Introduction

The materials which can be magnetized are known as **magnetic materials**.

Magnetism arises from the magnetic moment or magnetic dipole of the magnetic materials.

Magnetic materials are important industrial materials widely used in many engineering designs. The magnetic materials are used in electrical machines, computers, television picture tubes, electronic toys etc. Nowadays magnetic materials play important role in information storage devices.

In this unit, the origin of magnetic magnetism in materials, different types of magnetic materials, their important properties and applications are briefly explained.

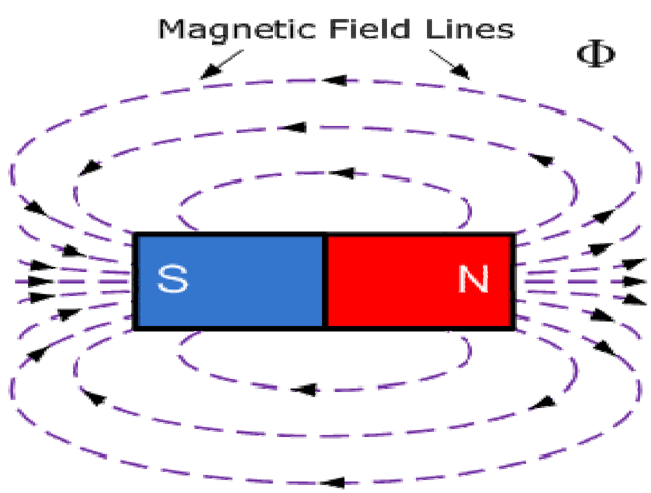
To begin with, we shall first discuss some of the **basic terms, units and relationship associated with magnetism and magnetic materials.**

Magnetic Poles: The two opposite end of a magnetic are known as magnetic poles. In general, magnetism is bipolar in nature and no magnetic monopoles has ever been discovered.

Magnetic Length: The distance between two poles is known as magnetic length.

Magnetic Filed: The region where a magnetic pole experiences a force is define as the magnetic filed. **Or** Magnetic Field is the space around a magnet where its magnetic effect is felt.

Magnetic Line of Force: The magnetic field is assumed to consist of lines of magnetic forces. These lines of magnetic forces to proceed from the N-pole and pass through the sourrounding medium and then re-enter the S-pole. It has been observed that , these lines from closed loops through the magnet as shown in Fig.



Magnetic Flux Density (B): The magnetic induction or magnetic flux density is defined as the magnetic flux passing normally through an unit area of cross-section at that point. It is denoted by the symbol B and is expressed in Wb/m2 or tesla (T).

$$\mathbf{B=\varphi/A}$$

Magnetic Moment (μm): Magnetic moment is a measure of the strength of a magnet. It is the product of strength of one of the poles and the distance between two poles of a magnet. Unit : Wb. m.

Magnetic Field Intensity or Magnetic Field Strength (H) : Magnetic field intensity or Magnetic field strength is a measure of the force experienced by an unit north pole when placed at a given point in a magnetic field. H= N/ Wb or A/m.

Magnetization (M): The magnetic moment per unit volume of the specimen.
Unit: A/m

Magnetic Susceptibility (χ): Magnetic Susceptibility is defined as the ratio of the intensity of magnetization (M) to the magnetic field strength (H).

$$\chi = \mathbf{M/H}$$

Permeability or Absolute Permeability (μ): It is defined as the ratio of magnetic induction B to the applied field H.

$$\mu = B/H$$

For Vacuum of Free space, $\mu_0 = B/H$, Value: **$4\pi \times 10^{(-7)}$ H/m**

The permeability of any given media is assessed relative to μ_0 in terms of relative permeability μ_r .

$$\mu_r = \mu/\mu_0 \quad \text{and } B = \mu_0 \mu_r H$$

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

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

$$\mu H = \mu_0 (H+M)$$

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

$$\boxed{\mu_r = (1 + \chi)}$$

Origin of Magnetic Moment:

Materials are made up of atoms. These atoms consist of positively charged nucleus, surrounded by cloud of electrons.

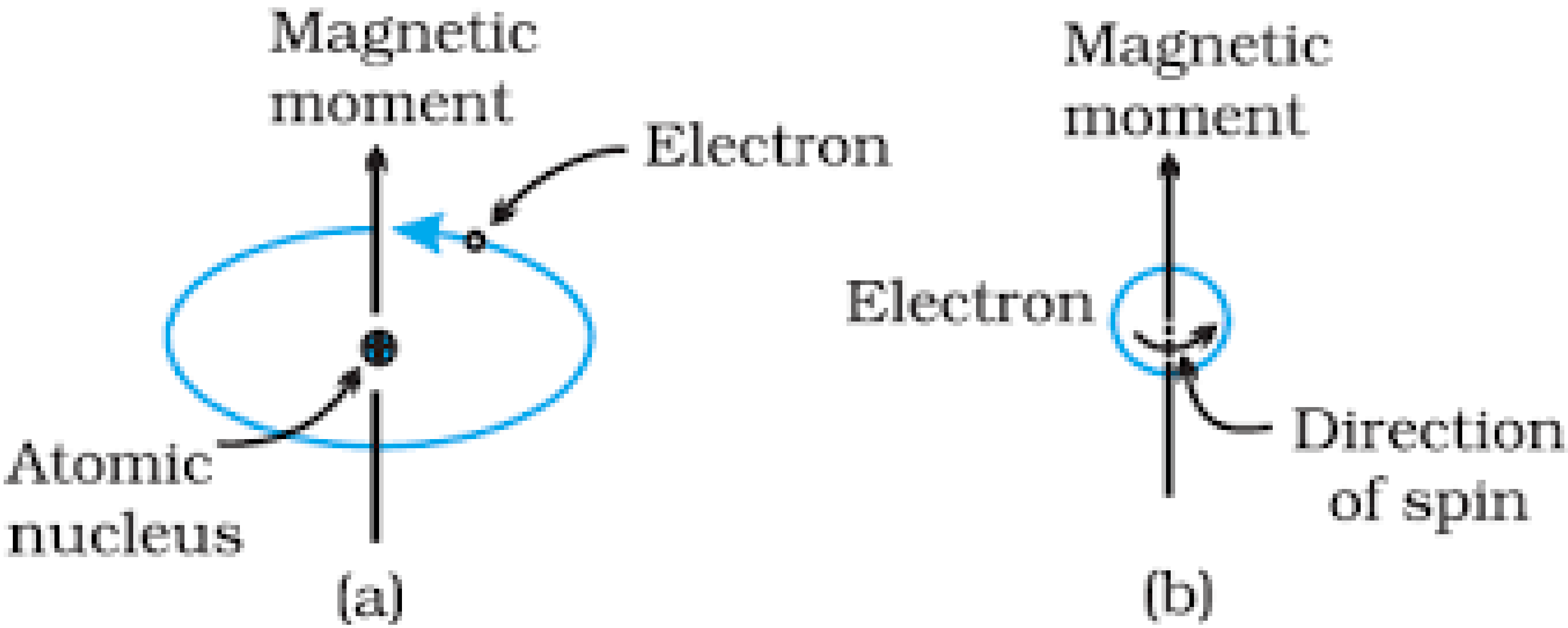
In all atoms electrons are revolving around the nucleus in different orbits and also spin about their own axis. These revolving electrons constitute an electrical current in the orbits. These revolving electron produces its own orbital magnetic dipole moment, measured in Bohr Magneton (μ_B) and there is also a spin magnetic moment associated with it (spin of orbital electrons and spin of nucleus).

