites which is produced by sintering of a mixture of barium and ferric oxides. It is entirely different from the above said ferrites both in crystal structure and magnetic properties. It has enormous high coercivity and can be used to produce large magnetic flux and operate efficiently without external soft iron circuits unlike Alnico alloy.

(d) Garnets

1. Garnets are also ferrimagnetic materials like ferrites with the general formula $M_3Fe_5O_{12}$ where M is a trivalent metal ion and Fe is the trivalent ferric ion.

2. These are soft magnetic materials with small eddy current losses due to their high resistivities and small hysteresis losses at microwave frequencies.

3. These have a narrow resonance line width and are widely used as microwave isolators in the GHz range.

4. The Yttrium - iron garnet (YIG or $Y_3\ Fe_5\ O_{12}$) belongs to the rare earth iron garnet group and has very low magnetic losses than those of ferrites due to ordered arrangement of ions in the lattice. The oxygen lattice on which the structure is built is again of cubic close packed form, with a unit cell containing eight molecules of $Y_3\ Fe_5\ O_{12}$. The large yttrium ion 'pushes back' oxygen ions to form a site neighboured by eight oxygen atoms. All sizable existing voids are then occupied by yttrium or iron ions and there is no randomness in the ion distribution.

5.19 HARD AND SOFT MATERIALS

Hard magnetic material	Soft magnetic material

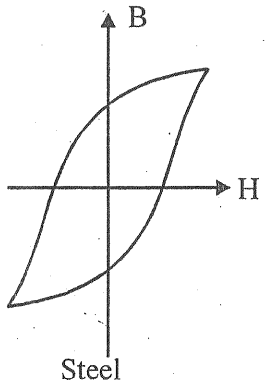
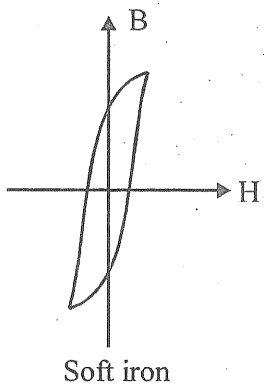

	

Figure 5.19 (a)	**Figure 5.19 (b)**
1. The above figure shows the nature of hysteresis loop of hard magnetic material.	The above figure shows the nature hysteresis loop of soft magnetic material.
2. Hard magnetic materials are magnetic materials which can not be easily magnetised and demagnetised.	Soft magnetic materials are magnetic materials which can be easily magnetised and demagnetised.
3. They have large hysteresis loss due to large hysteresis loop area.	They have small hysteresis loss due to small hysteresis loop area.
4. These materials have small values for permeability and susceptibility.	These materials have large values for permeability and susceptibility.

5. The eddy current loss is more due to its smaller resistivity.	The eddy current loss is more due to its higher resistivity.
6. In a hard magnetic material the domain wall movement is difficult owing to crystal imperfections and is irreversible in nature.	To obtain soft magnetic material the domain walls must be able to move easily and reversebly so that magnetisation changes by large amounts for small changes in the magnetising field.
7. The coercivity and retentivity are large.	The coercivity and retentivity are small.
8. In these materials, the irregularities (in the crystal structure) like mechanical strains will be more. Its magnetostatic energy is large.	These materials are free from irregularities (in the crystal structure) like strains or impurities. Its magnetostatic energy is very small.
9. These are produced by heating the material and then plunging it suddenly into cold oil (quenching process) which sets up internal stresses. So mechanical strains are purposely introduced to make it hard magnetic material.	These are manufactured as follows : Heating the pure material to a temperature where sufficient movement of the atoms is possible for them to settle into an ordered lattice, followed by a slow cooling (annealing process) so as not to disturb it.
10. **Examples** : Alnico alloy, Cunifes, Cunico and Silmanal.	**Examples** : Iron silicon alloy, ferrous nickel alloy, ferrite and garnets.
Uses :	**Uses :**
11. These are used to produce permanent magnets. Permanent magnets are used in magnetic detectors, microphones, flux meters, voltage regulators, damping devices and magnetic separators.	These are used in electro-magnetic machinery and in transformer cores. These are used in switching circuits, microwave isolators, shift registers amd matrix storage of computers and to produce electromagnets.

