11. Magnetic Materials

Can you recall?

1. What are magnetic lines of force?
2. Why magnetic monopoles do not exist?
3. Which materials are used in making magnetic compass needle?

11.1 Introduction:

You have studied about magnetic dipole and dipole moment due to a short bar magnet. Also you have studied about magnetic field due to a short bar magnet at any point in its vicinity. When such a small bar magnet is suspended freely, it remains along the geographic North South direction. (*This property can be readily used in Navigation.)*

In the present Chapter you will learn about the behaviour of a short bar magnet kept in two mutually perpendicular magnetic fields. You will also learn about different types of magnetism, viz. diamagnetism, paramagnetism and ferromagnetism with their properties and examples. At the end you will learn about the applications of magnetism such as permanent magnet, electromagnet, and magnetic shielding.

Activity

You have already studied in earlier classes that a short bar magnet suspended freely always aligns in North South direction (as shown in Fig. 11.1). Now if you try to forcefully move and bring it in the direction along East West and leave it free, you will observe that the magnet starts turning about the axis of suspension. Do you know from where does the torque which is necessary for rotational motion come from? (as studied in rotational dynamics a torque is necessary for rotational motion).

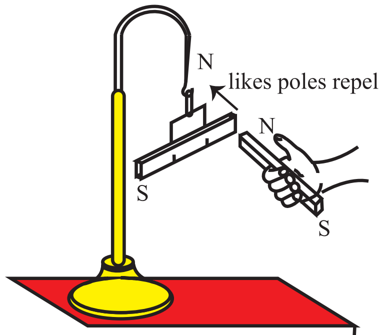


Fig. 11.1: Short bar magnet suspended freely with an inextensible string.

Try this

Now we will extend the above experiment further by bringing another short bar magnet near to the freely suspended magnet. Observe the change when the like and unlike poles of the two magnets are brought near each other. Draw conclusion. Does the suspended magnet rotate continuously or rotate through certain angle and remain stable?

11.2 Torque Acting on a Magnetic Dipole in a Uniform Magnetic Field:

You have studied in the preivous Chapter of that the torque acting on a rectangular current carrying coil kept in a uniform magnetic field is given by

$$\vec{\tau} = \vec{m} \times \vec{B}$$

$$\tau = mB\sin\theta \, , \qquad \text{--- (11.1)}$$

where θ is the angle between $\vec{m}$ and $\vec{B}$, the magnetic dipole moment and the external applied uniform magnetic field, respectively as shown in Fig. 11.2. The same can be observed when a small bar magnet is placed in a uniform magnetic field. The forces exerted on the poles of the bar magnet due to magnetic field are along different lines of action. These forces form a couple. As studied earlier, the couple produces pure rotational motion. Analogous to rectangular magnetic coil in uniform magnetic field, the bar magnet will follow the same Eq. (11.1).

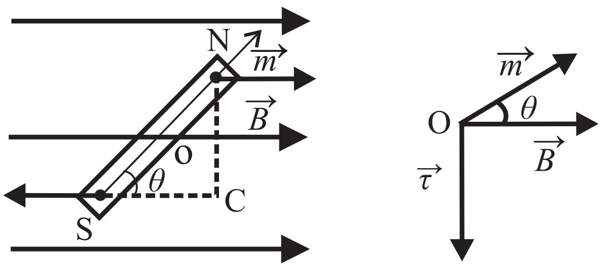


Fig. 11.2: Magnet kept in a Uniform Magnetic field.

$\tau = mB \sin\theta$ (m is the magnetic dipole moment of bar magnet and B the uniform magnetic field).

Due to the torque the bar magnet will undergo rotational motion. Whenever a displacement (linear or angular) is taking place, work is being done. Such work is stored in the form of potential energy in the new position (refer to Chapter 8). When the electric dipole is kept in the electric field the energy stored is the electrostatic Potential energy.

Magnetic potential energy

$$U_m = \int_0^\theta \tau(\theta)\, d\theta \quad \text{--- (11.2)}$$

$$U_m = \int_0^\theta mB\sin\theta\, d\theta$$

$$U_m = -mB\cos\theta \quad \text{--- (11.3)}$$

Let us consider various positions of the magnet and find the potential energy in those positions.

Case 1- When $\theta = 0°$, $\cos 0 = 1$ $\boldsymbol{U_m = -mB}$ This is the position when $\vec{m}$ and $\vec{B}$ are parallel and bar magnet possess minimum potential energy and is in the most stable state.

Case 2- When $\theta = 180°$, $\cos 180° = -1$ $\boldsymbol{U_m = mB}$. This is the position when $\vec{m}$ and $\vec{B}$ are antiparallel and bar magnet posseses maximum potential energy and thus is in the most unstable state.

Case 3- When $\theta = 90°$, $\cos 90° = 0$ $\boldsymbol{U_m = 0}$ This is the position when bar magnet is aligned perpendicular to the direction of magnetic field.

The potential energy as function of θ is shown in Fig. 11.3.

As discussed in the activity earlier, suppose the bar magnet is suspended using in extensible string. When we perform similar activity (Refer Fig. 11.1) we observe that the magnet rotates through angle and then becomes stationary. This happens because of the restoring torque as studied in Chapter 10 generated in the string opposite to the deflecting torque. In equilibrium both the torques balance.

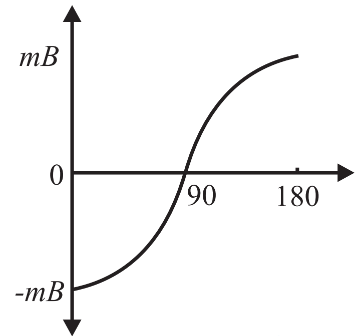


Fig. 11.3: Potential Energy v/s angular position of the magnet.

$$\tau = I\frac{d^2\theta}{dt^2} \quad \text{--- (11.4)}$$

where I is moment of inertia of bar magnet and $\frac{d^2\theta}{dt^2}$ is the angular acceleration. As seen from Fig. (11.2), the direction of the torque acting on the magnet is clockwise. Now if one tries to rotate the magnet anticlockwise through an angle dθ, then there will be a restoring torque acting as given by the equation, in opposite direction.

