Magnetic Properties of Matter

All substances possess magnetic properties and most general definition of magnetism defines it as a particular form of interactions originating between moving electrically charged particles.
Magnetic interaction relates spatially separate material objects and it is transmitted by means of magnetic field about which we have already studied .This magnetic field is important characteristics of EM form of matter.
We already know that source of magnetic field is a moving electric charge i.e. an electric current. On atomic scale, there are two types of macroscopic current associated with electrons.
a) Orbital current is which electron in an atom moves about the nucleus in closed paths constituting electric currents loops
b) Spin currents related to the internal degrees of freedom of the motion of electrons and this can only be understood through quantum mechanics.
Like electrons in an atom, atomic nucleus may also have magnetic properties like magnetic moment but it is fairly smaller then that of electrons.
Magnetic moment **m** is nothing but the quantitative measure of the magnetism of a particle.
For an elementary closed loop with a current i in it, the magnitude |**m**| of a magnetic moment vector equals the current times the loop area S i.e.
|**m**|=iS and direction of **m** can be determined using right hand rule.
All micro structural elements of matter electrons, protons and neutrons are elementary carriers of magnetic moment and combination of these can be principle sources of magnetism
Thus magnetic properties are inherent to all the substances i.e. they are all magnets
An external magnetic field has an influence on these atomic orbital and spin currents and two basic effects of an external field are observed
i) First is **diamagnetic effect** which is consequences of faraday's law of induction. According to the Lenz law□s, a magnetic field always sets up an induced current with its magnetic field direction opposite to an initial field .Therefore diamagnetic moment created by the external field is always negative related to this field
ii) Second effect occurs if there is a resultant non zero magnetic moment in the atom i.e. there is a spin magnetic moment and orbital magnetic moment .In this case external field will attempt to orient the intrinsic atomic magnetic moment in its own direction .As a result a positive moment parallel to the field is created and this is called **paramagnetic moment**.
Because of the universality of the diamagnetic effect, all substances possess diamagnetic.
However, diamagnetism is by no means actually observed in all matter. This is because in many instances the diamagnetic effect is masked by the more powerful paramagnetic effect.
Thus in paramagnetic substances we actually always observe a difference effect produced by the prominent Para magnetism and weaker diamagnetism.

(2) Important terms used in magnetism

(a) Intensity of Magnetization:

Intensity of magnetization is denoted by the letter I.
It represents the extent to which the material is magnetized.
When we place a material in the magnetic field, atomic dipoles of the material tends to align fully or partially in

the direction of the field.

So net magnetic moment is developed in the direction of the field in any small volume of the material.

Intensity of magnetism is defined as the magnetic moment per unit volume of the magnetized material so,

I=**M**/V ----(1)

where **M** is the total magnetic moment within volume due to the magnetizing field.

Unit of **I** is Am^{-1}.

(b) Magnetic Field strength

When a substance is placed in external magnetic field ,the material gets magnetized

The actual magnetic field inside the material is the sum of external field and the field due to magnetization

Now we can define a new vector **H** where

$\mathbf{H}=\mathbf{B}/\mu_0 - \mathbf{I}$ ----(2)

where **B** is the magnetic field induction inside the substance and **I** is the intensity of magnetization

Unit of **H** is same as that of **I** i.e Am^{-1}

CGS unit of **H** is oersted

In the absence of any material I=0 so

$\mathbf{H}=\mathbf{B}/\mu_0$ ----(3)

(c) Magnetic Susceptibility

Magnetic Susceptibility is a measure of how easily a substance is magnetized in a magnetic field

For paramagnetic and diamagnetic substances ,the intensity of magnetization **I** is directly proportional to the magnetic intensity .Thus

$\mathbf{I}=\chi\mathbf{H}$ ----(4)

where proportionality constant χ is known as Magnetic Susceptibility of the material

Since H and I have unit unit so χ is a dimensionless constant and it is a pure number

value of χ is zero in vacuum as there can no magnetization in vacuum

(d) Magnetic permeability

Magnetic intensity is given by

$\mathbf{H}=\mathbf{B}/\mu_0 - \mathbf{I}$

or

$\mathbf{B}=\mu_0(\mathbf{H}+\mathbf{I})$

$=\mu_0(\mathbf{H}+\chi\mathbf{H})$

$=\mu_0\mathbf{H}(1+\chi)$

we can also write this as

$\mathbf{B}=\mu\mathbf{H}$

where $\mu=\mu_0(1+\chi)$ is a constant called permeability of the material

μ_0 is the permeability of vacuum as $\chi=0$ for vacuum

The constant

$\mu_r=\mu/\mu_0=1+\chi$

is called the relative permeability of the material

Magnetic Properties of Matter

(A) Phenomenological classification

Such type of classification is based on sign and magnitude of magnetic susceptibility χ

