6.1 INTRODUCTION

In 800 B.C. shepherds on the island of Magnetia in Greece observed that the nails in their shoes were glued to the ground due to presence of magnetic ores in the area. The word magnet owes its origin to this island of Magnetia.

Since 400 B.C., Chinese had been using magnetic needles to determine direction while sailing. Caravans used magnetic needles to navigate across the Gobi desert.

In 1600 A.D. William Gilbert, a physician with Queen Elizabeth-I, wrote a book “De Magnet”. Some facts of magnetism given in the book are:

(1) Earth behaves as a giant magnet with its magnetic field along north south direction.

(2) A bar magnet hung to freely rotate horizontally aligns itself along the north-south direction. The end pointing towards north is called its magnetic North Pole and the end pointing towards the south is called its magnetic South Pole.

(3) Like magnetic poles repel each other, while unlike poles attract.

(4) When a magnet is cut into pieces, each piece behaves as a magnet having both types of magnetic poles (dipoles). However, in an electric dipole, positive and negative charges can be separated and each is called an electric monopole. Magnetic monopole does not exist.

(5) Magnets can be prepared using iron and its alloys.

Magnetic and Electric Field Lines:

(1) The magnetic field lines in a bar magnet or a solenoid form closed loops from north pole to south pole outside the magnet or solenoid and from south pole to north pole inside it. Electric field lines are not closed loops. They start from the positive charge and end on the negative charge in an electric dipole.

(2) Tangent to a field line at a point indicates the direction of the field at that point.

(3) The magnitude of field in a region is represented by the number of field lines per unit area in that region.

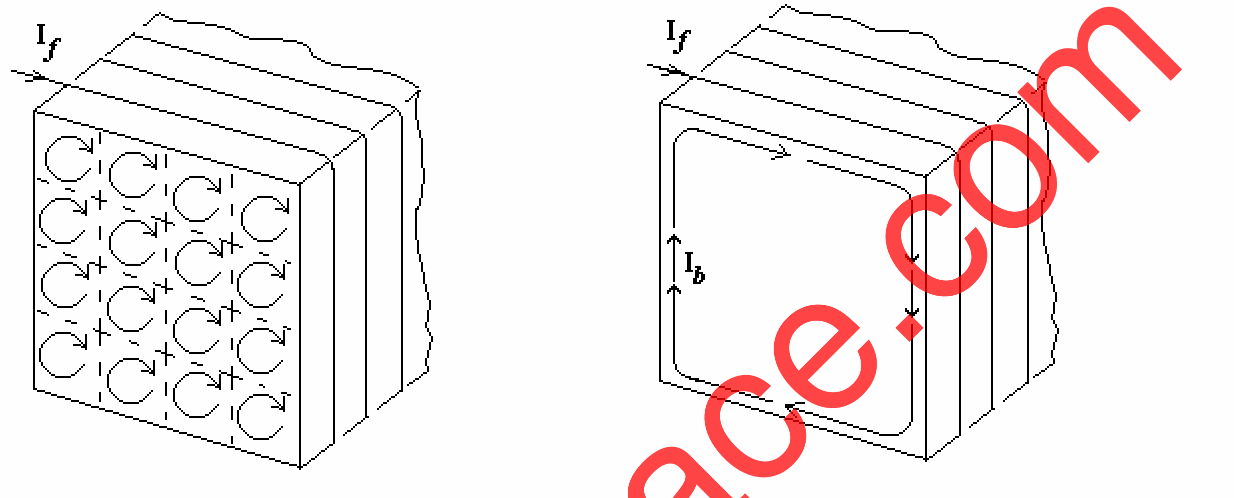
(4) Field lines do not intersect one another.

6.2 Equivalence between a Bar Magnet and a Solenoid

The magnetic field produced by a solenoid is due to passage of electric current through it. How a magnetic field is produced by a bar magnet without any apparent observable current can be explained as under.

A bar magnet is made up of atoms in which definite number of electrons move in various possible orbits. This constitutes electric current around a closed path. This current and the spin of electrons result in magnetic dipole moment. If the vector sum of magnetic dipole moments of all electrons is zero, then such a substance will NOT act as a bar magnet.

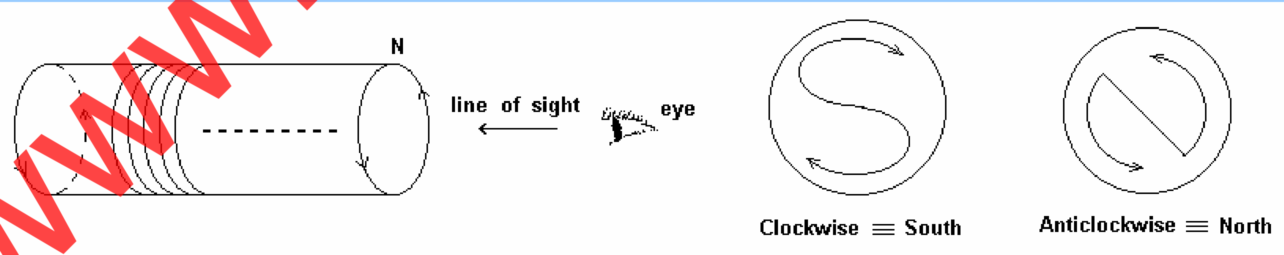
Despite the fact that the atoms of iron possess magnetic dipole moment, an ordinary piece of iron does not behave as a magnet. It can be converted into a magnet by keeping in a strong magnetic field for some time and reducing the magnetic field slowly to zero. When a piece of iron is kept in a strong magnetic field, the elemental atomic currents get redistributed in the iron piece and do not return to the original current distribution on removal of the externally applied magnetic field. The following figures represent this process.