Thus we write the restoring torque

$$\tau = -mB\sin\theta \quad \text{--- (11.5)}$$

From the two equations we get

$$I\frac{d^2\theta}{dt^2} = -mB\sin\theta\,.$$

When the angular displacement θ is very small, $\sin\theta \approx \theta$ and the above equation can be written as

$$I\frac{d^2\theta}{dt^2} = -mB\theta$$

$$\frac{d^2\theta}{dt^2} = -\left(\frac{mB}{I}\right)\theta \quad \text{--- (11.6)}$$

The above equation has angular acceleration on the left hand side and angular displacement θ on the right hand side of equation with m, B and I being held constant.

This is the angular simple harmonic motion (S.H.M) (Chapter 5) analogous to linear S.H.M. governed by the equation

$$\frac{d^2x}{dt^2} = -\omega^2 x .$$

Here $\omega^2 = \frac{mB}{I}$

$$\therefore \omega = \sqrt{\frac{mB}{I}} \qquad \text{--- (11.7)}$$

The time period of angular oscillations of the bar magnet will be

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{I}{mB}} \qquad \text{--- (11.8)}$$

Vibration Magnetometer:

Vibration Magnetometer is used for the comparison of magnetic moments and magnetic field. This device works on the principle, that whenever a freely suspended magnet in a uniform magnetic field, is disturbed from its equilibrium positions, it starts vibrating about the mean position. It can be used to determine horizontal component of Earth's magnetic field.

Examples 11.1: A bar magnet of moment of inertia of 500 g cm^2 makes 10 oscillations per minute in a horizontal plane. What is its magnetic moment, if the horizontal component of earth's magnetic field is 0.36 gauss?

Given: Moment of Inertia I = 500 g cm^2

Frequency n = 10 oscillation per minute

= 10/60 oscillations per second

Time period T = 6 sec

B_H = 0.36 gauss

Solution: From Eq. (11.8),

$$m = \frac{4\pi^2 I}{T^2 B}$$

$$m = \frac{4 \times (3.14)^2 \times 500 \times 10^{-7}}{36 \times 0.36 \times 10^{-4}}$$

m = 1.524 A m^2

Location of Magnetic poles of a Current Carrying Loop:

You have studied that a current carrying conductor produces magnetic field and if you bend the conductor in the form of loop, this loop, behaves like a bar magnet (as discussed in Chapter 10).

Observe and discuss

What is a North pole or South pole of a bar magnet? For understanding this, you just have to draw a circular loop on a plane glass plate and show the direction of current (say clockwise direction). Now place on it a wire loop having clockwise current flowing through it. According to right hand rule, the top surface will behave as a South pole. Now just turn the glass and see the same loop through other surface of glass. You will find that the direction of current is in anticlockwise direction (in reality there is no change in the direction of current) and hence the loop side surface behaves like North pole.

11.3 Origin of Magnetism in Materials:

In order to understand magnetism in materials we have to use the basic concepts such as magnetic poles and magnetic dipole moment. In XI[th] Std., you have studied about the magnetic property of a short bar magnet such as its magnetic field along its axial or equatorial direction. What makes some material behave like a magnet while others don't? To understand it one must consider the building blocks of any material i.e., atoms. In an atom, negatively charged electrons are revolving about the nucleus (consisting of protons and neutrons). The details about it will be studied in Chapter 15. You have studied in the periodic table in Chemistry in XI[th] Std. that chemical properties are dominated by the electrons orbiting in the outermost orbit of the atom. This also applies to magnetic properties as described below.

11.3.1 Magnetic Moment of an Electron Revolving Around the Nucleus of an Atom:

Let us consider an electron revolving around positively charged nucleus in a circular orbit as a simple model. A (negatively charged) electron revolving in an orbit is equivalent to a tiny current loop. The magnetic dipole moment due to a current loop is given by $m_{orb} = I A$ (A is the area enclosed by the loop and I is the current). It is only a part of the magnetic moment of an atom and is referred to as orbital magnetic moment. An electron possesses an intrinsic angular momentum, the spin angular momentum. Spin magnetic dipole moment results from this intrinsic spin. Consider an electron moving with constant speed v in a circular orbit of radius r about the nucleus as shown in Fig. 11.4. If the electron travels a distance of $2\pi r$ (circumference of the circle) in time T, then its orbital speed $v=2\pi r/T$. Thus the current I associated with this orbiting electron of charge e is

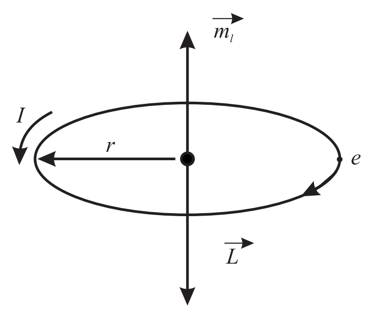


Fig. 11.4: Single electron revolving around the nucleus.

$$I=\frac{e}{T}$$

$$T=\frac{2\pi}{\omega} \text{ and } \omega=\frac{v}{r}\text{, the angular speed}$$

$$I=\frac{e\omega}{2\pi}=\frac{ev}{2\pi r} \qquad \text{--- (11.9)}$$

The **orbital magnetic moment** associated with orbital current loop is

$$m_{orb}=I\,A=\frac{ev}{2\pi r}\times\pi r^2=\frac{1}{2}evr \qquad \text{--- (11.10)}$$

For this electron, orbital angular momentum is

$$L=m_e vr\,,$$

where m_e is the mass of an electron.