According to this type of classification there are three type of magnetic material

i) Diamagnetic materials -> $\chi < 0$

i.e magnetic susceptibility is negative

ii) Paramagnetic material -> $\chi > 0$

i.e magnetic susceptibility is positive and less then unity **iii)** Ferromagnetic material -> $\chi >> 0$

i.e magnetic susceptibility is positive and is very high

This approach ignores the nature of microscopic carriers of magnetism and does not consider their interaction

Through this approach magnetic states like anti-ferromagnetic ,ferromagnetic cannot be recognized

(B) Main Effects of external Field

Main effects related to the actions of external field on magnetic moments of atomic carriers are

i) Diamagnetic effects

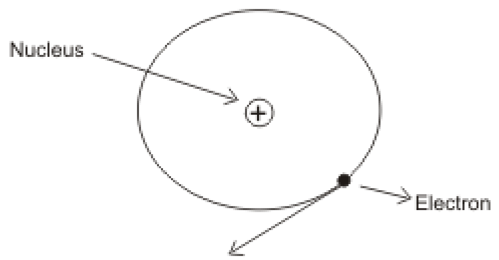
ii) Paramagnetic effects

It was first proposed by the Ampere that the magnetic properties of a material arises due to large number of tiny current loops within the material

These tiny microscopic current loops are associated with the motion of electrons within the atoms and each current loop has a magnetic moment associated with it

In addition to the orbital motion of electron around the nucleus electron also spin or rotate about their own axis

Thus internal magnetic field in a material is produced by electron orbiting around the nucleus and by the spin of the electrons as shown below in the figure .This is how internal magnetism is produced in the material



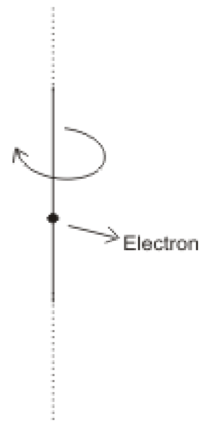


Figure 1(a) Electron orbiting round the nucleus   Figure 1 (b) Spin of electron about its own axis

(i) Diamagnetic effects

Diamagnetic effects occurs in materials where magnetic field due to electronic motions i.e orbiting and spinning completely cancels each other

Thus for diamagnetic materials intrinsic magnetic moments of all the atoms is zero and such materials are weakly affected by the magnetic field.

The diamagnetic effects in material is a result of inductive action of the externally applied field on the molecular currents

To explain the occurrence of this effect ,we first consider the Lenz law accordingly to which, whenever there is a change in a flux in a circuit, an induced current is setup to oppose the change in flux linked by the circuit

Here the circuit under consideration is orbiting electrons in an atom, ions or molecules constituting the material under consideration

We know that moving electron are equivalent to current and when there is a current ,there is a flux

On application of external field ,the current changes to oppose the change in flux and this appear as a change in the frequency of the revolution

The change in frequency gives rise to magnetization as a result of which each atom will get additional magnetic moment ,aligned opposite to the external field causing it.

It is this additional magnetic moment which gives diamagnetic susceptibility a negative sign which is order of 10^{-5} for most diamagnetic material (e g. bismith,lead,copper,silicon,diamond etc).

All substances are diamagnetic ,although diamagnetism may vary frequently be masked by a stronger positive paramagnetic effect on the part of external magnetic field and as a result of internal interactions

Diamagnetic susceptibility is independent of temperature as effect of thermal motion is very less on electron orbits as long as it deform them

(ii) paramagnetic effect

Materials having non zero permanent magnetic moment may either be paramagnetic or ferromagnetic but in this section we will only discuss paramagnetic effects

Para magnetism occurs in material where the magnetic field produced by orbital and spin motion of the electron do not cancel each other completely

Materials showing paramagnetic effects in the presence of external magnetic field have permanent magnetic moment of the atoms

In the absence of external field paramagnetic material have magnetic moments but they are oriented randomly.