(a) atomic current loops (b) current loop equivalent to loops in part (a)

The rectangular piece of iron is enclosed in a solenoid carrying current I_f. This produces the applied magnetic field. The randomly distributed atomic currents shown in part (a) of the figure gets redistributed as current I_b as shown in part (b) of the figure. This new distribution of currents remains even on removal of the external current I_f. It is because of this that the piece of iron behaves as a bar magnet.

Now consider a solenoid shown in the following figure. It has a large number of closely wound turns of current carrying conducting coil around a soft iron core. For clarity, a few turns separated from one another are shown. Each turn can be treated as a closed current loop possessing magnetic dipole moment. Thus each turn can be treated as a tiny magnet with north and south poles.



On looking normally at the plane of the loop, if the current appears to flow in the clockwise direction, then the side of the loop towards the eye behaves as the south pole and the other side behaves as the north pole. Similarly, if the current appears to flow in the anticlockwise direction, then the side of the loop towards the eye will behave as the north pole. This is shown in the two figures above on the right side. Thus, in the figure of the solenoid above, current in the circuit in front of the eye being in the anticlockwise direction, the side of the first turn towards the eye behaves as a North Pole, while the other side of the turn is the South Pole for that turn. For the second turn, the side towards the eye is again North Pole and so on for all the turns. Thus, magnetic dipole moment of each turn is in the same direction and hence the magnetic dipole moment of the solenoid is the vector sum of dipole moments of all the turns.

For current I through a solenoid with total number of turns N and with cross-sectional area A, the magnetic dipole moment of the solenoid is given by

$M_S = N I A$ ... ... (1)

The magnetic dipole moment of a bar magnet of pole strength, m, and length, 2l, is given by

$M_b = 2ml$ ... ... (2)

By analogy between solenoid and bar magnet, the pole strength, m_s, of the solenoid can be obtained using the above two equations as under.

$2 m_s l = N I A \Rightarrow m_s = \frac{N I A}{2 l} = n I A$, where, $n = \frac{N}{2l}$ = no. of turns per unit length of solenoid.

Thus Pole-strength of solenoid = Number of turns per unit length $\times$ electric current $\times$ cross-sectional area of solenoid.

The unit of pole-strength is Am (Ampere-meter)

6.2 (a) Bar Magnet, magnetic dipole and its magnetic field:

An electric dipole has electric dipole moment, $\vec{p} = 2 q \vec{a}$. Similarly, a magnetic dipole has magnetic dipole moment, $\vec{M} = 2 m \vec{l}$, where m is the magnetic pole strength. The direction of $\vec{p}$ is from negative to positive charge. Similarly, the direction of $\vec{M}$ is from south to north pole for a bar magnet. This analogy between the electric and magnetic dipoles suggests that the magnetic field due to a magnetic dipole can be calculated using a formulae similar to that of electric field due to an electric dipole.

Now, the electric field $\vec{E}$ at a distance z on the axis from the centre of an electric dipole,

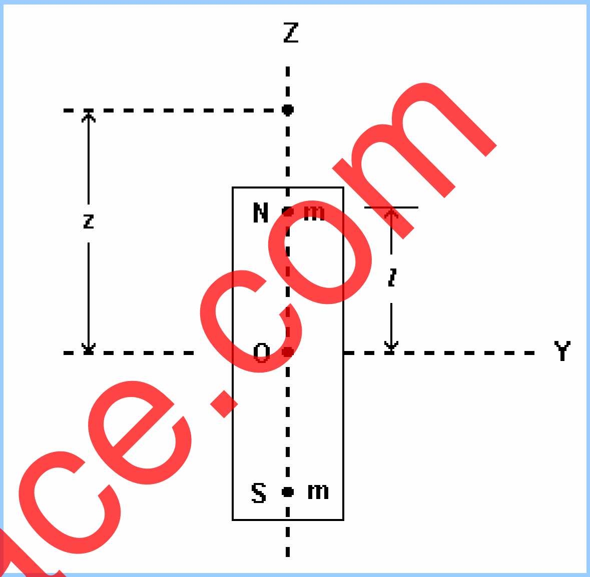
$$\vec{E}(z) = \frac{2 k p z}{(z^2 - a^2)^2} \hat{p}$$

Comparing, force between two charges given by Coulomb's law as $F = \frac{1}{4 \pi \varepsilon_0} \frac{q_1 q_2}{r^2}$ with the force between magnetic poles given by $F = \frac{\mu_0}{4\pi} \frac{m_1 m_2}{r^2}$, $k = \frac{1}{4 \pi \varepsilon_0}$ in the above equation for the electric field shall be replaced by $\frac{\mu_0}{4\pi}$ for the magnetic field. Similarly, p is to be replaced by M and a by l as the length of the bar magnet is $2l$.

(**Note:** Here, the length of the bar magnet is to be taken as the distance between the magnetic poles, $2 l_m$ which is slightly less than the geometric length of the bar magnet, $2 l_g$. For practical purpose, $2 l_m = (5/6)\, 2 l_g$.)

