2. Magnetic Properties of Matter

1. *Magnetization* of a magnetic material:

▶ When a magnetic field is applied to a magnetic matter the atomic or molecular magnetic dipoles are aligned along the applied field. This produces a net magnetic dipole moment in the matter. The magnetic dipole moment of the matter per unit volume is called *magnetization* of the material denoted as M. It is a vector quantity, having direction same as the net induced magnetic dipole moment or along the applied field. $\vec{M} = \frac{\vec{P}_m}{V}$. Its unit is, therefore, A/m.

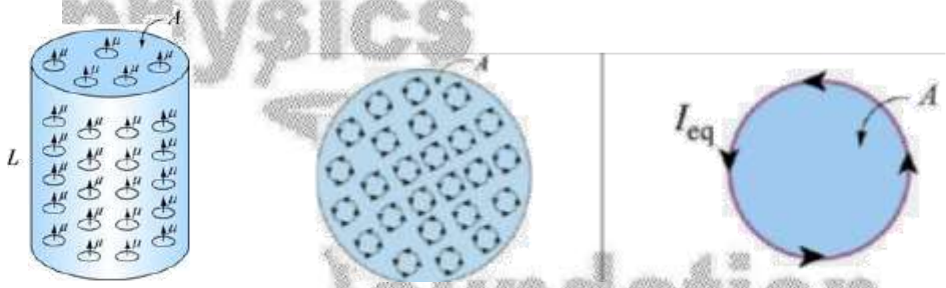
2.Bound surface current I_M in a magnetized material and equivalence of magnetization current density J_M to magnetization M:

▶ *Microscopic current in a magnetized material per unit length* of the cylinder is called magnetization current density J_M. This is just like the current in the solenoid per unit length, nI. Thus, $J_M = \frac{I_M}{l}$, where l is the length of the magnetized material.

Now, magnetic moment of a magnetized cylinder of cross section A with magnetization current I_M will be $P_m = I_M A$. Since $I_M = J_M l$, therefore, $P_m = J_M Al$.

Now magnetization is given as magnetic dipole moment per unit volume.

$\Rightarrow\ M = \frac{P_m}{Al}$ $\quad\Rightarrow M = \frac{J_M Al}{Al}$. Or, $M = J_M$.



3.Difference between *free currents* and *magnetization currents*:

▶ **Free currents:** Currents due to drift of charge carriers between two different potential points are called *free currents*, e.g. current flown in the conductors.

Magnetization currents: In a magnetic material the current due to elementary (atomic or molecular) current loops appearing on the surface of the material are called *magnetization currents* or '*surface currents*'. Magnetization current is also called ***bound current***.

4.Magnetic field in a magnetic material due to the *magnetization* of the material:

▶ Let there be a cylinder of a magnetized material with magnetization M. It can be considered to be a solenoid of current per unit length $(ni) = J_M = M$. Therefore field in the interior due to the *magnetization* will be $\vec{B}_M = \mu_0 \vec{M}$.

5.M*agnetic intensity*:

▶ Magnetic field in a solenoid without magnetic core is given as $B_0 = \mu_0 n i$. Here ni is the free current per unit length and this is defined as magnitude of a vector $\vec{H}$ called *magnetic intensity* vector, in the direction of magnetic field or along the dipole moment of the solenoid. Therefore $\vec{B} = \mu_0 \vec{H}$. *Amperes rule* for this vector is $\oint \vec{H} \cdot d\vec{l} = i_{free}$.

6.Relation between the *M*, *B* and *H*:

▶ Supposed there is a solenoid carrying current i and having field B_0 in its interior.

Therefore, $B_0 = \mu_0 ni = \mu_0 H$. If a magnetic material is filled in the solenoid, then material is magnetized. If magnetization is M, then an additional field $B_M = \mu_0 M$ appears in the magnetic material. Now the net magnetic field B in the material is combination of B_0 and B_M. $\Rightarrow B = B_0 + B_M$.

$\Rightarrow\ B = \mu_0 H + \mu_0 M$. For free space $M = 0$, hence $\vec{B} = \mu_0 \vec{H}$.

7.Magnetic susceptibility:

▶ *Magnetization* in a magnetic material is proportional to the magnetic intensity *H*. $\Rightarrow\ M \propto H$.

