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**B.Sc. => Solid-State Physics
Chapter - 3
Magnetic Properties of Matter**

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Magnetic Properties of Matter

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Syllabus: Dia, Para, Ferri and Ferromagnetic Materials, Classical Langevin Theory of dia – and Paramagnetic Domains. Quantum Mechanical Treatment of Paramagnetic. Curie's law, Weiss's Theory of Ferromagnetism and Ferromagnetic Domains. Discussion of B-H Curve. Hysteresis and Energy Loss.

Q.1. What are Dia, Para, Ferro and Ferrimagnetic substances?

Ans. (i) Diamagnetic substances are those substances which are feebly (weakly) magnetized in a direction opposite to the magnetising field in which they are placed. Thus these substances are feebly repelled by magnets and move from stronger to weaker regions of magnetic field. These substances are also simply known as dia- magnetics. Some examples of diamagnetics are water, copper, lead, zinc, bismuth, sodium- chloride, gold, mercury, graphite, hydrogen molecule, He, Ne etc.

(ii) Paramagnetic substances are those substances which are feebly magnetised in the direction of magnetising field in which they are placed. Thus these substances are feebly attracted by magnets and move from weaker to stronger parts of a magnetic field. These substances are also called paramagnetics. Some of paramagnetics are wood, aluminium, platinum, oxygen and cupric sulphate.

(iii) Ferromagnetic substances are those substances which are strongly magnetised in the direction of magnetising field in which they are placed. Thus these substances are strongly attracted by magnets and move from weaker to stronger parts of a magnetic field. These substances are also called ferromagnetism. Some prominent ferromagnetism are iron, steel, nickel, cobalt, and some alloys such as permalloy (Ni and Fe), omental (Ni, Fe, Cr and Cu) and alnico (Ni, Al, Co, Cu and Fe).

(iv) Antiferro and Ferrimagnetic substances: alllabexperiments.com

There are materials which exhibit very little external magnetism much less than the paramagnetism, are known as anti-ferromagnetics. For examples- Manganese dioxide in which the magnetic moments of various atoms are antiparallel i.e. the moments cancel each other completely and there is no net magnetization.

Further, there is one more type materials in which the magnetic moments are in opposite direction but there is only partial cancellation which results in

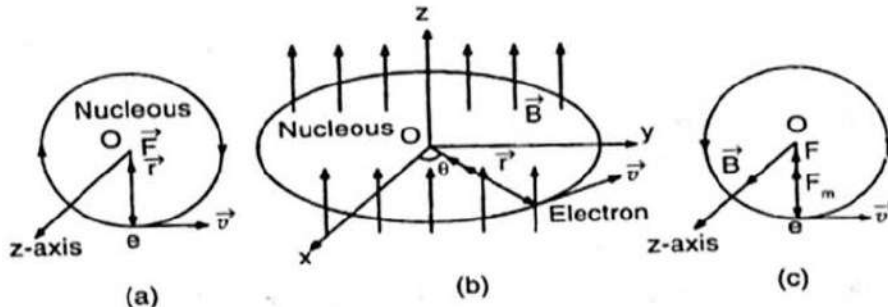
permanent magnetism, are known as ferrimagnetic. For example - Iron ferrite. Ferrites are very useful in the manufacturing of components of radio, computers and electrical communication equipments.

Q.2. What is Langevin Theory of Dia and paramagnetic domain? [Imp.]

Ans. We have seen that in an atom, electrons move around the nucleus in circular orbits. A moving electron is equivalent to an electric current which acquires magnetic dipole moment directed normally to the plane containing the electron orbit. An electron revolving in one direction will have magnetic moment in one direction and electron moving in opposite direction will have magnetic moment in the opposite direction. According to Langevin the electrons in the atoms of a diamagnetic substance revolve in such a way that the magnetic moments of the electron neutralize each other and there is no net magnetic moment due to orbital motion of electrons, i.e. there is no unpaired electron in a diamagnetic substance. When magnetic field is applied perpendicular to the plane of the orbit of the electron, the angular velocity of the electron would change without any change of the radius of the orbit. The increase or decrease in angular velocity will depend upon the direction of the magnetic field applied. The change in the angular velocity causes change in magnetic moment of the atom which is calculated as follows:

Determination of change in magnetic moment

Let us consider an electron of mass m and charge e coulomb is an atom revolving round the nucleus in a circular orbit of r in the X - Y plane with velocity \vec{v} in the anti-clockwise direction with nucleus at the origin (fig.(a)), then the orbital magnetic moment is



$$\vec{P}_m = \frac{-evr}{2} \hat{k} \quad \text{alllabexperiments.com}$$

$$\left(\therefore P_m = \text{orbital current} \times \text{area of orbit} = ev \times \pi r^2 = \frac{ev}{2\pi r} \times \pi r^2 = \frac{evr}{2} \right)$$