5.19.1 Applications of soft magnetic materials

The soft magnetic materials are used in electromagnetic machinery and transformers for making cores to increase the magnetic flux linkage.

Magnetic cores for use in alternating magnetic fields like those for transformers and rotating electrical machines are made from materials whose hysteresis loops are narrow in order to keep the hysteresis loss low. **Hysteresis loss** is directly proportional to area enclosed in the hysteresis loop for the material, frequency of the alternating current and volume of the material.

Alternating magnetic fields induce and e.m.f. in the cores and cause an electric current to flow in them. This current is called eddy current and the power loss, which appears in the form of heat, due to these eddy currents is called eddy current loss. **Eddy current loss** is inversely proportional to the resistivity of core material and directly proportional to square of maximum flux density, frequency of A.C. supply and thickness of each lamination of the core.

Thus the core material should have low hysteresis loss and low eddy current loss. We can get these properties from soft magnetic materials with high resistivity.

Recently ***metallic glasses*** which are metal alloys without having long range atomic order are also used as transformer core materials. These have high electrical resistivity and high permeability with low coercivity. They have negligible hysteresis loss and eddy current loss. Thus these are magnetically soft ferromagnetic materials. $Fe_{75}P_{15}C_{10}$, $Fe_{24}Zr_{76}$, $Ni_{60}Nb_{40}$ and $Fe_{40}Mo_{40}B_{20}$ are some examples for metallic glasses. These are not only used as light weight transformer cores but also used as magnetic shields and tape recorder heads. These are available in the form of films, tapes and thin sheets.

Other Examples for soft magnetic materials

(a) Iron - Silicon (Fe-Si) alloy

1. This alloy has more resistivity than pure iron. (4% of silicon is introduced). So it will reduce the eddy current loss and other transformer core losses.
2. These alloys will be suitable for operation at power frequencies of 50-60 Hz.
3. These are not suitable where high sensitivity and fidelity are required.

(b) Iron - Nickel (Fe-Ni) alloy

1. The above said properties are improved in these by magnetic annealing.

2. These alloys can be used upto audio frequencies.
3. Suppose if we want high sensitivity and high fidelity in an communication equipment then we can use Fi - Ni alloys such as permalloy (45% Nickel + 55% Iron) and superm alloy (79% Nickel + 16% Iron + 5% Molybdenum).
4. These have a high initial permeability than Fe-Si alloys. This tends to reduce the area under the hysteresis loop enabling their use at higher frequencies.
5. Mumetal (77% Ni + 16% Iron + 5% Copper + 2% Chromium) is also an important Nickel alloy.
6. These are used in AF and RF transformers.

(c) Ferrites and garnets are also soft magnetic materials (Refer section 5.18).

5.19.2 Different types of hard magnetic materials

Energy product (B_r H_c)

Energy product of a magnetic material is the product of residual magnetic induction (B_r) and demagnetising field strength (H_c).

When the value of the energy product of a material is very less, it is called soft magnetic material used for magnetic storage applications. When the value of the energy product is very large, the material is called hard magnetic material used for making permanent magnets. The energy product gives the energy required to demagnetise a permanent magnet.

High energy product materials for making permanent magnets

i) High carbon steels, low alloy tungsten and chromium steels and cobalt steels in the martensitic condition are used to produce permanent magnets. In these materials, the enormous value of mechanical hardness improves the resistance to domain wall motion.

Examples : Carbon steel (1% Mn, 0.9% C, 98.1% Fe)

Chrome steel (3.5% Cr, 0.9% C, 0.5% Mn, 95.1% Fe)

Cobalt steel (20% Co, 0.7% C, 7% W, 3% Cr, 69.3% Fe)

ii) Among the metallic alloys Alnico alloys are important. These are carbon free non-machinable alloys. Magnetic properties of these alloys are stable with time and temperature. These are difficult to cast and hence these are made with powder metallurgical techniques followed by age hardening in magnetic fields.