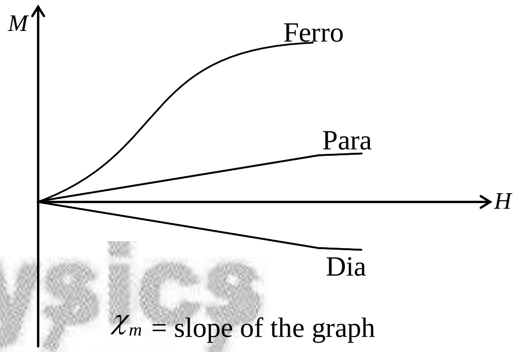
$\Rightarrow\ M = \chi_m H$, or, $\chi_m = \frac{M}{H}$.

This constant χ_m is called *magnetic susceptibility* of the material.

Hence magnetic susceptibility can be defined as "the ratio of magnetization of a material and the magnetic intensity."

In terms of magnetic induction, $M = \chi_m \frac{B}{\mu_0}$.

The materials which follow this relation are called **linear magnetic material**.
Paramagnetic and diamagnetic substances are linear magnetic materials but ferromagnetic is not.



χ_m = slope of the graph

8.Relation between *susceptibility* and relative *permeability*?

▶ Net magnetic field inside a magnetic material is $B = B_0 + B_M$.

$$\Rightarrow\ B = \mu_0 H + \mu_0 M \Rightarrow \mu_0 \mu_r H = \mu_0 H + \mu_0 \chi H . \Rightarrow\ \mu_r = 1 + \chi .$$

⁈ The susceptibility of magnesium at 300K is 1.2 × 10^{-5}. At what temperature will the susceptibility be equal to 1.44 × 10^{-5}. 1

Ans: By Curie law, $\chi_m \propto \frac{1}{T}$, therefore, $\frac{\chi_1}{\chi_2} = \frac{T_2}{T_1}$. Therefore $T_2 = \frac{300 \times 1.2 \times 10^{-5}}{1.44 \times 10^{-5}}$ K = 250K.

⁈ An iron rod of volume 10^{-4} m³ and relative permeability 1000 is placed inside a long solenoid wound with 5 turns/cm. If a current of 0.5A is passed through the solenoid, find the magnetic moment of the rod.

⁈ A permanent magnet in the shape of a thin cylinder of length 10 cm has M = 10^6A/m. Calculate the magnetization current I_M.
Ans: Magnetization current $I_M = J_M \times l = M \times l = 10^6 \times 0.1 = 10^5$A.

9.Classification of magnetic material, on the basis of their magnetic properties:

▶ There are three classes of magnetic materials:

(a) *Diamagnetic Substances*: The substances which develop weak magnetization opposite to the applied field are called diamagnetic substances.

Diamagnetic substances have following properties:

1. The atoms and molecules have no net magnetic dipole moment. When an external field is applied the molecules or the atoms develop a net dipole moment opposite to the applied field.
2. When a rod of diamagnetic substance is suspended freely in a magnetic field it orients perpendicular to the field.
3. When placed in a non-uniform field the diamagnetic substance is feebly repelled to the weaker part of the field.
4. Susceptibility (χ) is negative and relative permeamibility (μ_r) is less than 1.
5. Susceptibility (χ) doesn't depend upon temperature.
6. Diamagnetism is the universal properties of matter. It is masked by the para and ferro characters in para- and ferro- magnetic substances.

(b) ***Paramagnetic substances***: The substances which develop weak magnetization parallel to the applied field are called diamagnetic substances.

Paramagnetic substances have following properties:

1. Atoms and molecules have a net magnetic dipole moment. In an external field the dipoles align along the field.
2. When a rod of paramagnetic substance is places in a magnetic field it aligns itself along the field.
3. When placed in a non-uniform field it is feebly attracted towards the stronger part of the field.
4. Susceptibility (χ) is smaller and positive. Relative permeability (μ_r) is greater than 1.
5. Susceptibility (χ) depends upon temperature according to Curie Law.

(c) ***Ferromagnetic substance***: The substances which develop very strong magnetization parallel to the applied field are called ferromagnetic substances.

Ferromagnetic substances have following properties:

1. Atoms and molecules have pre-aligned atomic or molecular dipoles in small regions of a sample, called *domains*. When external field is applied the domains are aligned producing a strong induced dipole moment.
2. When a rod is placed in a magnetic field it aligns itself along the field.
3. When placed in a non uniform field it is strongly attracted by the stronger part of the field.
4. Susceptibility (χ) is much greater than paramagnetic substances. Relative permeability (μ_r) is much greater than 1.
5. Susceptibility (χ) depends upon temperature but not in a regular manner.