∴ the magnetic field on the axis at a distance z from the centre of the bar magnet is

$$\vec{B}(z) = \frac{2\mu_0 M z}{4\pi(z^2 - l^2)^2}\hat{M} = \frac{\mu_0 M z}{2\pi(z^2 - l^2)^2}\hat{M}$$



If z >> l, then the above equation reduces to

$$\vec{B}(z) = \frac{2\mu_0 M}{4\pi z^3}\hat{M} = \frac{\mu_0 M}{2\pi z^3}\hat{M}$$

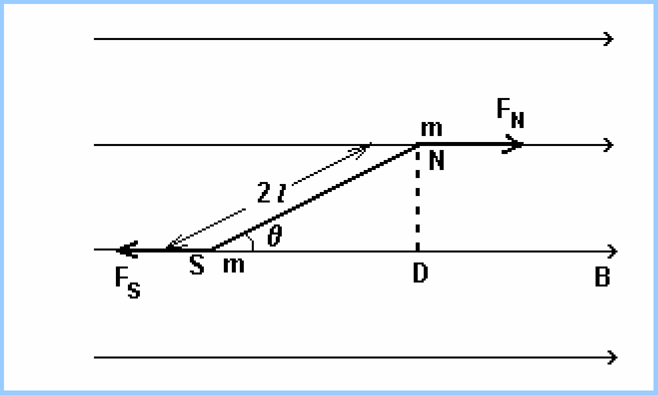
Similarly, the electric field on the Y-axis on the equatorial plane of the electric dipole is

$$\vec{E}(y) = -\frac{kp}{(y^2 + a^2)^{\frac{3}{2}}}\hat{p}$$ and based on this,

the corresponding magnetic field is

$$\vec{B}(y) = -\frac{\mu_0 M}{4\pi(y^2 + l^2)^{\frac{3}{2}}}\hat{M}$$ If y >> l, then $\vec{B}(y) = -\frac{\mu_0 M}{4\pi y^3}\hat{M}$

6.3 Torque acting on a Magnetic Dipole in a Uniform Magnetic Field



The adjoining figure shows a magnetic dipole with magnetic moment M and length 2 l in a uniform magnetic field $\vec{B}$. The direction of dipole moment is from south to north pole and it makes an angle θ with the direction of the magnetic field. The magnetic field $\vec{B}$ is the force on a magnetic pole of unit pole-strength. Hence, the forces $\vec{F}_n$ and $\vec{F}_s$ acting on the north and the south pole respectively are equal in magnitude, opposite in direction and separated by a distance ND. Hence they form a force couple. The torque on an electric dipole is $\vec{\tau} = \vec{p} \times \vec{E}$. Replacing $\vec{p}$ by $\vec{M}$ and $\vec{E}$ by $\vec{B}$ in this equation, the torque on the magnetic dipole is obtained as

$$\vec{\tau} = \vec{M} \times \vec{B} = M B \sin\theta = M B \theta$$ (If θ is very small),

where $M = 2 m l \hat{l}$, ($\hat{l}$ is the unit vector in the direction from south to north.)

Here, as θ is increased, torque increases in opposite direction trying to reduce θ.

$\therefore \quad \vec{\tau} = - MB\theta$

$\therefore \quad I \dfrac{d^2\theta}{dt^2} = - MB\theta$ (by Newton's second law for rotational motion),

where I is the moment of inertia of the dipole with respect to the axis perpendicular to the plane of the figure and passing through the centre of the dipole.

The above equation is the differential equation for angular simple harmonic motion.

$\therefore \quad \omega^2 = \dfrac{MB}{I}$ and periodic time $T = \dfrac{2\pi}{\omega} = 2\pi\sqrt{\dfrac{I}{MB}}$

Comparing with the equation for potential energy of electric dipole, $U = - \vec{p} \cdot \vec{E}$, the potential energy of a magnetic dipole in a uniform magnetic field can be written as

$U = - \vec{M} \cdot \vec{B}$

6.4 Gauss's Law for Magnetism

As magnetic monopole does not exist, magnetic field lines always form closed curves. As the number of field lines entering a closed surface equal the number of lines leaving it, the total flux over any closed surface is zero.

$$\therefore \quad \oint_{\text{closed surface}} \vec{B} \cdot \vec{da} = 0$$

where $\vec{B}$ is the magnetic field and $\vec{da}$ is an infinitesimal area vector on the closed surface.

"The net magnetic flux passing through any closed surface is zero." This statement is generally called Gauss's law for magnetism.

The unit of magnetic flux is weber (Wb). $Wb = Tm^2 = NmA^{-1}$

6.5 Geo magnetism

6.5 (a) Introduction:

Earth has its own magnetic field of the order of 10^{-5} tesla on its surface.

The following points are for information only.

(1) The imaginary magnetic axis of earth makes an angle of 20° with the geographic rotational axis.

(2) The magnetic south pole of earth is in north Canada at latitude 70.5° north and longitude 96° west and the magnetic north pole is at latitude 70.5° south and longitude 84° east.

(3) Magnetic poles are approximately 2000 kilometers away from the geographic poles.

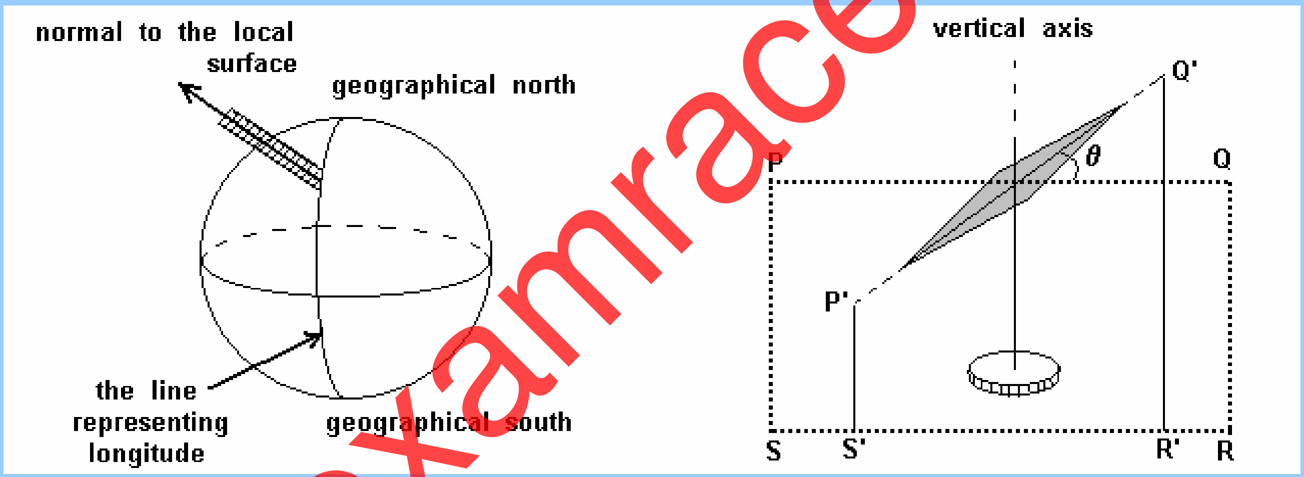
(4) Magnetic and geographic equators intersect each other at longitude 6° west and 174° east.