Hence the orbital magnetic moment, Eq. (11.10) can be written as

$$m_{orb}=\left(\frac{e}{2m_e}\right)(m_e vr)=\left(\frac{e}{2m_e}\right)L \qquad \text{--- (11.11)}$$

This equation shows that orbital magnetic moment is proportional to the angular momentum. But as the electron bears negative charge the vector m_{orb} and are L are in opposite directions and perpendicular to the plane of the orbit. Hence, vectorially $\vec{m}_{orb}=-\frac{e}{2m_e}\vec{L}$. The same result is obtained using quantum mechanics

The ratio $\frac{e}{2m_e}$ is called gyromagnetic ratio.

For an electron revolving in a circular orbit, the angular momentum is integral (n) multiple of $h/2\pi$. (from the second postulate of Bohr theory of hydrogen atom).

$$L=m_e vr=\frac{nh}{2\pi}$$

Substituting the value of L in Eq. (11.11) we get

$$m_{orb}=\frac{enh}{4\pi m_e}$$

For the 1st orbit $n = 1$, giving $m_{orb}=\frac{eh}{4\pi m_e}$,

The quantity $\frac{eh}{4\pi m_e}$ is called Bohr Magneton.

The value of Bohr Magneton is 9.274 x 10^{-24} A /m^2. The magnetic moment of an atom is stated in terms of Bohr Magnetons (B.M.).

Example 11.2: Calculate the gyromagnetic ratio of electron (given e = 1.6 x 10^{-19} C, m_e = 9.1 x 10^{-31} kg)

Solution:

$$Gyromagnetic\ raio=\frac{e}{2m_e}$$

$$= 1.6\times10^{-19}/(2\times9.1\times10^{-31})$$

$$= 8.8\times10^{10}\ \text{C kg}^{-1}$$

Do you know?

Effective magneton numbers for iron group ions (No. of Bohr magnetons)

Ion	Configuration	Effective magnetic moment in terms of Bohr magneton (B.M) (Expreimental values)
Fe^{3+}	$3d^5$	5.9
Fe^{2+}	$3d^6$	5.4
Co^{2+}	$3d^7$	4.8
N^{2+}	$3d^8$	3.2

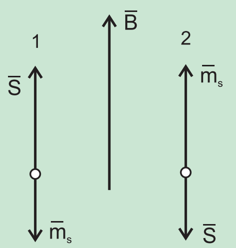
(Courtsey: Introduction to solid state physics by Charles Kittel, pg. 306)

These magnetic moments are calculated from the experimental value of magnetic susceptibility. In several ions the magnetic moment is due to both orbital and spin angular momenta.

As stated earlier, apart from the orbital motion, electron spin also contributes to the resultant magnetic moment of an atom. Vector sum of these two moments is the total magnetic moment of the atom.

Do you know?

Two possible orientations of spin angular momentum ($\vec{s}$) of an electron in an external magnetic field. Note that the



spin magnetic dipole moment is in a direction opposite to that of the angular momentum.

You have studied Pauli's exclusion principle. According to it, no two electrons can have the same set of quantum numbers viz. n, l, m_l and m_s defining a state. Therefore, the resultant magnetic dipole moment for these atoms with a pair of electrons in the same state, defined by n, l and m_l, will be zero as discussed in the box below.

The atoms with odd number of electrons in their outermost orbit will possess nonzero resultant magnetic moment. Inner orbits are completely filled and hence do not contribute to the total magnetic moment of the atom.

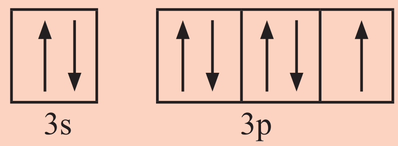
Observe and discuss

Let us see whether the given atom has paired electron or unpaired electrons in the outermost orbit. We will follow three steps-

1) Write electronic configuration
2) Draw valence orbital
3) Identify if unpaired electron exist

Ex. Chlorine Cl (it has total 17 electrons)

1) electronic configuration $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^5$
2) ignoring inner completely filled orbitals and just considering valence electrons.



3) There is one unpaired electron.

In a similar manner study Fe, Zn, He, B, Ni and draw your conclusions.

11.4 Magnetization and Magnetic Intensity:

In the earlier section you have seen that atoms with unpaired electrons have a net magnetic dipole moment. The bulk material is made up of a large number of such atoms each having an inherent magnetic moment. The magnetic dipole moments are randomly oriented and hence the net dipole moment of many of the bulk materials is zero. For some materials (such as Fe_3O_4), the vector addition of all these magnetic dipole moments may not be zero. Such materials have a net magnetic moment. The ratio of magnetic moment to the volume of the material is called magnetization .

$$M = m_{net} / \text{volume} \qquad \text{--- (11.12)}$$

M is vector quantity having dimension [L^{-1} A and SI units A m^{-1}].

Consider a rod of such a material with some net magnetization, placed in a solenoid with n turns per unit length, and carrying current I. Magnetic field inside the solenoid is given by

$$B_0 = \mu_0 n I$$

Let us denote the magnetic field due to the material kept inside the solenoid by B_m.

Thus, the net magnetic field inside the rod can be expressed as

$$B = B_0 + B_m \quad \text{--- (11.13)}$$

It has been observed that B_m is proportional to magnetisation M of the material

$$B_m = \mu_0 M ,$$

where μ_0 is permeability of free space.

$$\therefore B = \mu_0 n I + \mu_0 M \quad \text{--- (11.14)}$$

Here we will introduce one more quantity called magnetic field intensity H, where $H = nI$. The noticeable difference between the expression for B and H is that H does not depend on the material rod which is placed inside the solenoid.

$$B = \mu_0 H + \mu_0 M$$

$$B = \mu_0 (H + M) \quad \text{--- (11.15)}$$

$$\therefore H = \frac{B}{\mu_0} - M \quad \text{--- (11.16)}$$

From the above expression we conclude that H and M have the same unit i.e., ampere per metre. and also have the same dimensions. Thus the magnetic field induced in the material (B) depends on H and M. Further it is observed that if H is not too strong the magnetization M induced in the material is proportional to the magnetic intensity.