In most materials there is no resultant magnetic moments, due to the electrons being grouped in pairs causing the magnetic moment to be cancelled by its neighbor.

Under external applied magnetic field these dipoles experience torque in the direction of applied field and the atom acquires certain magnetism. So, the magnetic moment of an atom is due to

1. Orbital Magnetic Moment of the electrons.
2. Spin Magnetic Moment of the electrons.
3. Spin Magnetic Moment of the nucleus.

$$\boxed{\mu_B = \frac{e\hbar}{2m}}$$


Magnetic
moment
Electron
Atomic
nucleus
(a)
Magnetic
moment
Electron
Direction
of spin
(b)

Problems

Magnetic filed intensity of a paramagnetic material is 10^4 A/m. At room temperature, its susceptibility is 3.7×10^-3. Calculate the magnetization in the material.

A magnetic field strength of 2×10^5 A/m is applied to a paramagnetic material with a relative permeability of 1.01. Calculate the values of Magnetic Flux Density and Magnetization.

A silicone material is subjected to a magnetic field of strength 1000 A/m. If the magnetic susceptibility of silicon is -0.3 × 10^-5, calculates its magnetization. Also calculate the magnetic flux density of the field inside the material.

A magnetic material has a magnetization of 3400 A/m and flux density of 0.0048 Wb/M^2. Calculate the magnetic field and the relative permeability of the material.

Classification of Magnetic Materials

Magnetic materials are classified into different categories based on their magnetic parameters such as **susceptibility**, **permeability** and their microscopic magnetic structure under different environmental conditions (i.e., under the influence of **magnetic field, temperature** etc.)

Based on whether the atoms carry **permanent magnetic dipoles** or not, and on the basis of effect of temperature and magnetic field on the magnetic properties; all materials are classified broadly into the following three categories.

1. **Diamagnetic materials**
2. **Paramagnetic materials**
3. **Ferromagnetic materials**

Two more classes of materials have structure very close to ferromagnetic materials but possess quite different magnetic effects. They are,

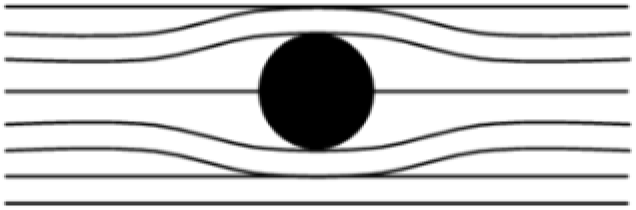
4. **Antiferromgnetic materials**
5. **Ferrimagnetic materials**

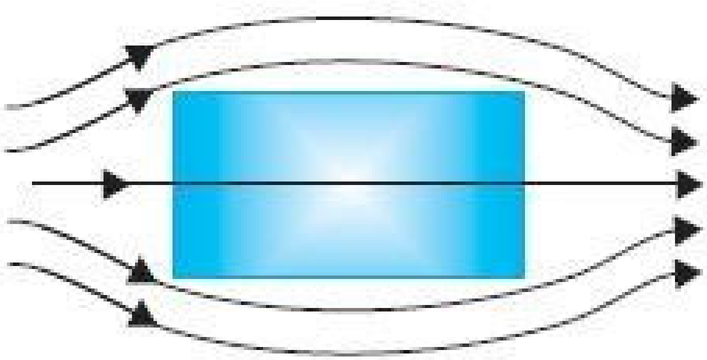
Diamagnetic materials

All materials are inherently diamagnetic . The orbital motion of electrons create tiny atomic current loops which produce magnetic field. Under such condition, when an external magnetic filed is applied to a material, these current loops will tend to align in such away as to oppose the applied field.

Thus diamagnetism can viewed as, the results of Lenz's law, i.e., an induced magnetic field tend to oppose the change which created them.

Diamagnetism occurs in substance whose atom consist of an even number of electrons, The electrons of such atoms are paired. The electrons in each pair have orbital motion as well as spin motions in opposite sense. Thus, the resultant magnetic dipole moment is zero.





Behaviour of magnetic field lines near a diamagnetic substance.

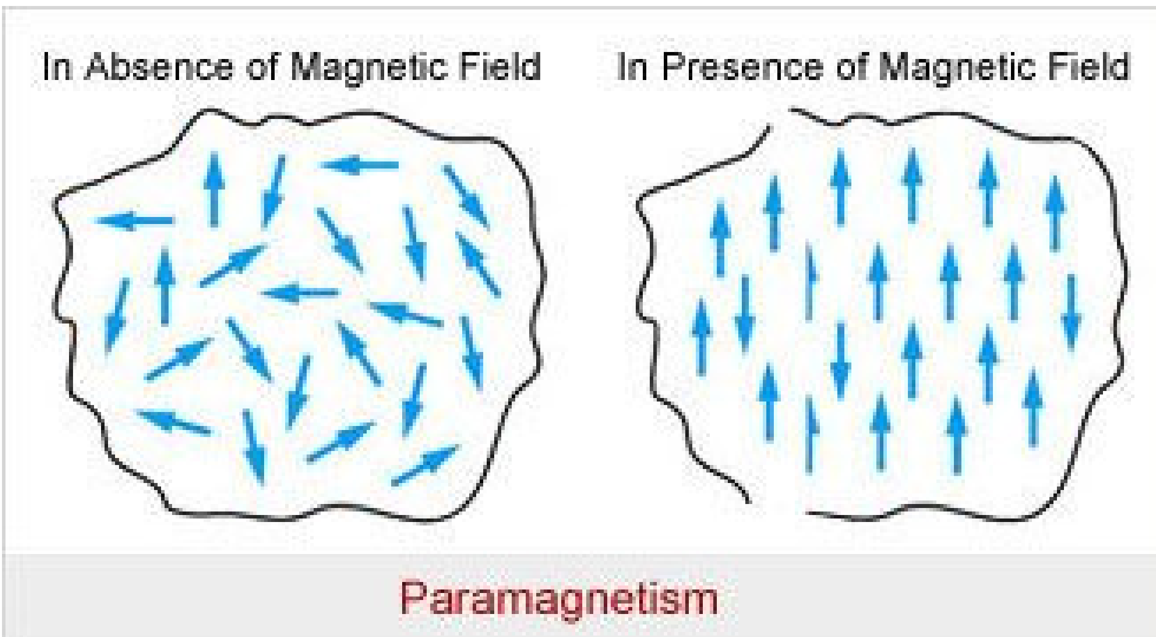
General Properties of Diamagnetic Materials