(5) Thumba near Trivandrum is on the magnetic equator and hence it has been selected for rocket propulsion experiments.

6.5 (b) Geo-magnetic Elements:

(1) Magnetic Declination

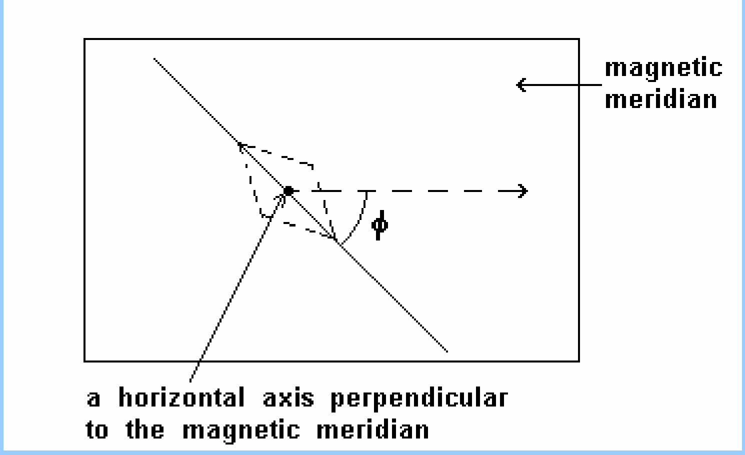
The geographic meridian of the place is the plane passing through its longitude and a perpendicular drawn on the surface of earth at that place. (Refer to the figure.)
The magnetic meridian at the place is the plane containing the magnetic field line passing through that place and the normal drawn at that place.



The angle between the magnetic meridian and the geographic meridian is called the magnetic declination of the place. The magnetic needle freely rotating horizontally on a vertical axis at any place aligns itself to the magnetic North-South direction. The angle between the magnetic needle in this position and the geographic North-South direction gives the magnetic declination at that place. In the figure above, PQRS represents the geographic meridian and P'Q'R'S' represents the magnetic meridian.

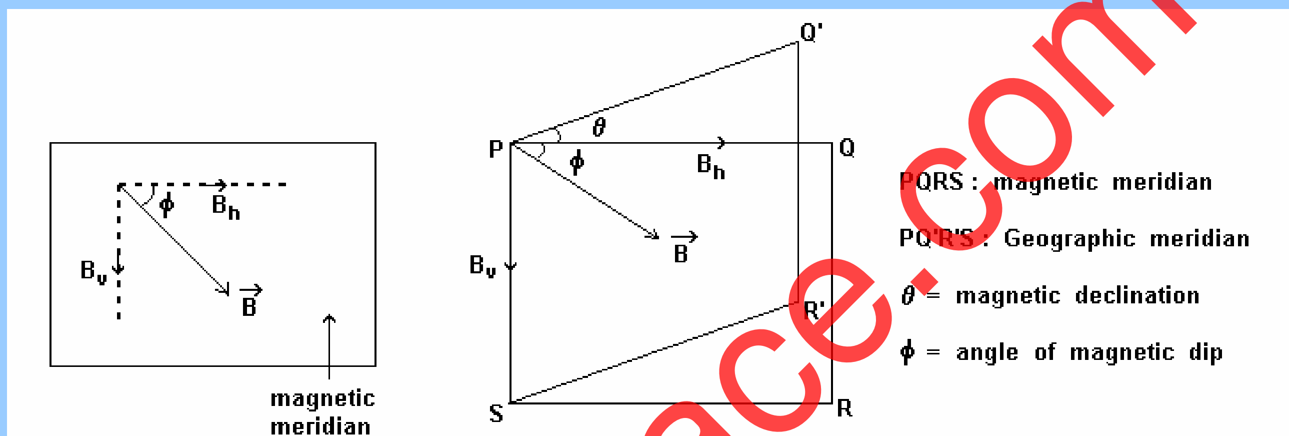
(2) Magnetic dip angle:

Magnetic field lines are not horizontal at all places on earth except at the magnetic equator. When a magnetic needle is kept at any place such that it freely rotates on a horizontal axis in the plane of magnetic meridian, the angle, ϕ, made by it with the horizontal as sown in the figure is called the magnetic dip angle at that place.



(3) Horizontal and vertical components of Earth's magnetic field:

The direction of magnetic field, $\vec{B}$, at some place is shown in left-hand side figure below along with the magnetic meridian. B_h is the horizontal component and B_v the vertical component of the earth's magnetic field $\vec{B}$



All the above-mentioned parameters of the earth's magnetic field are shown together in the right-hand side figure above.

6.5 (c) Origin of Earth's Magnetic Field:

The concept that the magnetic field of the earth is due to huge deposits of magnetic ores deep inside it is NOT correct.

The core of the earth is extremely hot and contains molten matter which is good conductor of electricity. The ions in this matter rotate due to the rotation of the earth and generate currents. It is believed that the earth's magnetic field is due to these electric currents though the correct reason for this is still under research.