$$M = \chi H , \quad \text{--- (11.17)}$$

where χ is called Magnetic Susceptibility. It is a measure of the magnetic behaviour of the material in external applied magnetic field. χ is the ratio of two quantities with the same units (Am^{-1}). Hence it is a dimensionless constant. From Eq. (11.15) and Eq. (11.17) we get

$$B = \mu_0 (H + \chi H)$$

$$B = \mu_0 (1 + \chi) H$$

$$B = \mu_0 \mu_r H \quad \text{--- (11.18)}$$

$$\mu_r = 1 + \chi$$

$$B = \mu H$$

$$\mu = \mu_0 \mu_r$$

$$\mu = \mu_0 (1 + \chi) \quad \text{--- (11.19)}$$

Here μ is magnetic permeability of the material analogous to ε in electrostatics and μ_r is the relative magnetic permeability of the substance.

Permeability and Permittivity:

Magnetic Permeability is a term analogous to permittivity in electrostatics. It basically tells us about the number of magnetic lines of force that are passing through a given substance when it is kept in an external magnetic field. The number is the indicator of the behaviour of the material in magnetic field. For superconductors $\chi = -1$. If you substitute in the Eq. (11.18), it is observed that permeability of material $\mu = 0$. This means no magnetic lines will pass through the superconductor.

Magnetic Susceptibility (χ) is the indicator of measure of the response of a given material to the external applied magnetic field. In other words it indicates as to how much magnetization will be produced in a given substance when kept in an external magnetic field. Again it is analogous to electrical susceptibility. This means when the substance is kept in a magnetic field, the atomic dipole moments either align or oppose the external magnetic field. If the atomic dipole moments of the substance are opposing the field, χ is observed to be negative, and if the atomic dipole moments align themselves in the direction of field, χ is observed to be positive. The number of atomic dipole moments of getting aligned in the direction of the applied magnetic field is proportional to χ. It is large for soft iron ($\chi > 1000$).

Example 11.2: The region inside a current carrying toroid winding is filled with Aluminium having susceptibility $\chi = 2.3 \times 10^{-5}$. What is the percentage increase in the magnetic field in the presence of

Aluminium over that without it?

Solution: The magnetic field inside the solenoid without Aluminium $B_0 = \mu_0 H$

The magnetic field inside the solenoid with Aluminium $B = \mu H$

$$\frac{B - B_0}{B_0} = \frac{\mu - \mu_0}{\mu_0}$$

$$\mu = \mu_0 (1 + \chi)$$

$$\frac{\mu}{\mu_0} - 1 = \chi$$

$$\frac{\mu - \mu_0}{\mu_0} = \chi$$

therefore $\frac{B - B_0}{B_0} = \frac{\mu - \mu_0}{\mu_0} = \chi$

Percentage increase in the magnetic field after inserting Aluminium is

$$\frac{B - B_0}{B_0} \times 100 = 2.3 \times 10^{-5} \times 100 = 0.0023\ \%$$

Table 11.1: Magnetic susceptibility of some materials

Diamagnetic Substance	χ	Paramagnetic Substance	χ
Silicon	-4.2×10^{-6}	Aluminium	2.3×10^{-5}
Bismuth	-1.66×10^{-5}	Calcium	1.9×10^{-5}
Copper	-9.8×10^{-6}	Choromium	2.7×10^{-4}
Diamond	-2.2×10^{-5}	Lithium	2.1×10^{-5}
Gold	-3.6×10^{-5}	Magnesium	1.2×10^{-5}
Lead	-1.7×10^{-5}	Niobium	2.6×10^{-5}
Mercury	-2.9×10^{-5}	Oxygen (STP)	2.1×10^{-6}
Nitrogen	-5.0×10^{-9}	Platinum	2.9×10^{-4}

11.5 Magnetic Properties of Materials:

The behaviour of a material in presence of external magnetic field classifies materials broadly into diamagnetic, paramagnetic and ferromagnetic materials. Magnetic susceptibility for diamagnetic material is negative and for paramagnetic positive but small. For ferromagnetic materials it is positive and large.

Table 11.2: Range of magnetic susceptibility of diamagnetic, paramagnetic and ferromagnetic materials

Types of material	χ
Diamagnetic	-10^{-3} — -10^{-5}
Paramagnetic	0 — 10^{-3}
Ferromagnetic	10^{2} — 10^{3}

11.5.1 Diamagnetism:

In the earlier section it is discussed that atoms/molecules with completely filled electron orbit possess no net magnetic dipole moment. Such materials behave as diamagnetic materials. When these materials are placed in external magnetic field they move from the stronger part of magnetic field to the weaker part of magnetic field. Unlike magnets attracting magnetic material, these materials are repelled by a magnet.

The simplest explanation for diamagnetism could be given using paired electron orbit. As discussed earlier, the net magnetic moment of such atoms is zero. When the orbiting electron or current loop is brought in external magnetic field, the field induces a current as per Lenz's law (refer to Chapter 12) as shown in Fig. 11.5. The direction of induced current I_i, is such that the direction of magnetic field created by the current is opposite to the direction of applied external magnetic field. Out of the pair of orbits, for one loop where the direction of induced current is the same as that of loop current will find increase in current I, (Fig. 11.5 (b)) resulting in increase in magnetic dipole moment. For the current loop where the direction of induced current is opposite to direction of loop current, (Fig. 11.5 (a)) the net current is reduced, effectively reducing the magnetic dipole moment. This results in net magnetic dipole moment opposite to the direction of applied external magnetic field.

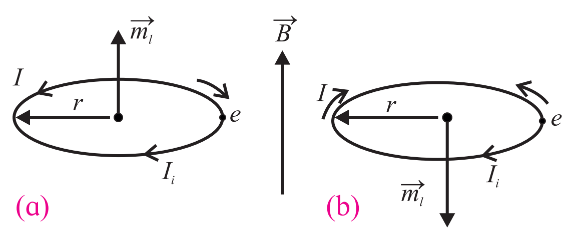


Fig. 11.5 The clockwise and anticlockwise motion of electron brought in a magnetic field.