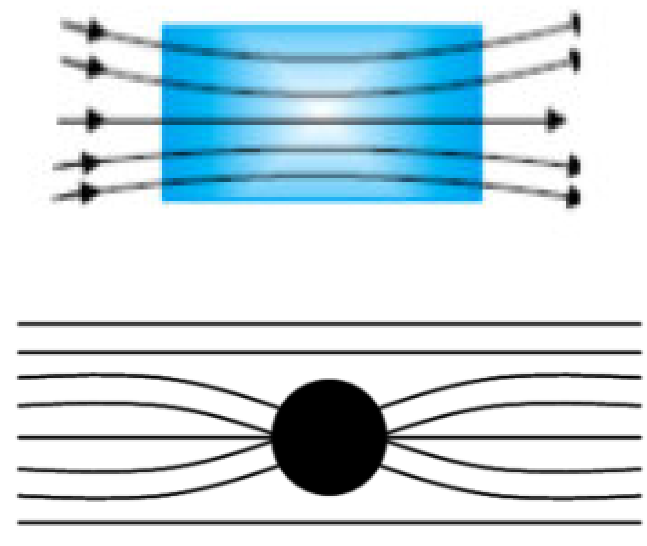
1. Diamagnetic materials experience a repelling force when brought near the pole of a strong magnet.
2. In non uniform magnetic field, they are repelled away from stronger parts of the field.
3. These materials do not retain the magnetic properties when the external field is removed.
4. The magnetic susceptibility χ of these materials is always negative.
5. The relative permeability μ_r is always less than one.
6. In the absence of an external magnetic filed, the net magnetic dipole moment over each atom or molecule of a diamagnetic material is zero. This is due to pairing of electrons.
7. Both susceptibility and relative permeability are independent of applied magnetic field and temperature.
8. **Examples:** Bismuth, Copper, Lead, Zinc and rare gases.

Paramagnetic materials

Paramagnetism is a results of the presence of some unpaired electrons and from the realignment of the electron orbits caused by the external magnetic field.

In paramagnetic materials, the magnetic fields due to the orbiting and spinning electrons do not cancel out. Thus there will be a net intrinsic moment.





Paramagnetic substances are weakly attracted by a magnetic field. They lose their magnetism in the absence of a magnetic field. Paramagnetism is due to the presence of one or more unpaired electrons which are attracted by the magnetic field.

General Properties of Paramagnetic Materials

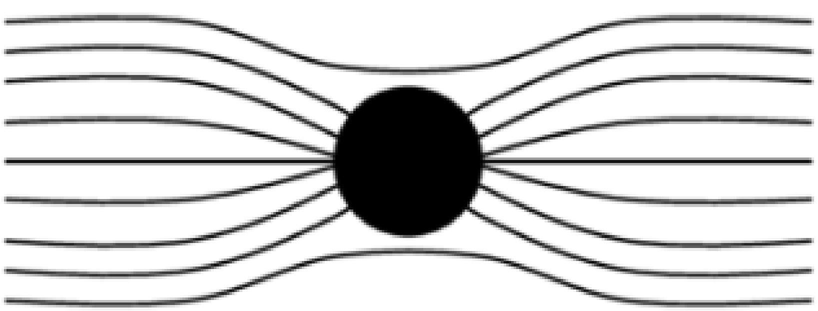
1. Paramagntic materials experience a feeble attractive force when brought near the pole of a magnet.
2. They are attracted towards the strong parts of a inhomogeneous magnetic filed.
3. These material possess some permanent dipole moment which arise due to some unpaired electrons.
4. In the absence of an external magnetic filed, the dipoles are randomly oriented. Thus the net magnetization is zero.
5. When these materials are placed in an external magnetic field , realignment of electron orbits and magnetic dipoles take place resulting in a small magnetization.
6. These materials do not retain the magnetic properties when the external filed is removed.
7. The magnetic susceptibility χ is small and positive. $\boxed{\chi = C/T}$
8. The permeability is slightly greater than one.
9. When the temperature is less than Curie temperature, paramagnetic materials become diamagnetic material.
10. **Example:** Platinum, Aluminum, Copper Sulphate, Manganese Sulphate etc.

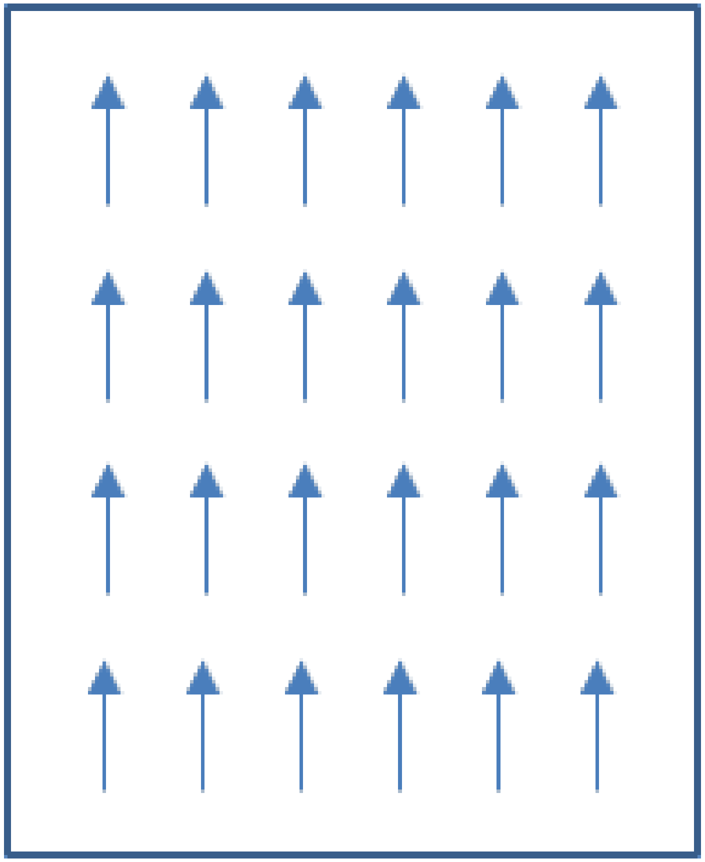
Ferromagnetic materials

Ferromagnetism is phenomenon in which a materials gets magnetized to a very large extent in the presence of an external filed

The direction in which the material gets magnetized is the same as that of the external filed.

Further, these materials exhibit magnetization even in the absence of an external magnetic field. This property is called spontaneous magnetization.