(Negative sign indicates that the direction of magnetic moment is along negative Z -direction)

As, $v = r\omega$, where ω is angular velocity of the electron so.

$$\vec{P}_m = \frac{e\omega r^2}{2} \hat{k} \quad \dots(1)$$

The total magnetic moment of the atom is the vector sum of the magnetic moments of each orbit. The centripetal force required for moving the electron in circular orbit is provided by the Coulomb's force of attraction between the nucleus and the electron and acts towards the centre O as shown in fig. and is given by

$$F = \frac{mv^2}{r} = mr\omega^2$$

Suppose a uniform magnetic field \vec{B} is now applied in the Z-direction. Then $\vec{B} = B\hat{k}$. The instantaneous velocity vector \vec{v} of the electron when its radius vector \vec{r} makes an angle θ with x-axis is given by $\vec{v} = v(-\sin\theta\hat{i} + \cos\theta\hat{j})$ when $(-\sin\theta\hat{i} + \cos\theta\hat{j})$ is the unit vector in the direction of \vec{v} . Thus the magnetic force exerted by the field \vec{B} on the electron is

$$\begin{aligned} \vec{F}_m &= -e\vec{v} \times \vec{B} \\ &= -ev(-\sin\theta\hat{i} + \cos\theta\hat{j}) \times B\hat{k} \\ &= -ev(-B\sin\theta(-\hat{j}) + B\cos\theta\hat{i}) \\ &= -evB(\cos\theta\hat{i} + \sin\theta\hat{j}) \end{aligned}$$

Now $(\cos\theta\hat{i} + \sin\theta\hat{j})$ is the unit vector in the direction of the radius vector \vec{r} of the electron and is usually called radially outward unit vector. The force \vec{F}_m is thus a radially inward force of magnitude evB and will aid the electrostatic force \vec{F} (as shown in fig.(c)). The net force acting on the electron is

$$\begin{aligned} f &= F + F_m \\ &= mr\omega^2 + eBv \\ &= mr\omega^2 + e\omega B \end{aligned} \quad \dots(2)$$

Thus the electron will experience a slightly greater inward force in the presence of magnetic field than in absence. Now the electron can absorb the additional force either by coming close to the nucleus or by moving faster in the original orbit or both. Since radii of electron orbit are governed by quantum law, so r will not change and the electron will move faster in the original

orbit under the additional magnetic force, i.e. velocity of the electron increase. It may be noted that faster motion of the electron should further increase the magnetic force, but this effect is very small and we are justified to calculate the magnetic force with the unperturbed velocity \vec{v} of the electron which it had before magnetic field was applied. If new angular velocity of electron after the application of magnetic field is $(\omega + \Delta\omega)$, then

$$f = mr(\omega + \Delta\omega)^2$$

so eqn. (2) becomes

$$mr\omega^2 + er\omega B = mr(\omega + \Delta\omega)^2$$

$$mr\omega^2 + er\omega B = mr\omega^2 + mr(\Delta\omega)^2 + 2mr\omega\Delta\omega$$

As $\Delta\omega$ is very small, so the term $(\Delta\omega)^2$ can be neglected

$$er\omega B = +2mr\omega\Delta\omega$$

or
$$\Delta\omega = \frac{eB}{2m} \quad \dots(3)$$

The frequency $\Delta\omega$ is called Larmor's frequency for the orbiting electrons. Because of this change in angular velocity, the new magnetic moment of the electron is obtained by changing ω to $\omega + \Delta\omega$ in eqn. (1). Therefore,

$$\vec{P}_m = \frac{-e(\omega + \Delta\omega)r^2}{2} \hat{k}$$

So, the change in magnetic moment of the electron due to applied magnetic field will be $\vec{P}_m = \text{final magnetic moment} - \text{initial magnetic moment}$

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$$= -\frac{e(\omega + \Delta\omega)r^2}{2} \hat{k} - \left(-\frac{e\omega r^2}{2} \hat{k} \right)$$

or
$$\vec{P}_m = -\frac{e\Delta\omega r^2}{2} \hat{k} \quad \text{Support by Donating} \quad \dots(4)$$

Let us consider the case when the electron is orbiting in the clockwise direction. Now the vector area \vec{a} of the current loop will be $-\pi r^2 \hat{k}$ and the original magnetic moment will be

$$\vec{I}\vec{a} = \left(-\frac{e\omega}{2\pi} \right) (-\pi r^2 \hat{k}) = \frac{e\omega r^2}{2} \hat{k}$$

Since the velocity of the electron is now $v(\sin\theta\hat{i} - \cos\theta\hat{j})$, the magnetic force

$$\begin{aligned} \vec{F}_m &= -e\vec{v} \times \vec{B} = -e\vec{v}B(\sin\theta\hat{i} - \cos\theta\hat{j}) \times \hat{k} \\ &= evB(\cos\theta\hat{i} + \sin\theta\hat{j}) \end{aligned}$$

and is hence in radially outward direction.