Examples of diamagnetic materials are copper, gold metal, bismuth and many metals, lead, silicon, glass, water, wood, plastics etc. Diamagnetic property is present in all materials. In some, it is weaker than other properties such as paramagnetism or ferromagnetism which mask the diamagnetism.

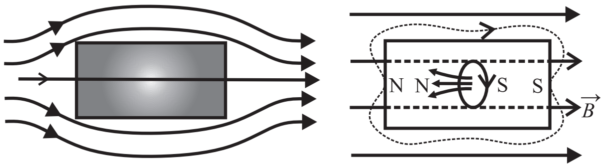


Fig. 11.6: Diamagnetic substance in uniform magnetic field.

When diamagnetic material is placed in an external magnetic field, the induced magnetic field inside the material repels the magnetic lines of forces resulting in reduction in magnetic field inside the material (See Fig. 11.6). Similarly when diamagnetic material is placed in non uniform magnetic field, it moves from stronger to weaker part of the field. If a diamagnetic liquid is filled in a U tube and one arm of the U tube is placed in an external magnetic field, the liquid is pushed in the arm which is outside the field. In general, these materials try to move to a place of weaker magnetic field. If a rod of diamagnetic material is suspended freely in the magnetic field it aligns itself in the direction perpendicular to the direction of external magnetic field. This is because there is a torque acting on induced dipole. As studied earlier, when the dipole is in a direction opposite to the direction of magnetic field it has a large magnetic potential energy and so is unstable. It will try to go into a position where the magnetic potential energy is least and that is when the rod is perpendicular to the direction of magnetic field. The magnetic susceptibility of diamagnetic material is negative.

Try this

Take a bar magnet (available in your laboratory), a small glass test tube with a cork partially filled with water and fixed on the piece of such a material say wood (float) that this system can float on water, . Let the test tube and the float be kept floating in a water bath or some plastic tray contining water available in the laboratory. Bring the pole of the bar magnet near the water filled glass tube. Note your observation. Repeat the experiment without water filled in the test tube. Record your observation and draw conclusions.

Do you know?

When superconductors (χ = - 1) are placed in an external magnetic field, the field lines are completely expelled. The phenomenon of perfect diamagnetism in superconductor is called Meissner effect. ***If a good electrical conductor is kept in a magnetic field, the field lines do penetrate the surface region to a certain extent.***

11.5.2 Paramagnetism:

In the earlier section you have studied that atoms/molecules having unpaired electrons possess a net magnetic dipole moment. As these dipole moments are randomly oriented, the resultant magnetic dipole moment of the material is, however, zero.

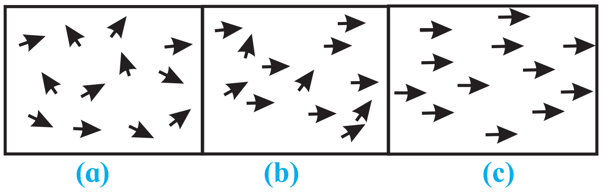


Fig. 11.7 : Paramagnetic substance (a) No external Magnetic Field (b) Weak external magnetic Field (c) Strong external Magnetic Field.

As seen from Fig. 11.7 (a) and (b), each atom/molecule of a paramagnetic material possesses net magnetic dipole moment, but because of thermal agitation these are randomly ariented. Due to this the net magnetic dipole moment of the material is zero in absence of an external magnetic field.

When such materials are placed in sufficiently strong external magnetic field at low temperature (to reduce thermal excitation) (Fig. 11.7 (c)), most of the magnetic dipoles align themselves in the direction of the applied field (to align in the direction corresponding to less potential energy). The field lines get closer inside such a material (see Fig. 11.8).

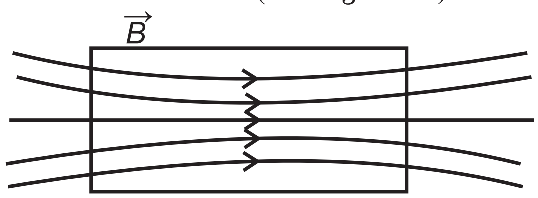


Fig . 11.8: Paramagnetic substance in external magnetic field.

When paramagnetic material is placed in a nonuniform magnetic field it tend to move itself from weaker region to stronger region. In other words, these materials are strongly attracted by external magnetic field. When a paramagnetic liquid is placed in a U tube manometer with a magnet kept in close vicinity of one of the arms, it is observed that the liquid rises into the arm close to the magnet.

When the external magnetic field is removed these magnetic dipoles get arranged themselves in random directions. Thus the net magnetic dipole moment is reduced to zero in the absence of a magnetic field. Metals such as magnesium, lithium, molybdenum, tantalum, and salts such as M_nSO_4, H_2O and oxygen gas are examples of paramagnetic materials.

In 1895 Piere Curie observed that the magnetization M in a paramagnetic material is directly proportional to applied magnetic field B and inversely proportional to absolute temperature T of the material. This is known as Curie Law.

$$M = C\frac{B}{T} \qquad \text{--- (11.20)}$$

$$B = \mu_0 H$$

$$M = C\frac{\mu_0 H}{T}$$

$$\frac{M}{H} = \chi = C\frac{\mu_0}{T}$$

$$\chi = \mu_r - 1 = C\frac{\mu_0}{T} \qquad \text{--- (11.21)}$$

$$\chi \propto \frac{1}{T}$$

Thus when we increase the applied magnetic field and reduce the temperature, more number of magnetic moments align themselves in the direction of magnetic field resulting in increase in Magnetization.

Use your brain power

Classify the following atoms as diamagnetic or paramagnetic.
H, O, Zn, Fe, F, Ar, He
(Hint : Write down their electronic configurations)
Is it true that all substances with even number of electrons are diamagnetic?