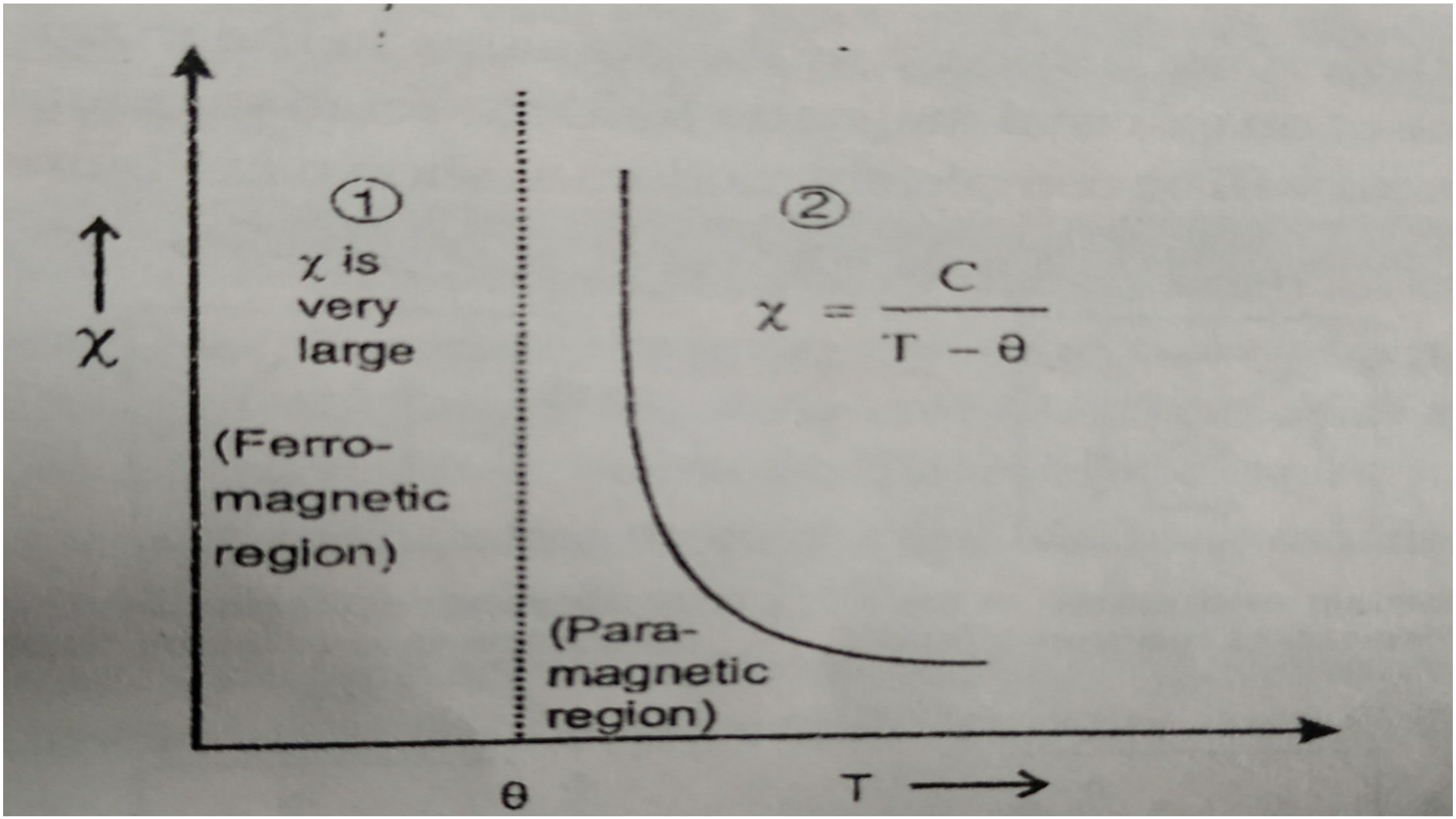


Ferromagnetic ordering

General Properties of Ferromagnetic Materials

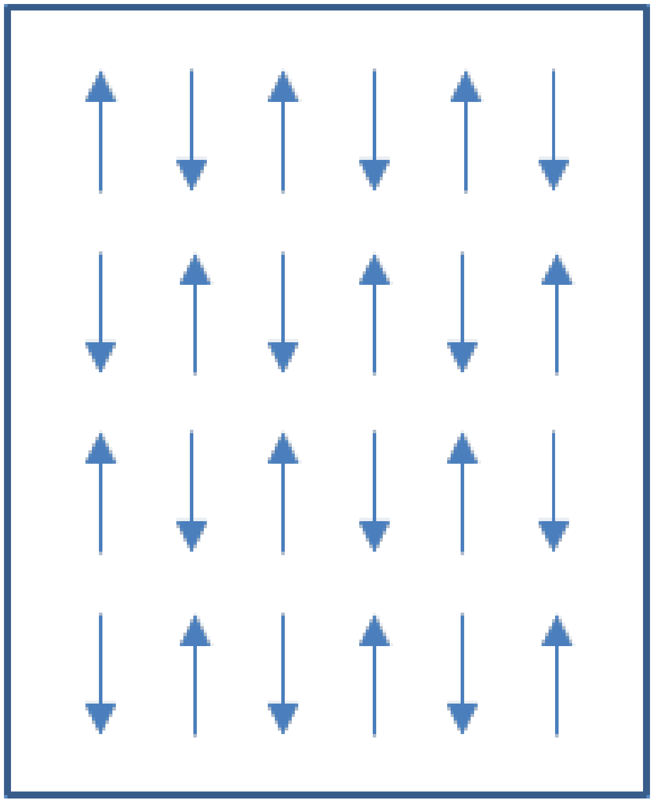
1. The atom or molecules of ferromagnetic materials have a net intrinsic magnetic dipole moment due to the spin of the electrons. So they act as strong magnets.
2. Ferromagnetic materials experience a very strong attractive force when brought near the pole of a magnet.
3. When a ferromagnetic material is subjected to the influence of a magnetic field , all magnetic lines of force through it.
4. These materials exhibit high degree of magnetization and get permanent magnetized, i.e., They will continue to retain the magnetic property even when the external filed is removed. This property is called spontaneous magnetized.
5. Permeability is very much greater than one.
6. Susceptibility is positive and high.
7. **Examples:** Fe, Co, Ni, Fe3O4, MnAs, Gadolinium etc.

8. Susceptibility, χ = C/T-θ which is called the Curie-Weiss Law. C is the Curie constant, T is the absolute temperature and θ is the ferromagnetic Curie temperature. When T<θ, the material is in ferromagnetic state.
9. When T > θ, ferromagnetic materials behave like an ordinary paramagnetic material. The variation of χ with temperature is shown in fig.