This will oppose the electrostatic force and the net force on the electron shall be less than what it was in the absence of the magnetic force i.e. $f = F - F_m$. The electron will thus be slowed down in its orbit and its new angular velocity will be $\omega - \Delta\omega$.

$$\therefore \text{Final magnetic moment} = \frac{e(\omega - \Delta)\omega r^2}{2} \hat{k}$$

so, change in magnetic moment

$$\begin{aligned} \Delta\vec{P}_m &= \frac{e(\omega - \Delta\omega)r^2}{2} \hat{k} - \frac{e\omega r^2}{2} \hat{k} \\ &= -\frac{e\Delta\omega r^2}{2} \hat{k} \end{aligned}$$

which is exactly the same when the electron was orbiting in anticlockwise direction. Thus, the magnetic moment of all the electrons orbiting around the nucleus in a plane perpendicular to the external magnetic field changes by the same amount irrespective of whether they are circling in the clockwise or anticlockwise directions.

Substituting for $\Delta\omega$ from eqn. (4), we get

$$\Delta\vec{P}_m = \frac{-e^2 r^2 B}{4m} \hat{k} = -\frac{e^2 r^2 \vec{B}}{4m}$$

Further if a specimen contains N electrons per unit volume, the diamagnetic moment per unit volume is obtained by multiplying $\Delta\vec{P}_m$ to N , then

$$\begin{aligned} \vec{I} &= N\Delta\vec{p}_m \\ &= -\frac{Ne^2 r^2}{4m} \vec{B} \\ &= -\frac{1}{\alpha} \vec{H} = \chi_D \vec{H} \end{aligned}$$

From the above eqn, we see that $\vec{I} \propto \vec{H}$ and the proportionally

$$\chi_D = -\frac{Ne^2r^2\mu_0}{4m}$$

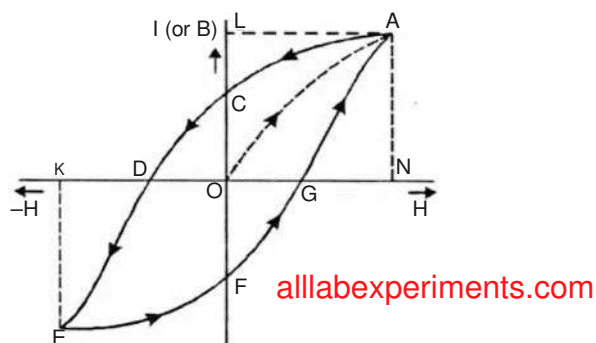
is called diamagnetic susceptibility. Substitution of known values given χ_D and is of the order of 10^{-8} Bohr magneton. This relation indicates that the diamagnetic susceptibility is independent of the temperature.

Q.3. What is Magnetic Hysteresis Curve also discuss about Hysteresis energy loss?

Ans. Magnetisation-Hysteresis: To select magnetic material for a specific purpose involves knowledge of magnetic properties of materia, which is turn depends upon permeability and susceptibility. To have knowledge of μ and χ_m , graphical relation between B and H (or I and H) are obtained. The curve is called magnetisation curve.

Consider a specimen of magnetic is placed in a magnetising field whose strength can be varied. Initially at 0 magnetising field H and intensity of magnetisation I (or magnetic flux density B) is zero. As H is increase from 0 $\rightarrow N$, the intensity of magnetisation (or magnetic flux density B) follows path OA as shown in figure.

As magnetising field H is gradually decreased to zero, increased to maximum value (OK) in opposite direction, then decrease to zero and increased finally to ON again the intensity of magnetisation I (or magnetic flux density B) follows path $ACDEFGA$. The curve is known as hysteresis curve and process is known as cycle of magnetisation.



(i) When magnetising field is maximum ($=ON$), the intensity of magnetisation I (or magnetic flux density B) is also maximum ($=OL$). As magnetising field os reduced to zero (at O), the intensity does not reduce.

To zero, but have value ($=OC$) i.e. some magnetism is left in the specimen.