11.5.3 Ferromagnetism:

Atoms/molecules of ferromagnetic material possess magnetic moments similar to those in paramagnetic materials. However, such substances exhibit strong magnetic properties and can become permanent magnets. Metals and rare earths such as iron, cobalt, nickel and some transition metal alloys exhibit ferromagnetism.

Domain theory: In ferromagnetic materials there is a strong interaction called exchange coupling or exchange interaction between neighbouring magnetic dipole moments.

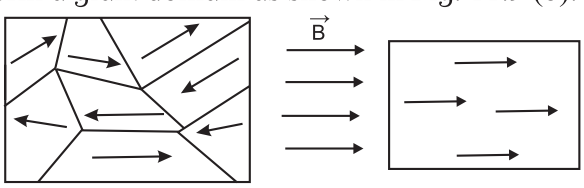
Due to this interaction, small regions are formed in which all the atoms have their magnetic moments aligned in the same direction. Such a region is called a *domain* and the common direction of magnetic moment is called the domain axis. Domain size can be a fraction of a millimetre (10^{-6} - 10^{-4} m) and contains about 10^{10} - 10^{17} atoms. The boundary between adjacent domains with a different orientation of magnetic moment is called a domain wall.

Do you know?

Exchange Interaction: This exchange interaction in stronger than usual dipole-dipole interaction by an order of magnitude. Due to this exchange interaction, all the atomic dipole moments in a domain get aligned with each other. Find out more about the origin of exchange interaction.

In unmagnetized state, the domain axes of different domains are oriented randomly, resulting in the net magnetic moment of the whole material to be zero, even if the magnetic moments of individual domains are nonzero as shown in Fig. 11. 9 (a).

When an external magnetic field is applied, domains try to align themselves along the direction of the applied magnetic field. The number of domains aligning in that direction increases as magnetic field is increased. This process is referred to as flipping or domain rotation. When sufficiently high magnetic field is applied, all the domains coalesce together to form a giant domain as shown in Fig. 11.9 (b).



(a) (b)

Fig. 11.9: Unmagnetised (a) and magnetised (b) ferromagnetic material with domains.

In nonuniform magnetic field ferromagnetic material tends to move from weaker part to stronger part of the field.

When the strong external magnetic field is completely removed, it does not set the domain boundaries back to original position and the net magnetic moment is still nonzero and ferromagnetic material is said to retain magnetization. Such materials are used in preparing permanent magnets.

Remember this

We have classified materials as diamagnetic, paramagnetic and ferromagnetic. However there exist additional types of magnetic materials such as ferrimagnetic, antiferrimagnetic, spin glass etc. with the exotic properties leading to various applications.

Example 11.3: A domain in ferromagnetic iron is in the form of cube of side 1 μm. Estimate the number of iron atoms in the domain, maximum possible dipole moment and magnetisation of the domain. The molecular mass of iron is 55 g/mole and density is 7.9 g/cm^3. Assume that each iron atom has a dipole moment of 9.27×10^{-24} Am^2.

Solution: The volume of the cubic domain

$V = (10^{-6})^3 = 10^{-18}\ \text{m}^3 = 10^{-12}\ \text{cm}^3$

mass = volume × density = 7.9×10^{-12} g.

An Avogadro number (6.023×10^{23}) of iron atoms has mass 55 g.

The number of atoms in the domain N

$$N = \frac{7.9\times10^{-12}\times6.023\times10^{23}}{55} = 8.651\times10^{10}$$

The maximum possible dipole moment m_{max} is achieved for the case when all the atomic moments are perfectly aligned (though this will not be possible in reality).

$m_{max} = 8.65 \times 10^{10} \times 9.27 \times 10^{-24}$

$= 8.019 \times 10^{-13}$ Am^2

Magnetisation $M = m_{max}$ / domain volume

$= 8.019 \times 10^{5}$ Am^{-1}

11.5.4 Effect of Temperature:

Ferromagnetism depends upon temperature. As the temperature of a ferromagnetic material is increased, the domain structure starts distorting because the exchange coupling between neighbouring moments weakens. At a certain temperature, depending upon the material, the domain structure collapses totally and the material behaves like paramagnetic material. The temperature at which a ferromagnetic material transforms into a paramagnetic substance is called Curie temperature (T_c) of that material.

The relation between the magnetic susceptibility of a material when it has acquired paramagnetic property and the temperature T is given by

$$\chi = \frac{C}{T - T_C} \quad \text{for} \quad T > T_C \qquad \text{--- (11.22)}$$

where C is a constant (Fig. 11.10) .

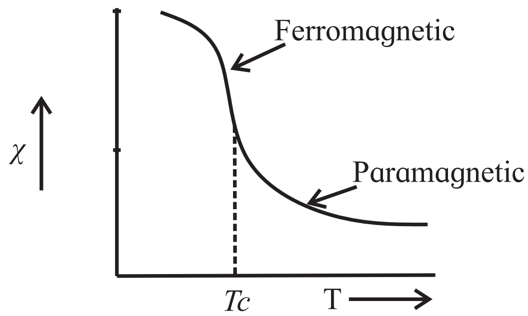


Fig. 11.10: Curie Temperature T_C of some Ferromagnetic material.