Heat treatment of Alnico alloys in a magnetic field increases the magnetostatic energy considerably. Among the common hard magnetic materials, only the Alnico alloys have higher energy product values. Alnico II (10% Al + 18% Ni + 12% Co + 6% Cu + 54% Fe) and Alnico V (8% Al + 14% Ni + 24% Co + 3% Cu + 51% Fe) are important types. The high percentage of cobalt (15% to 40%) promotes residual magnetism and coercive magnetic force in Iron. Thus Alnico V has more energy product than Alnico II. Very small powerful magnets can be produced from these alloys. Further permanent magnets with very large energy product are produced from Cobalt alloyed with rare earth elements.

iii) Cunifes (Cu, Ni, Fe), Cunico (Cu, Ni, Co) and Silmanal (Ag, Mn. Al) are important carbon free machinable magnet alloys. Magnetic properties are improved by precipitation hardening and by severe cold working.

iv) Permanent magnets with higher magnetostatic energy are made by pure iron with single domain or iron - cobalt powders compacted on a magnetic field. These are pressed powder magnets. ESD (elongated single domain) magnets are also made by the above process using fine particles of iron.

v) Metal oxide magnets are produced from metal oxide powders which are pressed into the desired shape, sintered and finally heat treated in a field. These have higher chemical stability.

Example : Iron - cobalt oxide magnet

$$(30\%\ Fe_2O_3 + 44\%\ Fe_3O_4 + 26\%\ Co_2\ O_3)$$

vi) There are some non metallic oxide magnets such as Barium Ferrite (already discussed in ferrites), Magnadur, etc., which have high energy product than Alnico alloys. Magnadur is also a hard ferrite with hexagonal ferrite structure.

Tables 5.2 and 5.3 show the important soft and hard magnetic materials properties and applications respectively.

Table 5.2 Important soft magnetic materials and their properties

Name of the alloy	Composition	Initial relative permeability (μ_r)	Resistivity ohm m	Hysteresis loss (J m^{-3})	Other properties	Applications
1. Fe - Si alloy	96% Fe, 4% Si	500	0.6×10^{-6}	100	1. Max. relative permeability is 7000 2. Resistivity is six times that of pure iron.	Cores of power transformers
2. Permalloy	55% Fe, 45% Ni	2700	0.55×10^{-6}	120	1. Max. relative permeability is 25000 2. higher hardness	Cores of audio and video transformers and communication equipment.
3. Supermalloy	79% Ni, 16% Fe, 5% Mo	100,000	0.65×10^{-6}	20	1. Max. relative permeability is 8000,000 2. Very high hardness	Cores of audio and radio transformers where low coercivity is required.
4. Mu metal	77% Ni, 5% Cu, 2% Cr, 16% Fe	80,000	0.6×10^{-6}	16	1. Max. relative permeability is 100,000 2. high stable magnetic properties even at very high frequencies. 3. high corrosion resistance	Cores of audio and radio transformers.
5. Ni-Zn ferrite	(80%NiO+ 20%ZnO) Fe_2O_3	500	10^6	35	1. very high resistivity 2. narrow hysteresis loop 3. max. relative permeability is 5000	Cores of audio and TV transformers
6. M_n-Z_n ferrite	(80%Mn O + 20%Zn O) Fe_2O_3	2000	10^8	40	1. max. relative permeability is 2500 2. very high dielectric constant.	Microwave isolators and gyrators
7. Mg - Mn ferrite	(50%MgO + 50% MnO) Fe_2O_3	4000	10^8	20	1. rectangular hysteresis 2. very high resistivity and low eddy current losses.	Memory cores in computers
8. Y I G	$Y_3Fe_5O_{12}$	3000	10^{11}	15	1. low eddy current losses 2. very high resistivity 3. very high dielectric constant	Microwave equipment as non reciprocal devices.