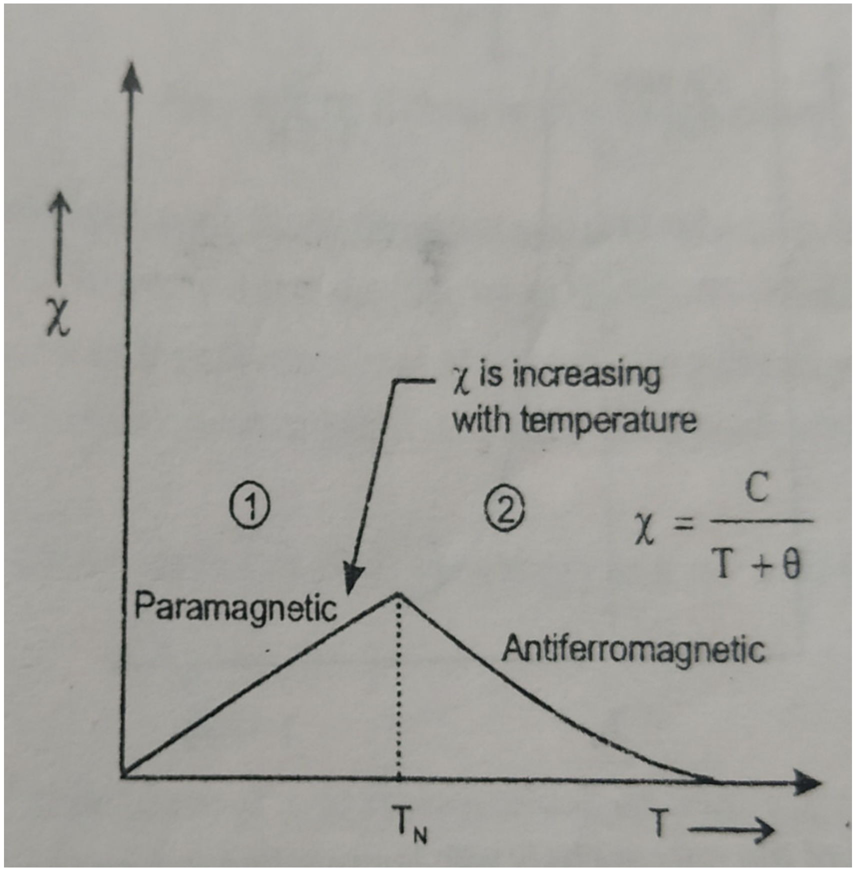


Antiferromgnetic materials

Antiferromagnetism refers to a phenomena in which the magnetic interaction between any two dipoles align themselves anti-parallel to each other. Since all the dipoles are of equal magnitude, the net magnetization is zero.



Antiferromagnetic ordering



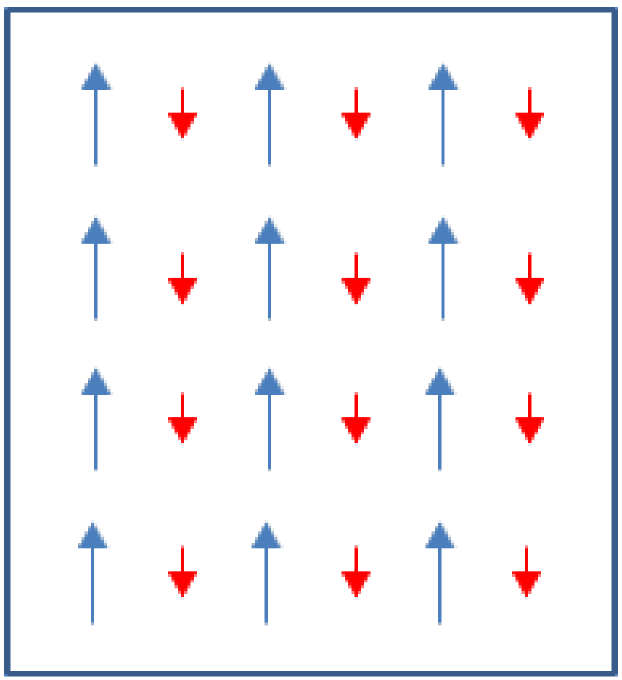
General Properties of Antiferromagnetic Materials

1. Like ferromagnetic materials antiferromagnetic materials also possess dipole moment due to spin of the electron.
2. The magnetic interaction between any two dipoles align themselves anti parallel to each other. Since all the dipoles are equal in magnitude and due to anti-parallel alignment the resultant magnetic effect is zero.
3. The opposite alignment of adjacent dipoles is due to an exchange interaction.
4. These materials have a temperature dependent magnetism due to the disruption of the magnetic moment alignment.
5. The susceptibility is very small and positive. It is given by $\chi = C/(T+\theta)$
6. Initially, the susceptibility increases slightly as temperature increases and beyond a particular temperature known as Neel temperature, the susceptibility decreases with temperature as shown in Fig.
7. **Examples:** FeO, MnO, Cr_2O_3, $CuCl_2$, FeF_2 etc.

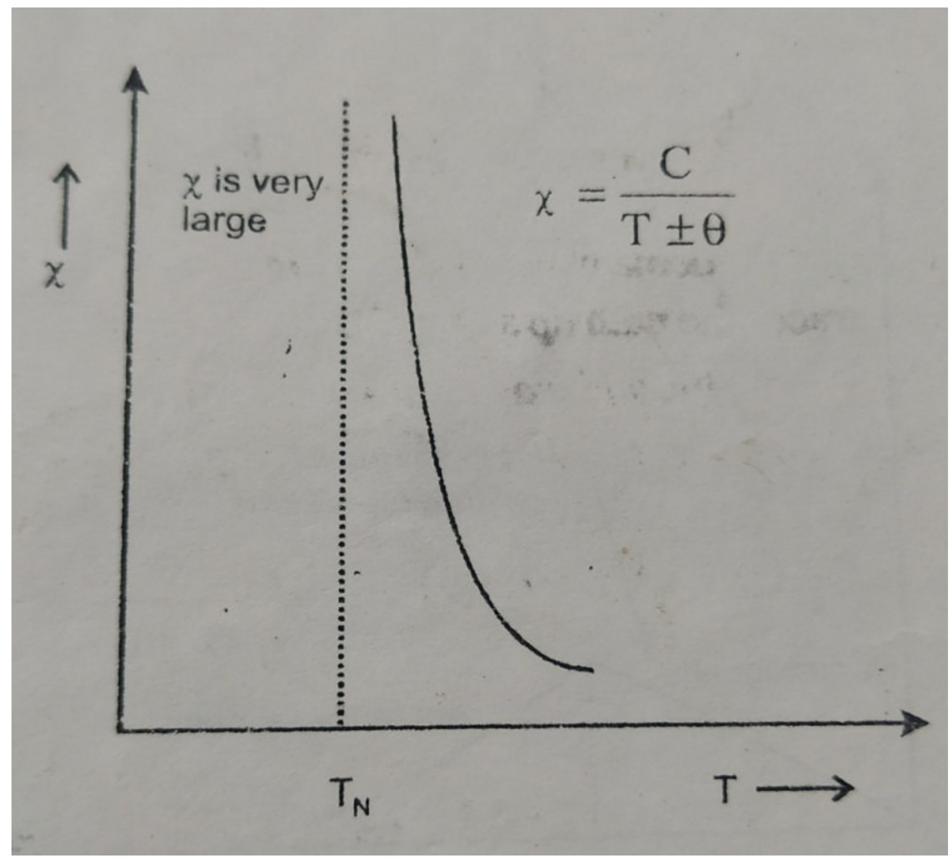
Ferrimagnetic materials.