Table 11.1 Curie Temperature of some materials

Material	T_C (K)
Metallic cobalt	1394
Metallic iron	1043
Fe_2O_3	893
Metallic nickel	631
Metallic gadolinium	317

11.6 Hysteresis:

The behaviour of ferromagnetic material when placed in external magnetic field is quite interesting and informative. It is nonlinear and provides information of magnetic history of the sample. To understand this, let us consider an unmagnetized ferromagnetic material in the form of a rod placed inside a solenoid. On passing the current through solenoid, magnetic field is generated which magnetises the rod. Knowing the value of χ of the material of the rod, M (magnetization) can be easily calculated from $M = \chi H$. From Eq. (11.16),

$$H = \frac{B}{\mu_0} - M$$

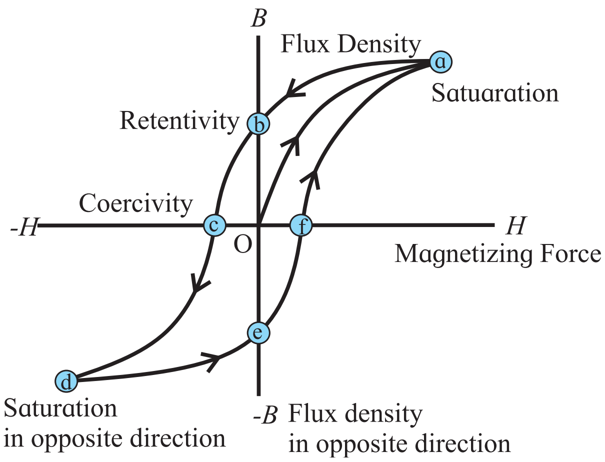


Fig. 11.11: Hysteresis cycle (loop).

Knowing the value of H (= nI) and M, one can calculate the corresponding magnetic field B from the above equation. Figure 11.11 shows the behaviour of the material as we take it through one cycle of magnetisation. At point O in the graph the material is in nonmagnetised state. As the strength of external magnetic intensity H is increased, B also increases as shown by the dotted line. But the increase is non linear. Near point a, the magnetic field is at its maximum value which is the saturation magnetization condition of the rod. This represents the complete alignment and merger of domains. If H is increased future, (by increasing the current flowing through the solenoid) there is no increase in B.

This process is not reversible. At this stage if the current in the solenoid is reduced, the earlier path of the graph is not retraced. (Earlier domain structure is not recovered). When $H = 0$ (current through the solenoid is made zero, point b in the figure) we do not get $B = 0$. The value of B when $H = 0$ is called retentivity or remanence. This means some domain alignment is still retained even when $H = 0$. Next, when the current in the solenoid is increased in the reverse direction, point c in the graph is reached, where $B = 0$ at a certain value of H. This value of H is called coercivity. At this point the domain axes are randomly oriented with respect to each other. If the current is further increased, in the reverse direction, B increases and again reaches a saturation state (point d). Here if H is increase further, B does not increase. From this point d onwards, when H is reduced, B also reduces along the path de. At this point e, again $H = 0$ but B is not zero. It means domain structure is present but the direction of magnetisation is reversed. Further increase in the current, gives the curve efa. On reaching point a, one loop is complete. This loop is called hysteresis loop and the process of taking magnetic material through the loop once is called hysteresis cycle.

Can you recall?

Do you recall a similar loop/effect?

It is similar to stress hysteresis you have studied in mechanical properties of solid in XIth Std. The stress strain curve for increasing and decreasing load was discussed. Area inside the loop gives the energy dissipated during deformation of the material.

Use your brain power

What does the area inside the curve B - H (hysteresis curve) indicate?

11.7 Permanent Magnet and Electromagnet:

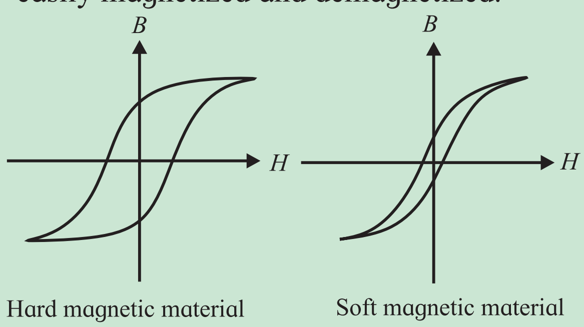
Soft iron having large permeability (>1000) and small amount of retaining magnetization, is used to make electromagnets. For this purpose, a soft iron rod (or that of a soft ferromagnetic material) is placed in a solenoid core. On passing current through the solenoid, the magnetic field associated with solenoid increases thousand folds. When the current through the solenoid is switched off, the associated magnetic field effectively becomes zero. These electromagnets are used in electric bells, loud speakers, circuit breakers, and also in research laboratories. Giant electromagnets are used in cranes to lift heavy loads made of iron. Superconducting magnets are used to prepare very high magnetic fields of the order of a few tesla. Such magnets are used in NMR (Nuclear Magnetic Resonance) spectroscopy.

Permanent magnets are prepared by using a hard ferromagnetic rod instead of soft used in earlier case. When the current is switched on, magnetic field of solenoid magnetises the rod. As the hard ferromagnetic material has a property to retain the magnetization to larger extent, the material remains magnetised even after switching off the current through the solenoid.

Do you know?

What is soft magnetic material?

Soft ferromagntic materials can be easily magnetized and demagnetized.



Hysteresis loop for hard and soft ferramagnetic materials.

11.8 Magnetic Shielding:

When a soft ferromagnetic material is kept in a uniform magnetic field, large number of magnetic lines crowd up inside the material leaving a few outside. If we have a closed structure of this material, say a spherical shell of iron kept in magnetic field, very few lines of force pass through the enclosed space. Most of the lines will be crowded into the iron shell (Fig. 11.12). This effect is known as magnetic shielding. The instrument which need to be protected from magnetic field is completely surrounded by a soft ferromagnetic substance. This technique is being used in space ships. Some scientific experiments require the experiment to be protected from magnetic field in the laboratory. There, high magnetic fields of magnets need to be shielded by providing a case made up of soft ferromagnetic material.

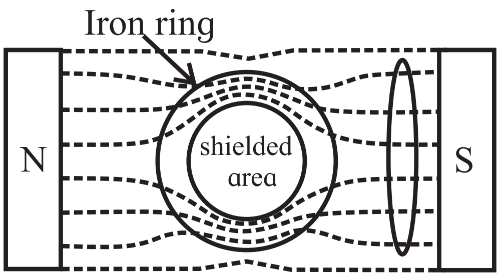


Fig. 11.12 Magnetic Shielding.