Table 5.3 Important hard magnetic materials and their properties

Name of the alloy	Composition	Retentivity B_r weber m^{-2}	Coercivity H_c kA m^{-1}	Energy product $B_r H_c$ k J m^{-3}	Other properties	Applications
1. Martensitic high carbon steel	upto 1% C	0.9	3.98	3.58	1. high strength and high hardness	for making permanent magnets
2. Tungsten steel	6%W, 0.7% C 0.3% Mn, 93% Fe	1.05	5.57	5.85	1. higher strength and higher hardness than carbon steels	for making permanent magnets
3. High chrome steel	3.5% Cr, 1%C, 0.4%Mn 95.1%Fe	0.95	5.17	4.91	1. higher hardness 2. higher corrosion resistance	for making permanent magnets with stable energy product.
4. Cobalt steel (K S magnet steel)	36%Co, 7%W 3.5%Cr, 0.9%C 56.3Fe	0.95	18.31	17.4	1. high coercivity 2. high magnetic strength	for making permanent magnets.
5. Al-Ni-Co alloys	12%Co, 17% Ni, 10%Al, 6%Cu 55% Fe	0.8-1.2	60-120	48-144	1. high magnetic strength 2. high mechanical strength 3. produced by powder metallurgy 4. Alnico V is more powerful than Alnico II due to higher percentage of cobalt.	for making powerful permanent small magnets.
6. Cunifes	6%Cu, 36%Ni, 58% Fe	0.53	36	19	1. carbon free machinable alloy 2. magnetic properties are improved by hardening	for making large permanent magnets
7. Cunico	6%Cu, 40%Ni, 54% Co	1	40	40	1. Carbon free machinable alloy	for making large permanent magnets
8. Barium ferrite	$BaO . 6Fe_2 O_3$	0.2	140	29.4	1. high coercivity 2. high stable magnetic properties	for making powerful magnets.

SOLVED PROBLEMS

1. **An iron rod of density 7.7×10^3 kg/m^3 and specific heat 0.462×10^{-3} J/kg K is subjected to cycles of magnetization at the rate of 50 cycles per second. If the area enclosed by B-H loop corresponds to energy loss of 10^{-2} J, find the rise of temperature per minute assuming that the heat generated is not radiated.**

Energy loss per second per unit volume $= 10^{-2} \times 50$ J

Heat produced in one minute per unit volume $= 10^{-2} \times 50 \times 60$ J

This is also equal to ρ s θ where θ is the rise in temperature in one minute

$\therefore\ 7.7 \times 10^3 \times 0.462 \times 10^{-3} \times \theta = 10^{-2} \times 50 \times 60$

$$\text{Temperature rise } '\theta' = \frac{30}{7.7 \times 0.462} = 8.43\text{K}$$

2. **In the Bohr model of the hydrogen atom the electron circulates around the nucleus in a path of radius 5.1×10^{-11} metre at a frequency ν of 6.8×10^{15} revolutions per second. What are the values of B at the centre and its dipole moment?**

$$i = \frac{dq}{dt} = e\nu = 1.6 \times 10^{-19} \times 6.8 \times 10^{15} = 1.1 \times 10^{-3} \text{ ampere.}$$

$$B = \frac{\mu_o i}{2R} = \frac{4\pi \times 10^{-7} \times 1.1 \times 10^{-3}}{2 \times 5.1 \times 10^{-11}} = 14 \text{ weber/m}^2$$

The dipole moment $= i\,A = 1.1 \times 10^{-3} \times \pi \times (5.1 \times 10^{-11})^2 = 9 \times 10^{-24}$ ampere/m^2

3. **In a magnetic material the field strength is found to be 10^6 ampere/m. If the magnetic susceptibility of the material is 0.5×10^{-5}, calculate the intensity of magnetization and flux density in the material.**