Diamagnetic	Paramagnetic	Ferromagnetic	Superconductor
$-1 \le \chi < 0$	$0 < \chi << 1$	$\chi >> 1$	$\chi = -1$ and $\mu_r = 0$
$0 \le \mu_r \le 1$	$0 < \mu_r > 1$	$\mu_r >> 1$	
$\mu < \mu_0$	$\mu > \mu_0$	$\mu >> \mu_0$	

❓ Which materials have negative value of magnetic susceptibility?

Ans: Diamagnetic.

❓ The relative permeability of a magnetic material is 0.9983. Name the type of magnetic materials it represents.

Ans: Diamagnetic.

❓ If a toroid uses Bismuth as its core, will the field in the core be lesser or greater than when it is empty?

Ans: Lesser, because bismuth is diamagnetic.

❓ Explain quantitatively the difference in the order of magnitude between the diamagnetic susceptibilities of N_2 (~5×10^{-9}) (at STP) and Cu (~10^{-5}).

❓ Name two elements, one having positive susceptibility and the other having negative susceptibility. What does negative susceptibility signify?

10.Factors on which the magnetic susceptibility depends:

▶ The magnetic susceptibility of the material depends upon two factors:

(i) Temperature: The susceptibility of paramagnetic substance is inversely proportional to the absolute temperature. The relation is called Curie Law: $\chi \propto \frac{1}{T}$.

Susceptibility of ferromagnetic substance decreases with temperature but not in defined way while that of diamagnetic substance doesn't depend upon the temperature.

(ii) Density: Susceptibility of a magnetic material is directly proportional to the density of the material. $\chi \propto \rho$.

11.*Curie law* :

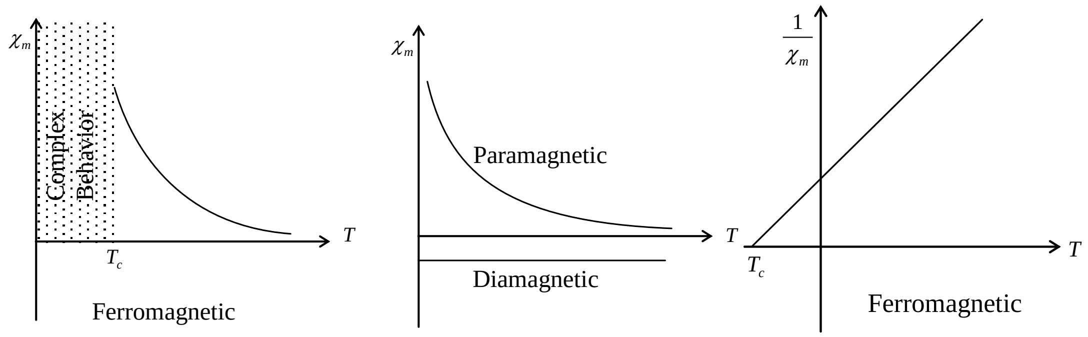
▶ Magnetic susceptibility of para-magnetic substance varies as inverse of the absolute temperature.

$\Rightarrow$ $\chi \propto 1/T$. Or $\chi = C/T$, where C is a constant called '*Curie constant*' (unit K^{-1}).

The law was proposed by Pierre Curie (1859-1906). This law can also be written as $M = C\frac{B_0}{T}$.

12.*Curie - Weiss's law*:

▶ For ferromagnetic substance there is a characteristic temperature called **Curie temperature** or **Curie point** above which a ferromagnetic substance becomes paramagnetic. The Curie law takes form $\chi = \frac{C'}{T - T_c}$, $T > T_c$, where C' is another constant. This is called ***Curie-Weiss law***.



Curie Temperature	
Material	**T_c (K)**
Cobalt	**1394**
Iron	**1043**
Fe2O3	**893**
Nickel	**631**
Gadolinium	**317**

Susceptibility of some magnetic materials:

Diamagnetic Substance	χ	Paramagnetic Substance	χ
Bi	-1.66×10^{-5}	**Al**	2.3×10^{-5}
Cu	-9.8×10^{-6}	**Ca**	1.9×10^{-5}
Diamond	-2.2×10^{-5}	**Cr**	2.7×10^{-4}
Au	-3.6×10^{-5}	**Li**	2.1×10^{-5}
Pb	-1.7×10^{-5}	**Mg**	1.2×10^{-5}
Hg	-2.9×10^{-5}	**Nb**	2.6×10^{-5}
N (STP)	-5×10^{-9}	**O (STP)**	2.1×10^{-6}
Ag	-2.6×10^{-5}	**Pt**	2.9×10^{-4}
Si	-4.2×10^{-5}	**W**	6.8×10^{-5}

❓ An iron bar magnet is heated to 1000°C and then cooled in a magnetic field free space. Will it retain its magnetism? 1

Ans: Yes! [Critical temperature of iron is 1043°C, hence it will not loose its magnetism at 1000°C].