This explanation suggest that if any planet containing molten matter in its core rotates with small angular frequency, it would have a weak magnetic field associated with it which is found to be case with the planet Venus. Mon contains no molten matter and hence has no magnetic field. Jupiter rotates with large angular velocity and hence has a very strong magnetic field.

Whenever ions move in a molten ore, the current loops generated behave like magnetic dipoles.

6.5 (d) Variation in Earth's Magnetic Field with Position on the Surface of the Earth and Height from the Surface of the Earth:

The magnetic field on the surface of the earth is of the order of 10^{-5} T (tesla) and it keeps on decreasing with the height above the surface of the earth. At a height of about 30,000 km, it is of the order of 10^{-6} T. The magnetic field of the galaxy is of the order of 10^{-12} T.

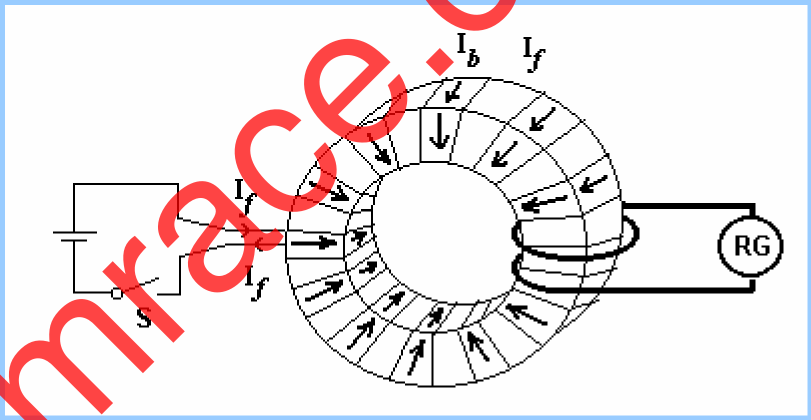
Beyond this height, solar winds which correspond to the flow of charged particles originating in the Sun disturb the earth's magnetic field. These charged particles excite atoms in the atmosphere in this region and ionize them creating show of lights called aurora borealis in the arctic region and aurora australis near the geographic south pole.

6.5 (e) Temporal Variations in the Earth's Magnetic Field:

The magnetic field of the earth varies. The magnetic declination of London had changed by 35° in 240 years. The magnetic south pole which is in the arctic region of Canada is shifting in northwesterly direction at a rate of 10 km / year for reason not known so far. The earth's magnetic field reverses in about a million years. This is known from the study of volcanic eruptions at the bottom of oceans. Studying the age of solidified lava from such eruptions gives a clue to the reversal of the earth's magnetic field.

6.6 Magnetization and Magnetic Intensity

The material whose magnetic properties are to be studied is generally taken in the form of a toroidal ring, known as Rowland ring. Magnetic field is approximately uniform in the region inside a toroidal winding. The following figure shows such a ring with its winding in which current I_f is flowing.



Winding on the ring is called magnetizing winding and the current, I_f, is called magnetizing current.

The magnetic field inside the toroidal region due to current in the absence of any material in the ring is

$B_f = \mu_0 n I_f = \mu_0 i_f$ (for a toroid with a large radius and small cross-sectional area),

where, n = number of turns per unit length on the circumference of the toroid

i_f = current per unit length

A small separate winding around the main winding with a sensitive galvanometer shown in the figure is used to magnetic induction (magnetic field or magnetic flux density) and its changes.

When the toroidal winding is on the ring of some material, the magnetic field generated by the winding current I_f induces current loops inside the material. Such current induced in the material due to the external magnetic field is called bound current (I_b). Let i_b denote such bound current per unit length. Then the magnetic field inside the toroidal region is due to combined effect of i_f and i_b and is given by

$$B = B_f + B_b = \mu_0 (i_f + i_b) = \mu_0 n (I_f + I_b) \quad \dots \quad \dots \quad \dots \quad (1)$$

where, B_b is the magnetic field produced in the material due to the bound current.

The corresponding induced magnetic dipole moment, M_1, due to bound current i_b per unit length of the circumference of the material is given by

$M_1 = i_b A$, where A is the area of cross-section of the ring.

The volume corresponding to the unit length of the circumference is $V = 1 \times A$ units.

$\therefore$ the induced dipole moment per unit volume

$$M = \frac{i_b A}{V} = \frac{i_b A}{1 \times A} = i_b$$ (M is called the intensity of magnetization)

Putting the value of i_b in equation (1),

$$B = \mu_0 (i_f + M)$$

$\therefore$ $\frac{B}{\mu_0} - M = i_f = H$, where H is defined as the magnetic intensity and should NOT be confused with magnetic field intensity which is B.

The current i_f can be controlled and hence it is denoted by i_f (i free). H of any desired value can be obtained by varying i_f. Hence, while studying the magnetic properties of matter, H is used in the equations.

The intensity of magnetization M is connected with i_b which in turn depends on the magnetic properties of the material. Further, current i_b is induced because of $i_f = H$. Hence the magnetizing intensity M depends on the material and magnetic intensity H. The ratio of magnetizing intensity M and magnetic intensity H is termed as magnetic susceptibility χ_m.

$$\therefore \chi_m = \frac{M}{H}$$

The value of χ_m depends on the material properties. Since the vacuum cannot be magnetized, M = 0 and hence from the above equation, $\chi_m = 0$.

$$\therefore H = \frac{B}{\mu_0} - M = \frac{B}{\mu_0}$$ (for vacuum)

$\therefore$ $B = \mu_0 H$ (for vacuum)

Comparing this with the formula $B = \mu_0 n I$ for the empty region in solenoid, we get

$H = n I$ ($\because$ $B = \mu_0 n I$ for the solenoid as well as empty toroid also.)