The magnetism so retained by the material is known as its residual magnetism or retentivity. Thus retentivity of a magnetic substance is defined

as the intensity of magnetisation of a substance retained in the material when magnetising field is reduced to zero.

(ii) As strength of magnetising field is measured in opposite direction, the intensity of magnetisation (I) becomes zero at D . Thus to reduce intensity of magnetisation to zero, magnetising field (OD) has to be applied in opposite direction, known as coercivity of the substance.

(iii) From graph it is clear that intensity of magnetisation (I) lags behind magnetising field (H). This phenomenon of lagging behind of I or B behind H when specimen is subjected to cycle to magnetisation is known as Hysteresis.

Energy Dissipated Due to Hysteresis

According to molecular theory of magnetisation, unmagnetised magnetic material consist of molecular magnets (magnetic dipoles) forming closed chains. When specimen of magnetic material taken through a cycle of magnetisation, the molecular magnets in the specimen are oriented and reoriented time and again. In the process some work has to be done by the magnetic field in turning the dipole along the field against mutual attractive forces.

However, when magnetic field is switched off, the magnetic material retains some magnetism and energy supplied is not fully recovered on removing the field. Since magnetisation does not falls to zero field has to be applied in reverse direction to make magnetisation of substance to zero. The balance energy retained in the material is converted into heat and cannot be recovered. It can be shown that loss of energy per unit volume of the specimen per cycle of magnetisation is equal to area of I - H loop in cgs system and is equal to area of B - H loop in SI system.

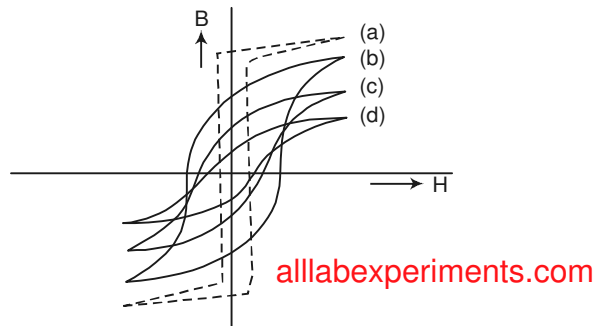
Q.4. Write differences between Hard and soft magnetic materials.

Ans. The shape and area of the hysteresis loop (I - H or B - H) is characteristic of material. So hysteresis loops of different materials have different shape and area depending upon their properties. The properties which are illustrated by a cycle of magnetisation are

- (i) maximum magnetic induction or permeability
- (ii) maximum magnetisation or susceptibility
- (iii) retentivity
- (iv) coercivity
- (v) hysteresis loss

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For a few materials the hysteresis loops are shown in fig. Curve (a), (b), (c) and (d) are respectively for the specimen of soft iron, steel, cobalt and nickel materials. The study of these curves gives the following information.



(i) **Susceptibility.** The susceptibility, the intensity of magnetisation per unit magnetising field (i.e. I/H) is greater for soft materials than for hard materials, because it is clear from curve (a) that I is larger in case of (a) and is smaller in curves (b), (c) and (d).

(ii) **Permeability.** The permeability, the magnetic induction per unit magnetising field (i.e. B/H) is greater for soft materials than for hard materials.

(iii) **Retentivity.** When a magnetic material is magnetised first by increasing H , and then the magnetising field is decreased to zero, the magnetic material retains intensity of magnetisation I (or magnetic induction B), which is known as retentivity (or residual magnetism). The retentivity is greater for soft materials than for hard materials.

(iv) **Coercivity.** For demagnetizing the magnetic material completely, a reverse magnetising field is applied. The value of reverse field H for reducing I or B to zero, is known as coercivity. It is less for soft material than for hard material is clear from curves (a), (b), (c) and (d).

(v) **Hysteresis loss.** The area of the hysteresis curve and hence the hysteresis loss per unit volume per cycle is less for soft material than for hard materials.

Q.5. What is Weiss theory also derive for variation of ferromagnetic susceptibility with temperature according to weiss theory?

Ans. Molecular Field Theory and Ferromagnetic Domains (Weiss Theory)

In 1907, Weiss postulated molecular field theory to explain salient features of ferromagnetism. This theory gives two postulates:

(1) Ferromagnetic Domains

According to first postulate, a ferromagnetic solid contains large number of small regions of spontaneous magnetisation called domains. Within each domains, adjacent atomic or molecular dipoles are very strongly coupled to the neighbouring dipoles by a stronger exchange interaction. Due to this exchange interaction among neighbouring dipoles, a large number of dipoles are aligned in the same direction. Such a group of atomic or molecular dipoles constitute a ferromagnetic domain. Each domain is all time spontaneously magnetised to a maximum value and has a define magnetic moment and definite direction as shown in figure.