These moments (both due to spin and orbital motion of electron) experience an orienting effect in the presence of externally applied magnetic field

Due to this orienting effect material gets magnetized parallel to the external applied field resulting in positive paramagnetic susceptibility

This alignment of atomic magnetic moments in paramagnetic substance is opposed by the thermal motion of the atoms ,so alignment increases with the decrease in temperature and increase in strength of applied magnetic field

Thus there is a sharp dependence of paramagnetic susceptibility on temperature

For paramagnetic substance magnetic susceptibility is of the order of 10^{-5} to 10^{-3} and it is temperature dependent

Magnetic Properties of Matter

Ferromagnetism is the existence of the spontaneous magnetization ,even in the absence of an external magnetic field

Internal magnetic field in ferromagnetism may be hundred or thousand times greater than that of diamagnetic and paramagnetic material

Relation between I and H magnetization intensity and magnetic field is not linear. I and H are no longer have direct proportionality in case of ferromagnetic materials .hence magnetic susceptibility is very large but no longer constant

Even in the absence of external field some ferromagnetic material exhibits large magnetization and can become permanent magnetized

Some of the elements exhibiting ferromagnetic properties at room temperature are iron ,nickle,cobalt and gadolinium

Because of complicated relation ship between I and H in case of ferromagnetic material, it is not possible to express I as a function of H

So when a piece of unmagnetized iron is brought near a magnet or is subjected to the magnetic field of an electric current, the magnetization induced in iron by the field is described by a magnetization curve obtained by plotting the intensity of magnetization I against the field strength H

Ferromagnetism can occur only in paramagnetic material i.e molecule and atoms of a ferromagnetic material also has unpaired electrons and hence non -zero permanent magnetic moment

all ferromagnetic materials are composed of many small magnets or domains ,each of which consists of many atoms within a domain. Size of a domain is usually microscopic

Within the domain, all magnetic moments are aligned ,but the alignment of magnetic moments varies from domain to domain which result in zero net magnetic moment of the macroscopic piece of material as a whole shown below in fig 2(a)

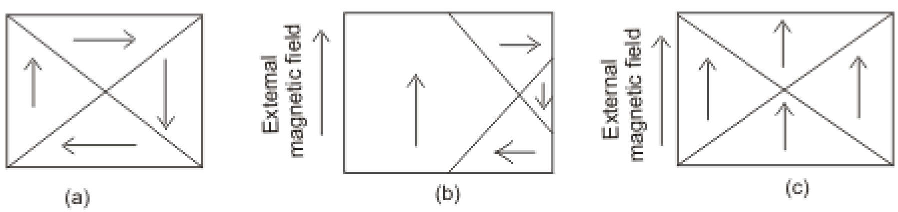


Figure 2

when the substance is placed in an external field ,magnetism of substance can increase in two different ways

i) By the displacement of the boundaries of the domain where domains oriented favorably with respect to the external field increase in and those oriented opposite to the external field are reduced in size as shown in fig 2(b)

ii) By the rotation of domain that is the domain rotate until their magnetic moments are aligned more or less in the direction of the externally applied magnetic field

In presence of week magnetic field material is magnetized mostly by the displacement of the domains and in presence of strong fields magnetization takes place mostly by the rotation of the domains.

In case of ferromagnetic materials on removal of the external magnetic field ,material is not completely

demagnetized and some residual magnetization remains in it
Every ferromagnetic material has a critical temperature known as curie temperature (T_c) above which material becomes paramagnetic and this transition of material from ferromagnetic to paramagnetic is a phase change or phase transition analogous to those between solid, liquid and gaseous phases of the matter

(5) Hysteresis

We have already mentioned that in case of ferromagnetic materials ,the relation between I and H is not linear
This relation can even depend on the history of the sample i.e whether it has been previously magnetized or not
when we place a ferromagnetic material in the magnetic field it gets magnetized by induction
If the field strength is first increased from a zero to high value and then decreased again, it is observed that the original curve is not retraced, the induction lags behind and follows a characteristics curve. This phenomenon is known as Hysteresis and characteristics curve is known as hysteresis loop as shown below in the curve

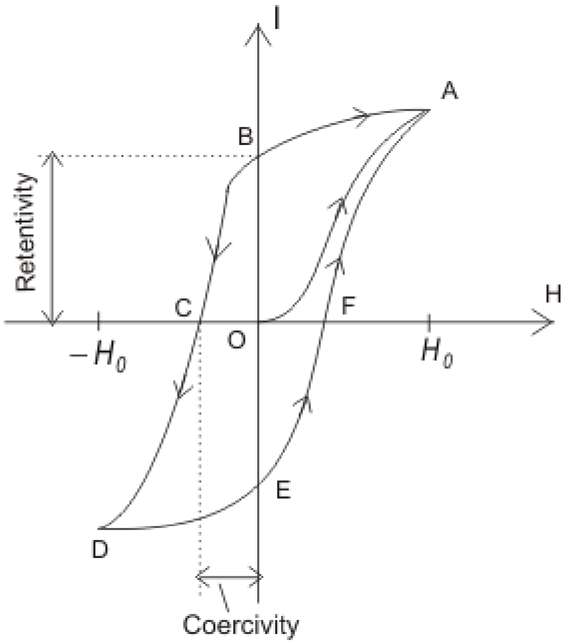


Figure 3:- Variation of I with H

Figure 3 shows the variation of I and H.In the beginning I= 0 and H=0 as represented by the point O in the figure. At this instant the sample is in unmagnetized state