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

$$\therefore\ I = \chi H = 0.5 \times 10^{-5} \times 10^6 = 5 \text{ ampere/m}$$

$$B = \mu_o (I+H) = 4\pi \times 10^{-7} (5+10^6) = 1.257 \text{ weber/m}^2$$

4. **The saturation value of magnetization of iron is 1.76×10^6 ampere/m. Iron has body centred cubic structure with an elementary cube edge of 2.86 Å. Calculate the average number of Bohr magnetons contributed to the magnetization per atom.**

$$1 \text{ Bohr magneton} = \frac{e\hbar}{2m} = 9.27 \times 10^{-24} \text{ ampere m}^2$$

$$N = \frac{2}{(2.86 \times 10^{-10})^3} \text{ per } m^3$$

Saturation magnetization $I_s = N\bar{\mu}$

$$\bar{\mu} = \frac{I_s}{N} = \frac{1.76 \times 10^6 \times (2.86 \times 10^{-10})^3}{2} \text{ per atom}$$

$$= 20.586 \times 10^{-24} \text{ ampere } m^2$$

In terms of Bohr magneton,

$$\bar{\mu} = \frac{20.586 \times 10^{-24}}{9.27 \times 10^{-24}} = 2.22 \text{ Bohr magneton / atom}$$

5. **A paramagnetic material is subjected to homogeneous field of 10^6 ampere/m at a room temperature of 30°C. Calculate the average magnetic moment along the field direction per spin in Bohr magnetons.**

Let us assume that single spin moment is equal to one Bohr magneton.

Magnetization of the material due to parallel spin is given by

$$I = N\beta \tanh\left(\frac{\mu_o H\beta}{kT}\right)$$

where β = Bohr magneton = $\frac{e\hbar}{2m}$

Average magnetic moment along the field direction per spin = $\frac{I}{N\beta}$

$$= \tanh\left(\frac{\mu_o H\beta}{kT}\right) \approx \frac{\mu_o H\beta}{kT} \text{ at room temperature.}$$

$$= \frac{4\pi \times 10^{-27} \times 9.27 \times 10^{-24} \times 10^6}{1.38 \times 10^{-23} \times 303}$$

$$= 2.79 \times 10^{-3} \text{ Bohr magneton/spin.}$$

6. **The area of the hysteresis loop drawn between B and H is 94m². Each unit space along the vertical axis represents 0.1 weber/m² and each unit space along the horizontal axis represents 20 ampereturns per metre . The steel used for drawing hysteresis loop weighs 7650 kg/m³. Determine**

   i. The hysteresis loss per cycle.

   ii. The hysteresis power loss in watt per cubic metre when there are 50 magnetization cycles per second and

iii. The power loss in watt per kilogram at 50 Hz.

i. The hysteresis loss per cycle.

= area of the hysteresis loop × value of unit length along Y - axis × value of unit length along X - axis

$= 94 \times 0.1 \times 20 = 188 \text{ J/m}^3$

ii. The hysteresis power loss per second $= 188 \times 500 = 9400 \text{ watt/m}^3$

iii. The power loss $= \frac{9400}{7650} = 1.23$ watt /kg.

SUMMARY

1. Magnetism arises from the orbital and spinning motion of the revolving electrons in atoms.
2. Dia, para and ferromagnetic materials are the important magnetic materials.
3. Diamagnetic materials have negative susceptibility, para and ferromagnetic materials have positive susceptibility.
4. Enormous magnetization in ferromagnetic materials even in the weak applied magnetic field is due to spontaneous magnetization which arises from the favourable exchange interaction between adjacent spins.
5. Domains are the small regions in a ferromagnetic material and are completely magnetised by favouroable exchange interaction among the electron spins aligned in the parallel manner.
6. The hysteresis loss will be small for soft magnetic materials and large for hard magnetic materials.
7. The area of the B-H loop represents the energy loss per m^3 of the specimen during one cycle of magnetization.
8. Ferrites are the ferrimagnetic materials in which the spins of adjacent ions in the lattice are in opposite directions with different magnitudes.
9. The general formula for ferrites is XFe_2O_4 where X may be a metal such as Mg, Mn or Zn.
10. Soft ferrites are used in the magnetic floppy disks, magnetic tapes, memory devices and magnetic bubble memories. Further they are also used as radio frequency transformer core materials and in the nonreciprocal microwave communication devices.