Putting $M = H \chi_m$ in the equation, $\frac{B}{\mu_0} - M = H$, we get

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

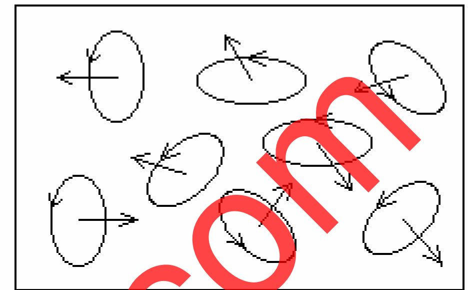
In this equation, $\mu_0 (1 + \chi_m)$ depends on the properties of the medium and is called the permeability μ of the material.

$\therefore$ $\frac{\mu}{\mu_0} = K_m = (1 + \chi_m)$ is called relative permeability of the material.

6.7 Dia, Para and Ferro Magnetism

(1) Paramagnetic materials:

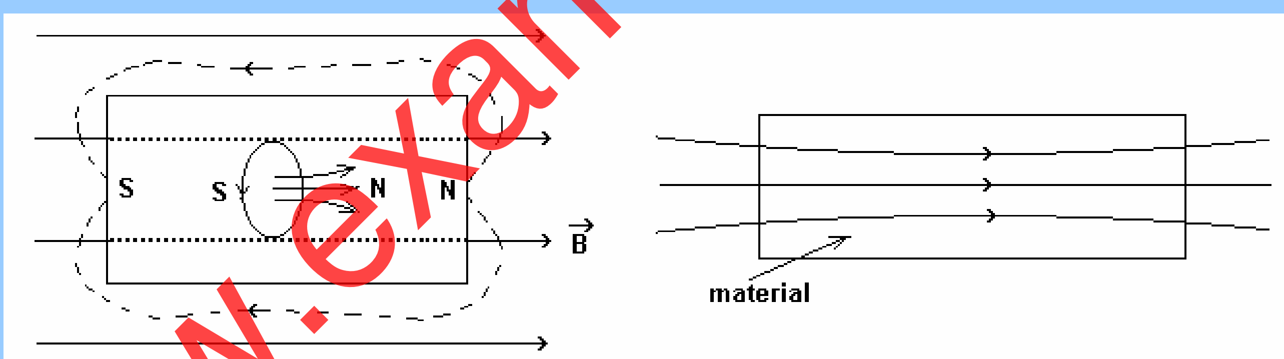
A material is called paramagnetic, if its molecules / atoms possess permanent magnetic dipole moment. Normally, the molecules are so arranged that their magnetic dipole moments are randomly distributed with zero resultant. Symbolically, molecular / atomic magnetic dipoles can be represented by tiny current loops as shown in the figure.



Normal dipole-distribution in paramagnetic material

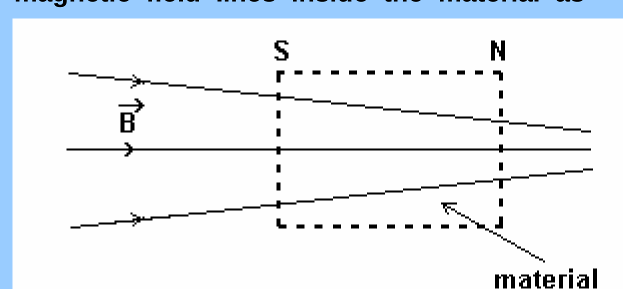
When kept in uniform magnetic field, these tiny dipoles align themselves in the direction of the magnetic field as shown in the following figure to the left side.

Due to thermal oscillations, all the dipoles do not attain 100 % parallel positions to the external magnetic field. In the figure, just one dipole is shown parallel to the external magnetic field, $\vec{B}$. Here micro magnets arrange themselves parallel to the external magnetic field in such a way that the magnetic South Pole of one micro-magnet is adjacent to the magnetic North Pole of the immediately next micro magnet. As the magnetic dipole moments of all are pointing in the same direction, they add up vectorially to produce a resultant magnetization of the material and the resultant poles are as shown in the figure.



The magnetic field lines produced inside the material are in the same direction as that of the external magnetic field increasing the density of the magnetic field lines inside the material as shown in the above figure to the right hand side.

In the adjoining figure, a paramagnetic material is kept in a non-uniform magnetic field which increases towards the right. The resultant north pole of the magnetized material is in a strong magnetic field as compared to its south pole. Thus, there is a resultant force on it towards right (i.e., the stronger magnetic field region).



This shows that whenever a paramagnetic material is placed in a non-uniform magnetic field, it is attracted towards the region of strong magnetic field. As this force is very weak, light weight paramagnetic materials are used in the experiments to observe this effect.

Aluminium, Sodium, Calcium, Oxygen at STP and copper chloride are few examples of

paramagnetic materials. The magnetic susceptibility, χ_m, of these materials is positive.
On increasing the temperature, the magnetic dipoles get more randomly arranged due to increased thermal oscillations. This results in the decrease in the value of magnetization, M, and hence of χ_m.

In 1895, Pierre Curie observed that $M = C \frac{B}{T}$, where C is called the Curie constant.

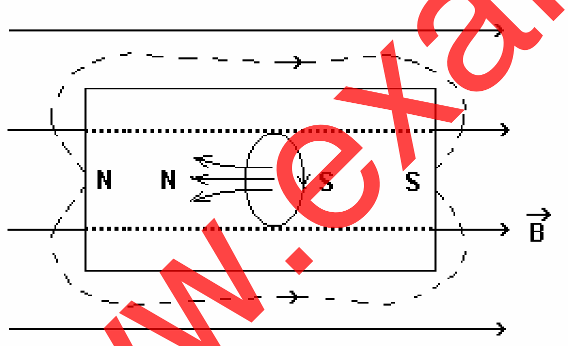
Now, $\chi_m = \frac{M}{H}$ and $B = \mu_0 H$ $\therefore$ $M = \frac{C \mu_0 H}{T}$ and $\chi_m = \frac{C \mu_0}{T}$

On increasing the applied external magnetic field and reducing the temperature, more and more of atomic / molecular dipoles align themselves parallel to the external magnetic field, increasing M and χ_m which become maximum when all the dipoles become completely parallel to the external magnetic field. This situation is called saturation magnetization after which Curie's law is not obeyed.