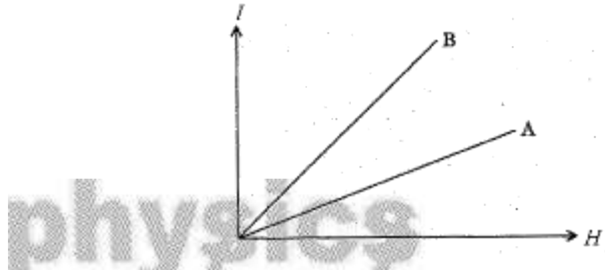
⁈ From molecular view point, discuss the temperature dependence of susceptibility for diamagnetism, paramagnetism and ferromagnetism.

Ans: On increasing the temperature, the vibration of the molecules increases, which decreases the alignment of the molecular dipoles in paramagnetic substance. The diamagnetism is not dependent on the molecular dipoles, hence increased or decreased vibration doesn't affect diamagnetism. Similarly in ferromagnetism, the alignment is so strong and complete that it is not affected by the change in vibrational motion.

⁈ What is the basic difference between the atom or molecule of a diamagnetic and a paramagnetic material? Why are elements with even atomic number more likely to be diamagnetic?

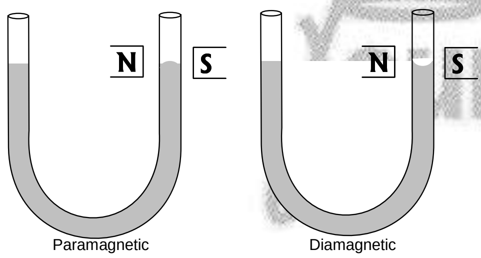
Ans: Atoms or molecules of diamagnetic substance have a net zero magnetic moment while atoms and molecules of the paramagnetic substance have a net non-zero magnetic moment. In the atoms with even number of electros magnetic momenta of orbital electrons are in pairs and may cancel each other giving a net zero magnetic moment hence the element will be more likely to be diamagnetic.

The following figure shows the variation of intensity of magnetization versus the applied magnetic field intensity, *H*, for two magnetic materials A and B : (a) Identify the materials A and B. (b) Why does the material B, have a larger susceptibility than A, for a given field at constant temperature?

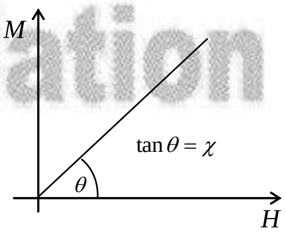


13.Behavior of liquid substances in magnetic field :

▶ The liquid to be tested is filled in a U-tube and one of the arms is placed between the poles of a magnet. The level of liquid in this arm rises if it is paramagnetic. If level is depressed then liquid is diamagnetic.

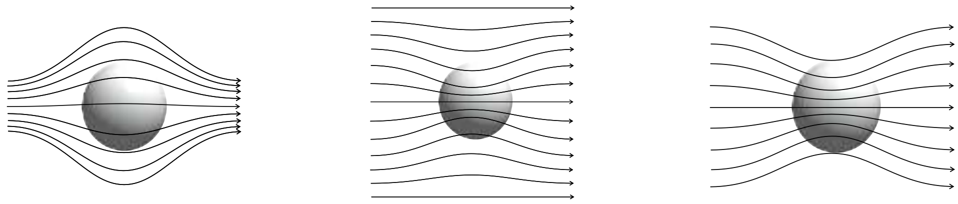


Behavior of liquid material



Magnetization vs Magnetic Intensity

Comparison of Magnetic Materials



Diamagnetic Paramagnetic Ferromagnetic

⁈ Two similar bars, made from two different materials P and Q are placed one by one in a non uniform magnetic field. It is observed that (a) the bar P tends to move from the weak to the strong field region.
(b) the bar Q tends to move from the strong to the weak field region.
(c) What are the nature of the magnetic materials used for making these two bars?