Ferrimagnetism is a phenomenon in which the magnetic interaction between any two dipoles align anti-parallel to each other. But since the magnitude of dipoles are not equal, the cancellation of magnetic moments become incomplete resulting in a net magnetization in the material.

The magnetization of these materials is intermediate between ferromagnetic and antiferromagnetic materials.

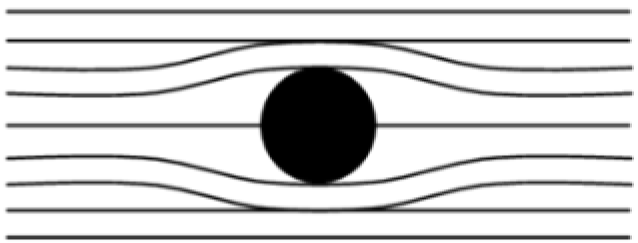


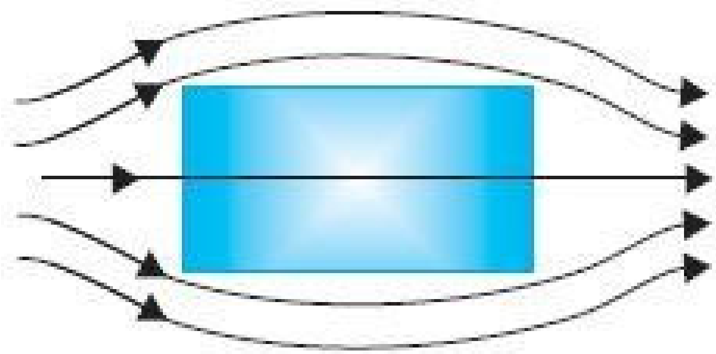
Ferrimagnetic ordering



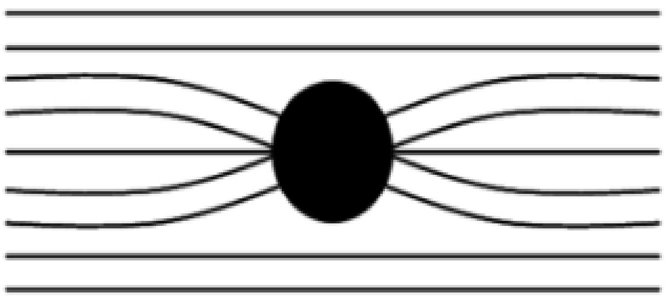
General Properties of ferrimagnetic Materials

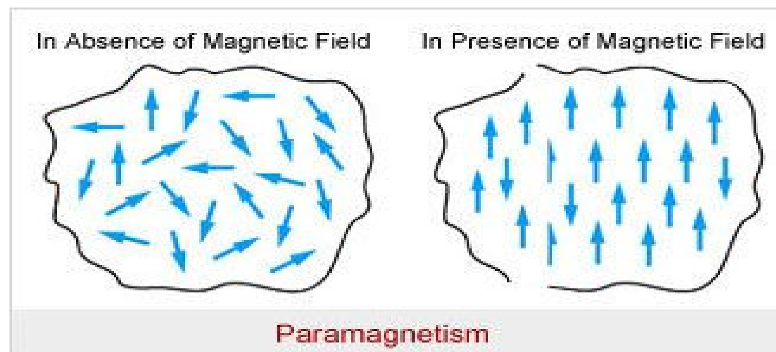
1. Ferrimagnetic materials possess magnetic dipoles moment due to the spin of electrons.
2. The magnetic interaction between any two dipoles align themselves anti-parallel to each other. But since the magnitude of moments are unequal, the cancellation of magnetic moment become incomplete resulting in a net magnetization in the materials.
3. A ferrimagnetic material is composed of more sets of different transition elements.
4. The susceptibility is very large and positive. It is given by $\chi = C/(T \pm \theta)$
5. The most important ferrimagnetic materials are ferrites and rare earth garnets.
6. **Examples:** Nickel ferrite and Ferrous ferrite.



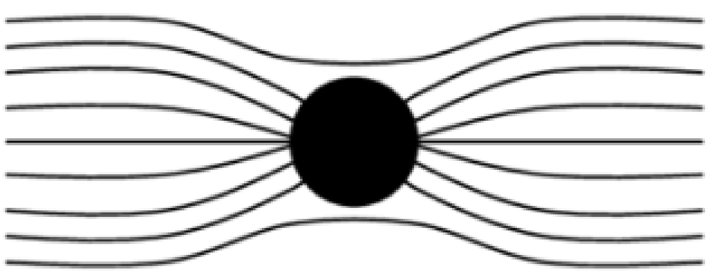


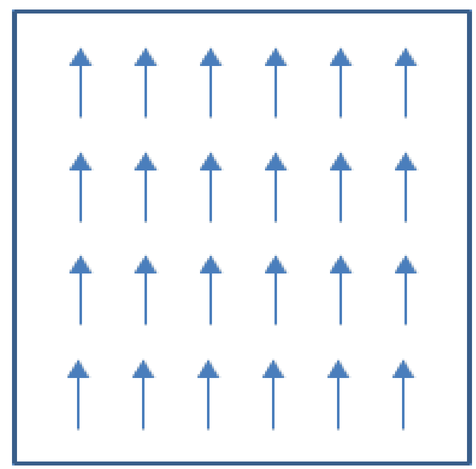
Behaviour of magnetic field lines near a diamagnetic substance.