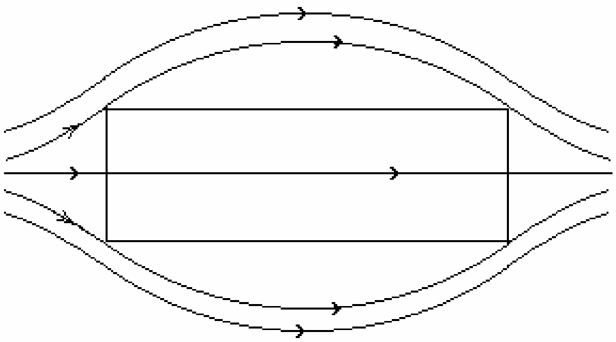
(2) Diamagnetic materials:

The atoms / molecules of Gold, Silver, Copper, Water and Bismuth etc. do not possess permanent magnetic dipole moments. The orbital motion of the electrons and their spin is such that their total magnetic dipole moment is zero. Such materials are called diamagnetic materials.

On keeping such materials in a magnetic field, the electron orbital motion changes in such a way that magnetic dipole moments are induced on the atoms / molecules in the direction opposite to the external magnetic field as shown in the left hand side figure below.



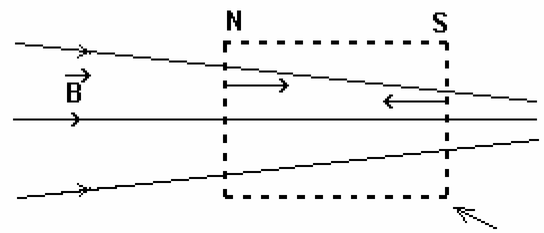
Diamagnetic material in external magnetic field



Field lines in diamagnetic material

The external magnetic field and the magnetic field generated inside the material oppose one another, reduced into reduced magnetic field inside the material as compared to the external magnetic field. The density of field lines also reduces inside the material as shown in the right-hand side figure above.

If the diamagnetic substance is kept in a non-uniform magnetic field, then the magnetic south pole of the substance is in the strong magnetic field and the north pole is in the weak magnetic field as shown in the figure. As the force on S-pole is more than on N-pole, it experiences a resultant force towards the region of the weaker magnetic field.

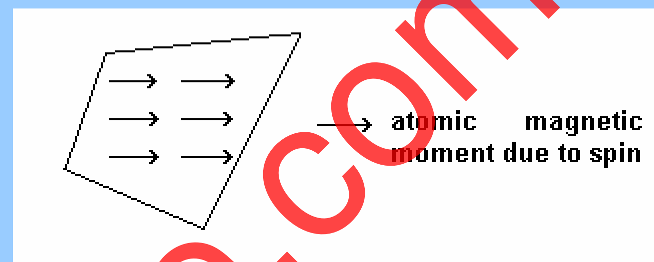


Magnetic susceptibility of a diamagnetic substance, χ_m , is negative.

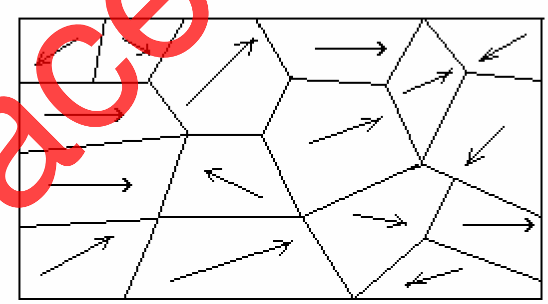
Certain substances, when they behave as superconductors, have susceptibility χ_m = - 1 and K_m = 0. If such a substance is kept in an external magnetic field, and then brought into its superconducting condition, then all the magnetic field lines are expelled from the substance (Meissner effect).

(3) Ferromagnetic substances:

The atoms of iron, cobalt and nickel possess permanent magnetic dipole moments due to the spin of electrons in outermost orbits, but still they do not behave as paramagnetic materials. This is because the atoms of these three elements have a strong bonding with neighbouring atoms. The atoms are arranged in such a way that the magnetic dipole moment (due to spin) of one atom and that of its neighbouring atoms are in the same direction as shown in the figure.



Despite this, they do not behave as permanent magnets. This is because the strong bonding between the atoms is restricted to a limited region called domains which can be explained with the help of quantum mechanics. Every domain in such materials has a resultant magnetic dipole moment and all such dipole moments are randomly directed resulting into zero net magnetic dipole moment. Hence the substance does not behave as a permanent magnet. Using etching techniques, coupled with powerful microscopes, one can observe such domains as shown in the figure.



Random arrangement of domains

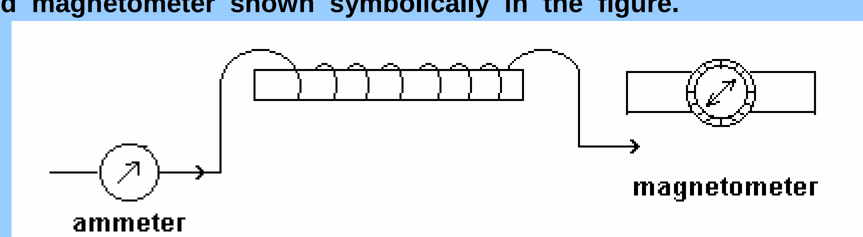
Domains are approximately of the order of 1 mm in size and may consist of nearly 10^{11} atoms. The materials with such a constitution are called ferromagnetic materials.