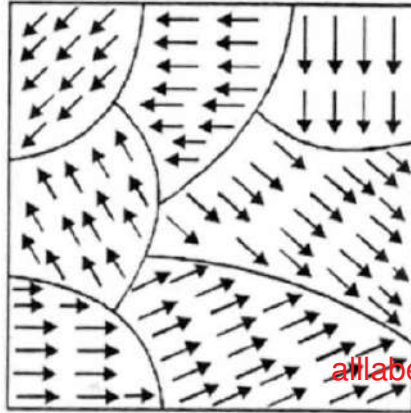


Fig. Orientation of Domains

A domain contains about 10^{16} or more dipoles and has a volume between 10^{-8} to 10^{-12} cubic meter. Hence domains are local regions in which atomic or molecular dipoles are aligned perfectly even in the absence of external magnetic field. The magnetic of spontaneous magnetisation of a ferromagnetic domains is determined by the vector sum of the magnetic moments of all the individual dipoles. The process of magnetisation of specimen causes rotations of magnetic moments of different domains in the direction of applied field and the specimen acquires a large magnetisation even to presence of a weak magnetic field.

(2) Internal Molecular field

According to second postulate, spontaneous magnetization of each domains is due to presence of internal molecular field, also called exchange field or Weiss field. This molecular field tends to produce alignment of molecular or atomic dipoles. This theory, however, does not explain origin and nature of this molecular field. This field may be consider due to strong exchange interaction of dipole with the neighbouring dipoles. The molecular field, H_m , is proportional to magnetisation, M .

$$\text{i.e.} \quad H_m = \lambda M \quad \dots(1)$$

where λ is constant as molecular field coefficient. It determines the strength of the interaction or cooperation between magnetic dipoles in a material. Hence, ' λM ' is a measure of already existing internal molecular field. Number value of λ for iron =1000 (experimentally observed).

If H be the external applied field, then effective , H_{eff} will be

$$H_{eff} = H + \lambda M \quad \dots(2)$$

where ' M ' is spontaneous magnetization.

But, from Langevin's paramagnetic theory, magnetization, M , is given by Curie law

$$M = \frac{\mu_0 P_m^2 N}{3k_B T} H = \frac{C'H}{T} \quad \dots(3)$$

where $C' = \frac{\mu_0 P_m^2 N}{3k_B}$ is called Curie constant

Similarly, for ferromagnetic solids, equation (3) can be written as

$$M = \frac{C'H_{eff}}{T} \quad \dots(4)$$

From (2) and (4), we get $\frac{M}{H + \lambda M} = \frac{C'}{T}$ alllabexperiments.com

or $MT = C'H + C'\lambda M$ or $M(T - C'\lambda) = C'H$

or $M = \frac{C'H}{T - C'\lambda}$ Support by Donating $\dots(5)$

Hence, ferromagnetic susceptibility,

$$\chi_{ferro} = \frac{M}{H} = \frac{C'}{T - T_c} \quad \dots(6)$$

where $T_c = C'\lambda$ is called Curie temperature.

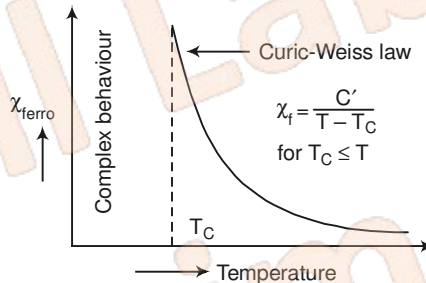


Figure. Variation of ferromagnetic susceptibility with temperature according to Curie - Weiss law.

Equation (6) represents Curie - Weiss law. Variation of susceptibility with temperature is shown below in figure. As long as $T \geq T_c$, the Curie - Weiss curve is similar to Curie curve. However, as T approaches T_c , the Curie - Weiss susceptibility tends to infinity.

For $T \geq T_c$, there exists spontaneous magnetization even in the absence of applied field. Infinite susceptibility means magnetization without any external magnetic field. It means that interactions of individual magnetic dipoles with the neighbouring dipoles reinforce each other and align them parallel to each

for temperature $T \geq T_c$. It is nothing but spontaneous magnetization. Clearly, for $T \geq T_c$ Curie - Weiss for ferromagnetic solids is similar to the curve for paramagnetic solids. It means that for temperature $T \geq T_c$, the ferromagnetic materials loses its special characters of spontaneous magnetization and becomes paramagnet.



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