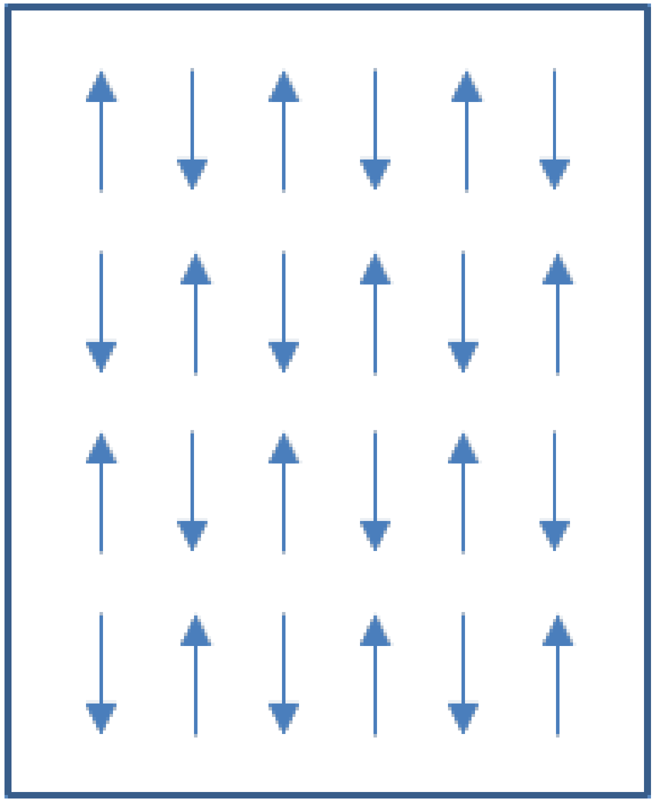


Paramagnetism

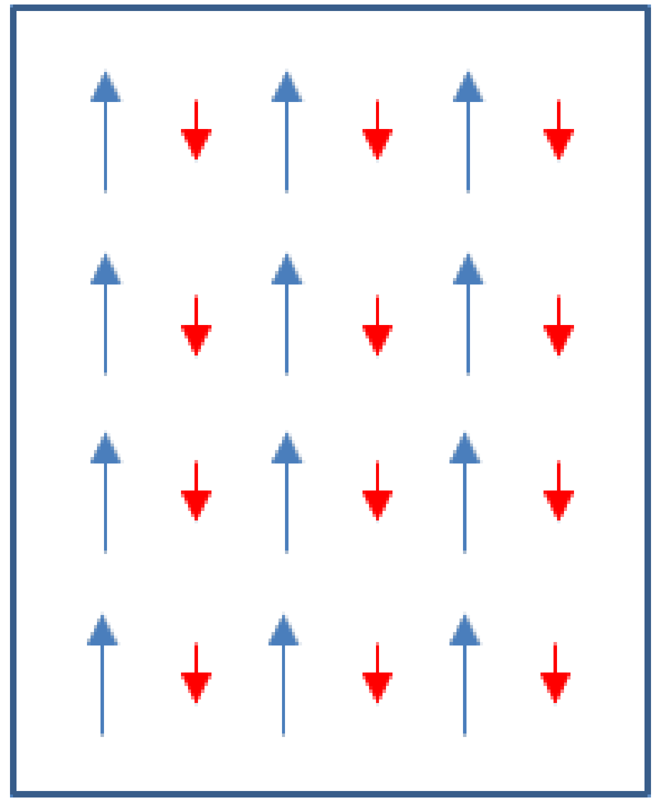




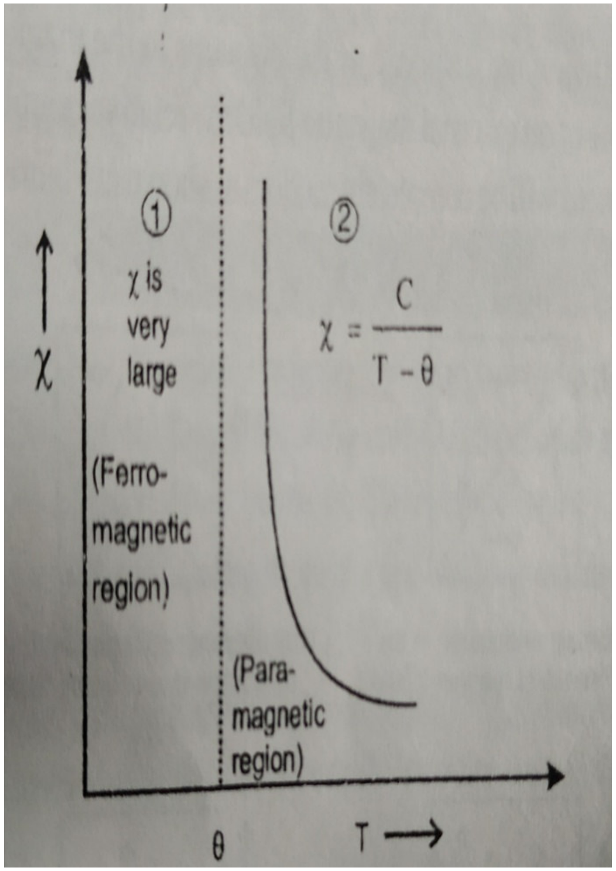
Ferromagnetic ordering



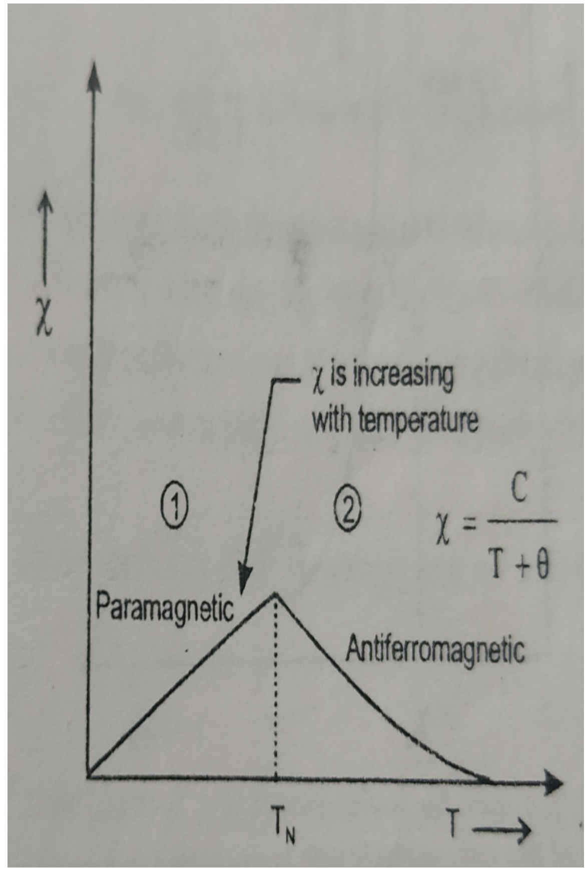
Antiferromagnetic ordering



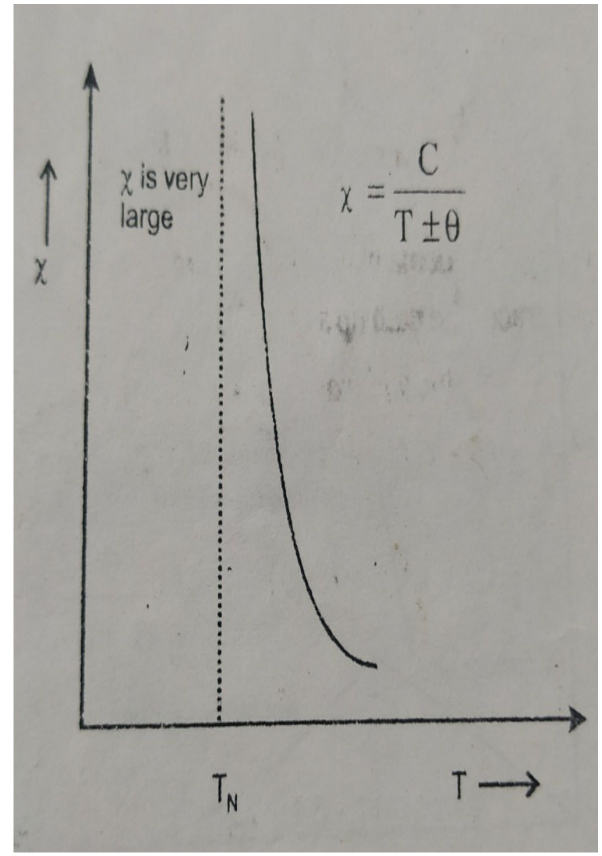
Ferrimagnetic ordering



①
②
χ is
very
large
(Ferro-
magnetic
region)
(Para-
magnetic
region)
$\chi = \frac{C}{T-\theta}$
χ
θ
T ⟶



χ
χ is increasing
with temperature
①
②
$\chi = \frac{C}{T+\theta}$
Paramagnetic
Antiferromagnetic
T_N
T ⟶

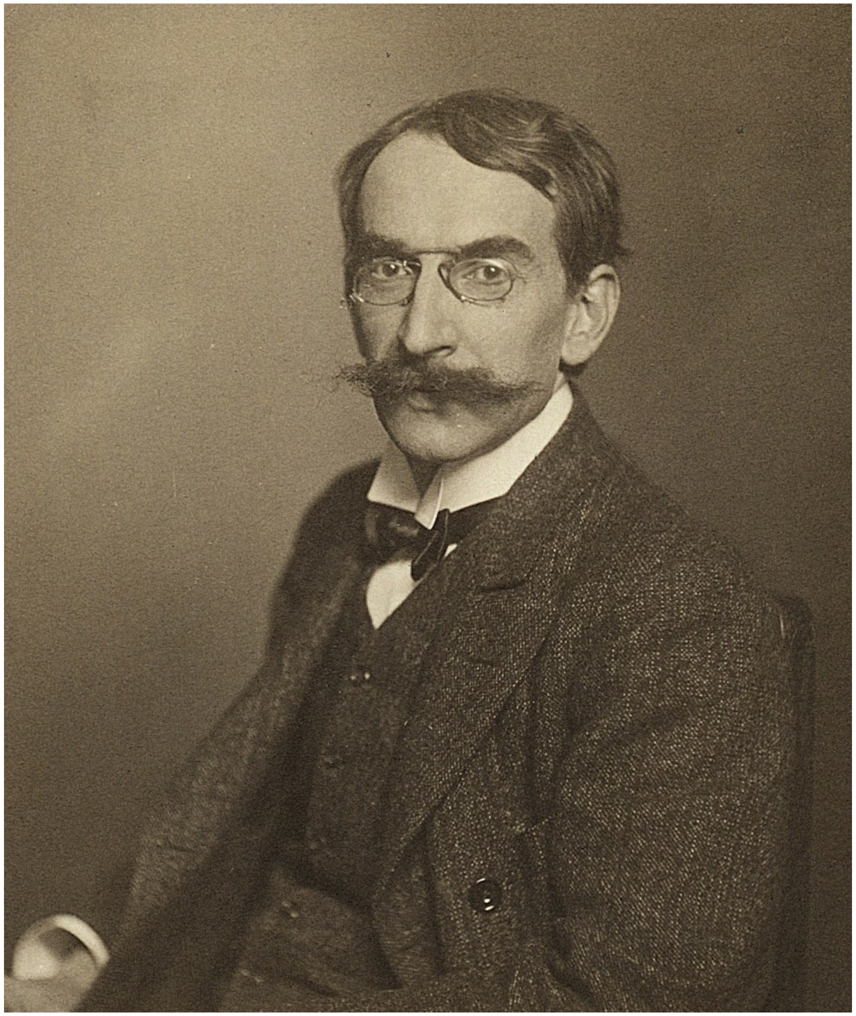


χ
χ is very
large
$\chi = \frac{C}{T \pm \theta}$