⁈ Draw magnetic field lines when a (i) diamagnetic, (ii) paramagnetic substance is placed in an external magnetic field. Which magnetic property distinguishes this behavior of the field lines due to the two substances?

14. Diamagnetism is a universal character:

▶ Regardless that an atom already possesses a magnetic dipole moment or not, when it is subjected to a magnetic field, those electrons having orbital magnetic moment in the same direction slow down and those in the opposite direction speed up, due to induced electric field in accordance with the Lenz's law. Thus, the substance develops a net magnetic moment in direction opposite to that of the applied field, which is the diamagnetic character.

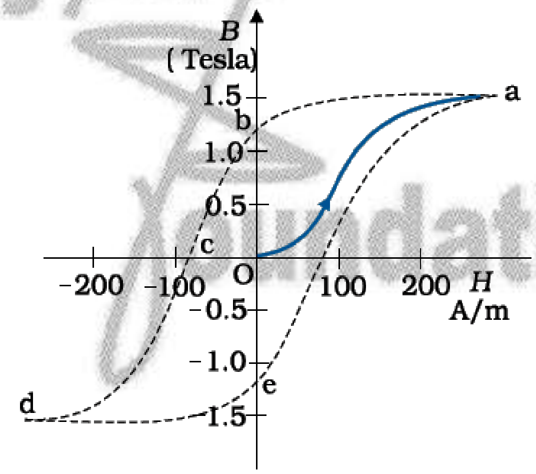
In the substances, in which the atoms already possess a net dipole moment, the induced opposite magnetic moment or diamagnetic effect is offset by the strong dipole moment due to alignment of polar molecules.

So the diamagnetism is a universal property.

15.*Hysteresis*:

▶ When a ferromagnetic substance is subjected to a magnetic field, the magnetization hence magnetic induction $\vec{B}$ increases and decreases with applied intensity $\vec{H}$ non-linearly. The increase and decrease of $\vec{B}$ with applied $\vec{H}$ doesn't takes place through the same path and making $\vec{H}$ zero doesn't makes $\vec{B}$ zero. In a cycle of magnetization and demagnetization, the $\vec{B}$ versus $\vec{H}$ curve forms a closed loop. The phenomenon is called **hysteresis** and this is a characteristic of ferro-magnetic substances. The $\vec{B}$ versus $\vec{H}$ loop is called *hysteresis loop*.

When $\vec{H}$ is increased, $\vec{B}$ increases and attains a **saturation value**. On decreasing $\vec{H}$ magnetic field $\vec{B}$ also decreases but through different path and at $\vec{H}=0$, $\vec{B}=\vec{B}_R \neq 0$. To remove remaining *B*, the field *H* is increased in opposite direction and for a given value of $\vec{H}=\vec{H}_C$, *B* becomes zero.



The area bounded by the loop represents the energy lost per unit volume of the material as heat in a cycle of magnetization and demagnetization. The area bounded by the loop is greater for the hard iron and less for the soft iron.

For a material which undergoes magnetization and demagnetization repeatedly as in transformer core of AC or telephone diaphragms, area of the hysteresis loop must be small with low coercivity and retentivity.

16.*Coercivity* and *retentivity*.

▶ **Coercivity:** The capacity of retaining magnetization is called *coercivity*. It is measured by the magnitude of *H* in reversed direction (H_C), required to remove the remaining magnetization. This point is marked as c in the graph.

Retentivity: The residual magnetization left in a magnetic material even after the magnetizing *H* field becomes zero is called "retentivity"(B_R) This point is marked as *b* in the graph.

17. Hard and soft ferromagnetic material:

▶ **(i) Hard ferromagnetic materials:** The ferromagnetic materials in which the magnetization persists after the magnetizing filed is removed. Such materials are called *hard* magnetic materials or *hard ferromagnets*.

Characteristics:

1. *Hard magnets* are characterized by high remainant inductions and high coercivities.
2. These are also called *permanent magnets* or *hard magnets*.
3. These are found useful in many applications including fractional horse-power motors, automobiles, audio- and video- recorders, earphones, computer peripherals, and clocks.
4. They generally exhibit large hysteresis losses.

Ex.: Co-steel, Tungsten steel, $SmCo_5$, $Nd_2Fe_{14}B$, ferrite $Bao.6Fe_2O_3$, Cunife (60% Cu 20% Ni-20% Fe), Alnico (alloy of Al, Ni, Co and Fe), etc.