Hysteresis

A simple experiment is performed to study the effect of an external magnetic field on ferromagnetic materials. A rod of ferromagnetic material to be studied is kept inside a solenoid as shown in the following figure. On passing a current through the solenoid, the magnetic field generated induces magnetic moment inside the rod, the value of which can be measured by an instrument called magnetometer shown symbolically in the figure.

Knowing the volume of the rod, the magnetic moment per unit volume, M, can be evaluated using the formula

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

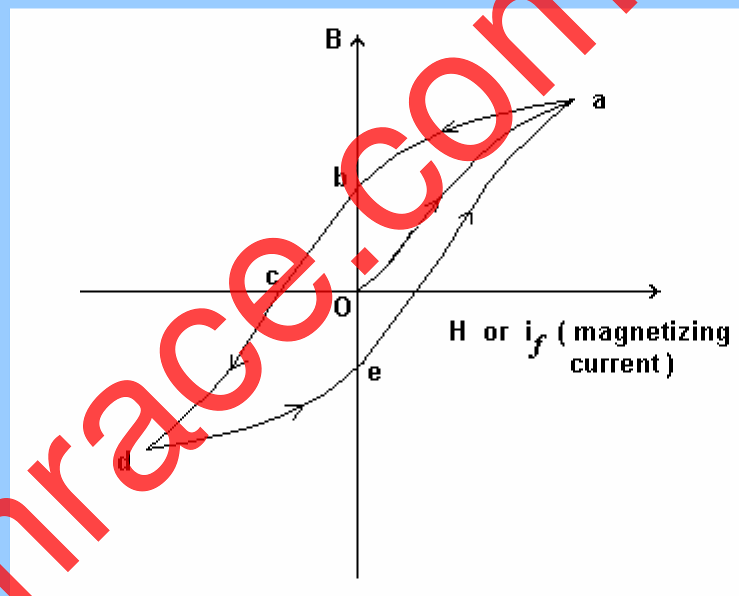


where, i_f = current through unit length of the solenoid which can be found from the current in ammeter and the number of turns per unit length of the solenoid. Thus, from the experimental values of H and M, B can be evaluated and its variation with i_f can be studied.

The graph of B vs. H can be drawn using the observations. One such representative graph for a ferromagnetic material is shown in the figure on the next page.

At the point O in the graph, there is no magnetic field inside the substance. As H (or i_f) is increased, B increases non-linearly becoming maximum at 'a' which is the saturation magnetization condition of the rod.

Starting from O, for small values of H, most of the atoms do not respond to the external magnetic field due to their strong bonding with their neighbours. But, the situation is different for atoms near the domain boundary. Domain boundaries, instead of remaining sharp, start shifting. One of the two adjacent domains increases in size and the other reduces. On further increasing H, only one domain survives ultimately and the saturation magnetization is acquired near point 'a' on the graph.



This process is irreversible. On reducing the current, we do not return to the original condition, i.e., when H = 0, we do not get B = 0 and the substance retains some magnetic moment as shown by the curve ab. The value of B when H = 0 is called retentivity or remanence.
Now, if the current is increased in the reverse direction, then at point c on the graph, the value of H at which B = 0 is called coercivity. At this point, the magnetic moments of the domains are again in random directions but with different domain structure.

On further increasing the current in the reverse direction, B goes on increasing in the reverse direction and reaches the maximum value at 'd' which is the saturation magnetization in the reverse direction. Now on reducing the current, the substance follows curve de and again by reversing the current direction and increasing its value, we obtain the curve ea. This process is called hysteresis cycle. The area enclosed by the B-H curve represents the heat energy (in joule) lost in the sample per unit volume.

Hard and soft ferromagnetic substances:

The substances with large retentivity are called hard ferromagnetic substances which are used in producing permanent magnets. The hysteresis cycle for such substances is broad. Alnico (an alloy of Al, Ni, Co and Cu) is a hard ferromagnetic material. Hence permanent magnets are made using Alnico. The substances with small retentivity, i.e., with narrow hysteresis cycle, are called soft ferromagnetic substances, e.g., soft iron. Such materials are used for making electromagnets.

Effect of temperature:

With increase of temperature, the domain of ferromagnetic substance starts getting distorted and is totally broken up at a certain temperature depending upon the material. All atomic magnetic moments become independent of each other and the substance gets converted to a paramagnetic material. This temperature is called Curie temperature, T_C, of that substance. The relation between the magnetic susceptibility of the substance in the acquired paramagnetic form and the temperature T is given by

$\chi_m = \dfrac{C_1}{T - T_C}$, $(T > T_C)$, where C_1 is a constant. The ferromagnetic material is attracted towards the strong magnetic field region whenever kept in a non-uniform magnetic field.

Permanent Magnets and Electromagnets

The ferromagnetic substances which retain magnetism for a long time at room temperature are called permanent magnets. 400 years back, iron rods fixed in north-south direction were tapped using a hammer in order to prepare a magnet. Another way is to continuously run one end of a magnet on a fixed steel rod always in one direction. The steel rod then acquires permanent magnetism. When current is passed through a solenoid containing a steel rod, then the rod acquires permanent magnetism. Steel or hard iron or hard alloys or iron like alnico are considered best for this purpose.

Soft iron has large permeability and small retentivity and hence is suitable for making electromagnets. When current is passed through a solenoid containing a rod of soft iron, magnetic field in it increases many times making it an electromagnet. On switching off the current, magnetic field more or less vanishes due to small retentivity of soft iron. Thus, the soft iron rod attains magnetism as long as there is current in the solenoid. Electromagnets are used in electric bells, loud-speakers and telephone receivers. Huge electromagnets are used in cranes to lift heavy things made of iron.