As value of H is increased, I also increases non uniformly .If we increase H indefinitely the intensity of magnetization of ferromagnetic material approaches finite limit known as saturation

Thus at $H=H_0$,the magnetization becomes nearly saturated and magnetization and magnetization varies along path OA

Now if we begin to decrease the value of magnetic field ,the magnetization I of the substance also begin to decrease but this time not following the path AO but following a new path AB

when H becomes equal to zero, I still have value equal to OB,This magnetization remaining in substance when magnetizing field becomes equal to zero is called the residual magnetism and the remaining value of I at point B is known as retentively of the material

To reduce I to zero, we will increase field H in reverse direction and the magnetization I decreases following curve BC where at point C,I becomes equal to zero where H=OC

The value OC of the magnetizing field is called coercivity of the substance

the coercivity of the substance is a measure of the reverse magnetizing field required to bring magnetization I equal to zero

if we further increase H beyond OC the sample begins to get magnetized in reverse direction ,again getting saturated at D at $H=-H_0$

while taking back H from its negative value through zero to its original maximum positive value H_0,we symmetrical curve DEFA

Thus we see that if the field strength is first increased from zero to saturated and then decreased again, it is observed that original curve is not retraced, the induction lags behind the field and follows a characteristic curve .This phenomenon is known as hysteresis and the characteristic curve (Here ABCDEFA) is known as

- Magnetic materials tend to point in the north – south direction.
- Like magnetic poles repel and unlike ones attract.
- Magnetic poles cannot be isolated.
- When a bar magnet of dipole moment $\vec{m}$ is placed in a uniform magnetic field $\vec{B}$, then,
  a) The force on it is zero
  b) The torque on it is $\vec{m}x\vec{B}$
  c) Its potential energy is $-\vec{m}.\vec{B}$

  where we choose the zero of energy at the orientation when $\vec{m}$ is perpendicular to $\vec{B}$.
- Consider a bar magnet of size l and magnetic moment $\vec{m}$, at a distance r from its mid – point, where r >>*l*, the magnetic field $\vec{B}$ due to this bar is,

  $$\vec{B} = \frac{\mu_0 \vec{m}}{2\Pi r^3} \qquad \text{(along axis)}$$

  $$= \frac{\mu_0 \vec{m}}{4\Pi r^3} \qquad \text{(along equator)}$$
- **Gauss's Law for Magnetism:**
  It states that the net magnet flux through any closed surface is zero

  $$\phi_B = \sum_{\substack{all\ \text{area} \\ elements \Delta \vec{s}}} \vec{B}.\Delta\vec{S} = 0$$
- **Poles:**
  a) The pole near the geographic north pole of the earth is called the north magnetic pole.
  b) The pole near the geographic south – pole is called the south magnetic pole.
  c) The magnitude of the magnetic field on the earth's surface = 4 x 10^{-5} T.
- **Elements of the Earth's Magnetic Field:**
  Three quantities are needed to specify the magnetic field of the earth on its surface,
  a) The horizontal component
  b) The magnetic declination
  c) The magnetic dip.

  These are known as the elements of the earth's magnetic field.
- **Magnetic Intensity:**
  Consider a material placed in an external magnetic field $\vec{B_0}$. The magnetic intensity is,

  $$\vec{H} = \frac{\vec{B_0}}{\mu_0}$$

  If the magnetization $\vec{M}$ of the material is its dipole moment per unit volume, then the magnetic field $\vec{B}$ in the material will be,

$$\vec{B} = \mu_0(\vec{H} + \vec{M})$$

For a linear material,

$$\vec{M} = \chi \vec{H}$$

So that,

$$\vec{B} = \mu \vec{H}$$

Where χ is the magnetic susceptibility of the material and μ_r is the relative magnetic permeability.

- **Relationship between $\mu, \mu_0 and \mu_r$:**

  The magnetic permeability area, μ is related as,

  $$\mu = \mu_0 \mu_r$$

  $$\mu_r = 1 + \chi$$

- **Classification of Magnetic Materials:**

  Magnetic materials are broadly classified as,

  a) Diamagnetic

  b) Paramagnetic

  c) Ferromagnetic

- **Magnetic Susceptibility of the Material for Magnetic Materials:**

  a) For diamagnetic materials χ is negative and small.

  b) For paramagnetic materials χ is positive and small.

  c) For ferromagnetic materials χ lies between $\vec{B}$ and $\vec{H}$

- **Permanent Magnets:**

  Substances which retain their ferromagnetic property for a long period of time at room temperature are called permanent magnets.