Internet my friend

1. http://www.nde-ed.org
2. https://physics.info/magnetism/

Do you know?

There are different types of shielding available like electrical and accoustic shielding apart from magnetic shielding discussed above. Electrical insulator functions as an electrical barrier or shield and comes in a wide array of materials. Normally the electrical wires used in our households are also shielded. In case of audio recording it is necessary to reduce other stray sound which may interfere with the sound to be recorded. So the recording studios are sound insulated using acoustic material.

Exercises

1. Choose the correct option.

i) Intensity of magnetic field of the earth at the point inside a hollow iron box is.
   (A) less than that outside
   (B) more than that outside
   (C) same as that outside
   (D) zero

ii) Soft iron is used to make the core of transformer because of its
   (A) low coercivity and low retentivity
   (B) low coercivity and high retentivity
   (C) high coercivity and high retentivity
   (D) high coercivity and low retentivity

iii) Which of the following statements is correct for diamagnetic materials?
   (A) $\mu_r < 1$
   (B) χ is negative and low
   (C) χ does not depend on temperature
   (D) All of above

iv) A rectangular magnet suspended freely has a period of oscillation equal to T. Now it is broken into two equal halves (each having half of the original length) and one piece is made to oscillate freely. Its period of oscillation is T', the ratio of T' / T is.
   (A) $1/2\sqrt{2}$ (B) 1 / 2
   (C) 2 (D) 1/4

v) A magnetising field of 360 Am^{-1} produces a magnetic flux density (B) = 0.6 T in a ferromagnetic material. What is its permeability in Tm A^{-1} ?
   (A) 1/300 (B) 300
   (C) 1/600 (D) 600

2 Answer in brief.

i) Which property of soft iron makes it useful for preparing electromagnet?

ii) What happens to a ferromagnetic material when its temperature increases above curie temperature?

iii) What should be retentivity and coercivity of permanent magnet?

iv) Discuss the Curie law for paramagnetic material.

v) Obtain and expression for orbital magnetic moment of an electron rotating about the nucleus in an atom.

vi) What does the hysteresis loop represents?

vii) Explain one application of electromagnet.

3. When a plate of magnetic material of size 10 cm × 0.5 cm × 0.2 cm (length , breadth and thickness respectively) is located in magnetising field of 0.5 × 10^4 Am^{-1} then a magnetic moment of 0.5 Am^2 is induced in it. Find out magnetic induction in plate.

[Ans: 0.634 Wb/m^2]

4. A rod of magnetic material of cross section 0.25 cm^2 is located in 4000 Am^{-1} magnetising field. Magnetic flux passing through the rod is 25×10^{-6} Wb. Find out (a) relative permeability (b) magnetic susceptibility and (c) magnetisation of the rod

[Ans: 199, 198 and 7.92×10^5 Am^{-1}]

5. The work done for rotating a magnet with magnetic dipole moment m, through 90° from its magnetic meridian is n times the work done to rotate it through 60°. Find the value of n.

[Ans: 2]

6. An electron in an atom is revolving round the nucleus in a circular orbit of radius 5.3×10^{-11} m, with a speed of 2×10^6 ms^{-1}. Find the resultant orbital magnetic moment and angular momentum of electron. (charge on electron $e = 1.6 \times 10^{-19}$ C, mass of electron $m = 9.1 \times 10^{-31}$ kg.)

[Ans: 8.48×10^{-24} Am^2, 9.645×10^{-35} N m s]

7. A paramagnetic gas has 2.0×10^{26} atoms/m with atomic magnetic dipole moment of 1.5×10^{-23} A m^2 each. The gas is at 27° C. (a) Find the maximum magnetization intensity of this sample. (b) If the gas in this problem is kept in a uniform magnetic field of 3 T, is it possible to achieve saturation magnetization? Why? (k_B = 1.38×10^{-23} JK^{-1})[Ans: 3.0×10^3 A m^{-1}, No] (Hint: Find the ratio of Thermal energy of atom of a gas (3/2 $k_B T$) and maximum potential energy of the atom (mB) and draw your conclusion)

8. A magnetic needle placed in uniform magnetic field has magnetic moment of 2×10^{-2} A m^2, and moment of inertia of 7.2×10^{-7} kg m^2. It performs 10 complete oscillations in 6 s. What is the magnitude of the magnetic field ?

[Ans: 39.48×10^{-4} Wb/m^2]

9. A short bar magnet is placed in an external magnetic field of 700 guass. When its axis makes an angle of 30° with the external magnetic field, it experiences a torque of 0.014 Nm. Find the magnetic moment of the magnet, and the work done in moving it from its most stable to most unstable position.

[Ans: 0.4 A m^2 , 0.056 J]

10. A magnetic needle is suspended freely so that it can rotate freely in the magnetic meridian. In order to keep it in the horizontal position, a weight of 0.1 g is kept on one end of the needle. If the pole strength of this needle is 20 Am , find the value of the vertical component of the earth's magnetic field. (g = 9.8 m s^{-2})

[Ans: 9.8×10^{-5} T]

11. The susceptibility of a paramagnetic material is χ at 27° C. At what temperature its susceptibility be $\chi/3$?

[Ans: 627° C]

Exercise : Chapter 10

1. Distinguish between the forces experienced by a moving charge in a uniform electric field and in a uniform magnetic field.
2. Under what condition a charge undergoes uniform circular motion in a magnetic field? Describe, with a neat diagram, cyclotron as an application of this principle. Obtain an expression for the frequency of revolution in terms of the specific charge and magnetic field.
3. What is special about a radial magnetic field ? Why is it useful in a moving coil galvanometer ?
4. State Biot-Savert law. Apply it to (i) infinitely long current carrying conductor and (ii) a point on the axis of a current carrying circular loop.
5. State Ampere's law. Explain how is it useful in different situations.