OBJECTIVE TYPE QUESTIONS

1. **Cobalt is**

   a. ferromagnetic b. ferroelectric c. dielectric d. paramagnetic

2. **Molecular**

   a. hydrogen is paramagnetic b. nitrogen is paramagnetic
   c. oxygen is triatomic d. oxygen is paramagnetic

3. **Which of the following materials has maximum magnetic permeability?**

   a. pure iron b. 4% silicon steel c. grain oriented Si-Fe d. cast iron

4. **If the steel at room temperature is magnetic the presence of which constituent can be ruled out?**

   a. ferrite b. pearlite c. austenite d. cementite

5. **Ferrites are sub - group of**

   a. ferro-magnetic materials b. ferri-magnetic materials
   c. diamagnetic materials d. paramagnetic materials

6. **Ferroxcube is most commonly made from**

   a. ferric-oxide b. magnesium-manganese ferrite
   c. iron dust d. none of the above

7. **Nickel is used in**

   a. automatic voltage regulators b. bulb filaments
   c. electrodes of thermionic valves d. pressure sensitive elements

8. **In case of ferromagnetic materials the spin moments associated with two sets of atoms are aligned**

   a. parallel to each other b. antiparallel to each other
   c. anti parallel but of unequal magnitude d. randomly

9. **Above the curie temperature, a magnetic material becomes**

   a. ferromagnetic b. paramagnetic c. diamagnetic d. none of the above

10. **In which of the following materials, the magnetization is nonlinearly related to the applied field?**

    a. ferromagnetic materials b. paramagnetic materials
    c. diamagnetic materials d. all of the above

11. In case of ferrimagnetic materials the spin moments of two sets of atoms are aligned

a. parallel to each other b. antiparallel to each other
c. antiparallel but of unequal magnitude d. randomly

12. Materials which lack permanent magnetic dipoles are called

a. diamagnetic b. ferromagnetic c. semimagnetic d. none of the above

13. Permalloy is

a. a non ferrous alloy used in air craft industry b. a polymer
c. a nickel and iron alloy having high permeability d. a kind of stainless steel

14. Magnetic recording tape is most commonly made from

a. small particles of iron b. silicon - iron c. ferric oxide d. silver nitrate

15. Which of the following is not a permanent magnetic material?

a. chromium steel b. silicon iron c. cobalt steel d. alnico

16. Ferrites are

a. ferro - magnetic materials b. non - magnetic materials
c. ferro - electric materials d. ferri - magnetic materials

17. Which of the following sets gives the ferro magnetic curie temperatures in ascending order.

a. Ni, Fe, Co b. Co, Ni, Fe c. Ni, Co, Fe d. Fe, Co, Ni

18. The following material is used for making permanent magnets

a. platinum cobalt b. alnico V c. carbon steel d. all the three

19. The converse of magnetostriction effect is

a. thompson effect b. villari effect c. curie effect d. bitter powder effect

20. Magnetostriction is the phenomenon

a. of producing electricity in ferromagnetic materials
b. of producing magnetism in conductors
c. of changes in permeability of ferromagnetic material during magnetization
d. of changes in physical dimensions of ferromagnetic materials during magnetization

ANS :

1. a	2. d	3. b	4. c	5. b	6. b	7. c	8. a	9. b	10.a
11. c	12. a	13. c	14. c	15. b	16. d	17. c	18. d	19. b	20. d

QUESTIONS

1. **Define magnetic moment. Explain the origin of magnetic moment at atomic level. What is a Bohr magneton?**

[May 2003, Set No.1]

2. **What are the sources of permanent dipole moment in magnetic materials?**

[May 2003, Set No.2]

3. **Explain the origin of magnetic moment. Find the magnetic dipole moments due to orbital and spin motions of an electron.**

[May 2003, Set No.4, Supplementary 2001]

4. **Find the value of spin magnetic moment of an electron if it has one Bohr magneton.**

[May 2003, Set No.2, Supplementary 2000]

5. **What is Bohr magneton? How is it related to magnetic moment of electron?**

[Jan 2003, Set No.1, Supplementary 2001]

6. **Define the terms magnetic susceptibility, magnetic permeability magnetic induction and magnetization.**