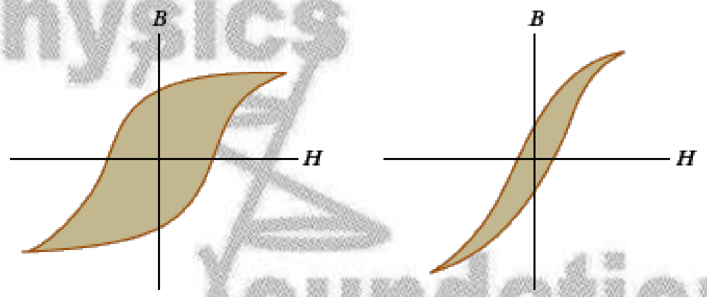
Such materials form permanent magnets to be used among other things as a compass needle.

(ii) Soft ferromagnetic materials: Ferromagnetic materials in which the magnetization disappears on removal of the external field are called *soft ferromagnetic materials*.

Characteristics:

1. *Soft magnetic material* are characterized by low coercive forces and high magnetic permeabilities; and are easily magnetized and de-magnetized.
2. They generally exhibit small hysteresis losses.
3. Application of soft magnets include: cores for electro-magnets, electric motors, transformers, generators, and other electrical equipment.

Ex.: ingot iron, low-carbon steel, Silicon iron, superalloy (80% Ni-5% Mo-Fe), 45 Permalloy (55%Fe-45%Ni), 2-79 Permalloy (79% Ni-4% Mo-Fe), MnZn ferrite / Ferroxcube A (48% $MnFe_2O_4$-52%$ZnFe_2O_4$), NiZn ferrite / Ferroxcube B (36% $NiFe_2O_4$-64% $ZnFe_2O_4$).



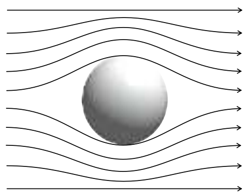
Hard Ferromagnetic Substance   Soft Ferromagnetic Substance

Such materials are used for electromagnets.

⁈ Why permanent magnets are made of steel while the core of the transformer is made of soft iron?
Ans: Steel has greater coercivity and retentivity, while soft iron has lesser coercivity and retentivity.
⁈ What type of magnetic material is used in making permanent magnets?
Ans: Material having higher coercivity and retentivity.
Why the core of moving coil galvanometer is made of soft iron?
Ans: 1. to intensify the magnetic field through the coil to increase the sensitivity.
2. to give a radial magnetic flux of uniform density, thereby enabling the scale to be uniformly divided.
⁈ (i) Write two characteristics of a material used for making permanent magnets. (ii) Why is core of an electromagnet made of ferromagnetic materials?
Ans: (i) The two characteristics of a material used for permanent magnet are: (a) Higher coercivity (b) Higher retentivity.
(ii) Core of an electromagnet is made of ferromagnetic substance because in ferromagnetic core thousand times stronger magnetic field than in air is produced by the same current.
⁈ Magnetic field arises due to charges in motion. Can a system have magnetic moments even though its net charge is zero? Justify.
Ans: Yes a paramagnetic substance has a magnetic moment and a zero net charge.

18.Superconductivity:

▶ In some metals and ceramics the resistivity becomes zero at a certain low temperature, called critical temperature (T_C). Such a metal or ceramic is called superconductor. They exhibit both *perfect conductivity* and *perfect diamagnetism*.



Field lines near perfect Diamagnetic Material (Superconductor)

Here the field lines are completely expelled, therefore susceptibility for them is χ□ = –1 and $\mu_r = 0$. A superconductor repels a magnet and (by Newton's third law) is repelled by the magnet. The phenomenon of perfect diamagnetism in superconductors is called the *Meissner effect*, after the name of its discoverer.
Superconducting magnets can be gainfully exploited in variety of situations, for example, for running magnetically levitated super fast trains.

⁈ A ball of superconducting material is dipped in liquid nitrogen and placed near a bar magnet. (i) In which direction will it move? (ii) What will be the direction of its magnetic moment?
Ans: (i) Away from the magnet. (ii) opposite to the diploe moment of the magnet.
⁈What properties should a material have to be used to make (i) Permanent magnet, (ii) Electromagnet?
Ans: (i) The material to be used as permanent magnet should have high coercivity and high retentivity.
(ii) The material to be used as electromagnet should have low coercivity and low retentivity.
⁈ How a magnetic material is demagnetized by taking the material through cycles of hysteresis loops.
Ans: For demagnetization the material is subjected to repeated demagnetizing cycles as shown below.