[May 2003, Set No.21]

7. **How materials are classified as dia, para and ferromagnetic? Explain.**

[May 2003, Set No.3]

8. **In hydrogen atom an electron 'e' revolves around the nucleus at a distance of 'r' metre with an angular velocity 'ω' radian. Obtain expression for magnetic moment associated with it due to its orbital motion.**

[May 2003, Set No.1]

9. **What is ferromagnetism? What are the special features of ferromagnetism?**

[May 2003, Set No.3, Set No.2]

10. **Explain classical theory of paramagnetism.**

[May 2003, Set No.2, Supplementary 2000]

11. **Explain the Weiss theory of ferromagnetism.**

[May 2003, Set No.1, Set No.2, Supplementary 2000]

12. **Explain quantum theory of paramagnetism**

[May 2003, Set No.4, Supplementary 2000]

13. **Explain ferrimagnetism.**

[May 2003, Set No.4, Supplementary 2000]

14. **Explain the domain theory of ferromagnetism. List out what further this theory can explain?**

[May 2003, Set No.1, Jan.2003, Set No.1, Supplementary 2001]

15. **What is ferromagnetism? Explain the hysteresis curve on the basis of domains.**

[May 2003, Set No.3, Supplementary 2000]

16. **Describe hysteresis loop. How is it used to classify the magnets?**

[May 2003, Set No.2, Supplementary 2001]

17. **What are ferrites? Explain the magnetic properties of ferrites and mention their industrial applications.**

[May 2003, Set No.3]

18. **Explain ferri and antiferromagnetism.**

[May 2003, Set No.3]

19. **Draw the alignment of magnetic dipole moments in ferro, ferri and antiferromagnetic materials.**

[May 2003, Set No.3, Supplemtnary 2001]

20. **Explain the hysteresis curve and its uses.**

[May 2003, Set No.1, Supplementary 2000]

21. **Distinguish between ferro, antiferro and ferrimagnetic materials.**

[May 2003, Set No.1, Supplementary 2000]

PROBLEMS

1. A magnetic material hs a magnetization of 3300 ampere/metre and flux density of 0.0044 weber/m^2. Calculate the intensity of magnetic field and relative permeability of the material.

[Ans: 203 Am^{-1} and 17.26]

2. The saturation magnetic induction of nickel is 0.65 weber/m^2. If the density of nickel is 8906 kg/m^3 and its atomic weight is 58.7, calculte the magnetic moment of nickel atom in Bohr magneton.

(**Hint**: Since $\chi >> 1$, $1 + \chi = \chi = \frac{\mu}{\mu_0}$ $\therefore$ magnetic moment = $\frac{B_s}{N\mu_0}$).

[Ans: 0.61 μ_B]

3. Calculate the diamagnetic susceptibility of copper. Assume 0.1 nm as the radius and only one elctron per atom contributes. Given : the lattice constant 'a' = 0.3608 nm for copper.

[Ans: -5×10^{-6}]

4. Using Langevin's relation, calculate the paramagnetic susceptibility at 300 K for a paramagnetic substance having 10^{28} atoms/m^3. The magnetic moment of each atom is 1.8×10^{-23} ampere–m^2. What would be the dipole moment of a bar of this material 0.1 metre long and 1 cm^2 cross-section placed in a field of 8×10^4 ampere/metre?

[Ans: 3.28×10^{-4}; 2.62 Am^2]

5. The saturation value of magnetization of iron is 1.74×10^6 ampere/metre. Iron has BCC structure with an elementary cube edge of 0.286 nm. Calculate the average number of Bohr magnetons contributed to the magnetization per atom.

[Ans: 2.2 Bohr magneton]

6. Consider a helium atom in its ground state. The mean radius of the atom = 0.528 nm. Density and atomic weight of helium are 0.178 kg/m^3 and 4.003 respectively. Calculate the diamagnetic susceptibility of a helium atom.

(**Hint**: Replace $\sum \bar{r}^2 = 2\bar{r}^2$ due to two electrons per atom in the formula)

[Ans: -0.8×10^{-9}]