T_N
T ⟶

Domain Theory of Ferromagnetism

The magnetization and hysteresis observed in a ferromagnetic material is explained using the concept of domain proposed by P. Weiss in 1907.

According to this domain concept, a specimen of ferromagnetic materials consist of different region which are spontaneously, magnetized below the Curie temperature. These spontaneously magnetized or self magnetized regions in a ferromagnetic material is called **domains.**

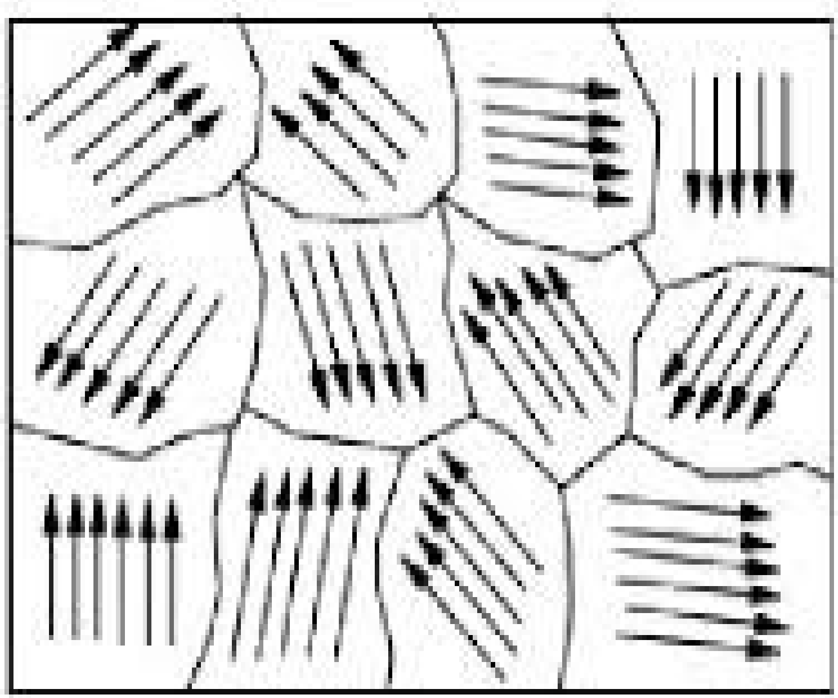


Each domain is separated by domain is separated by the other domain by **domain walls** which has finite dimension.

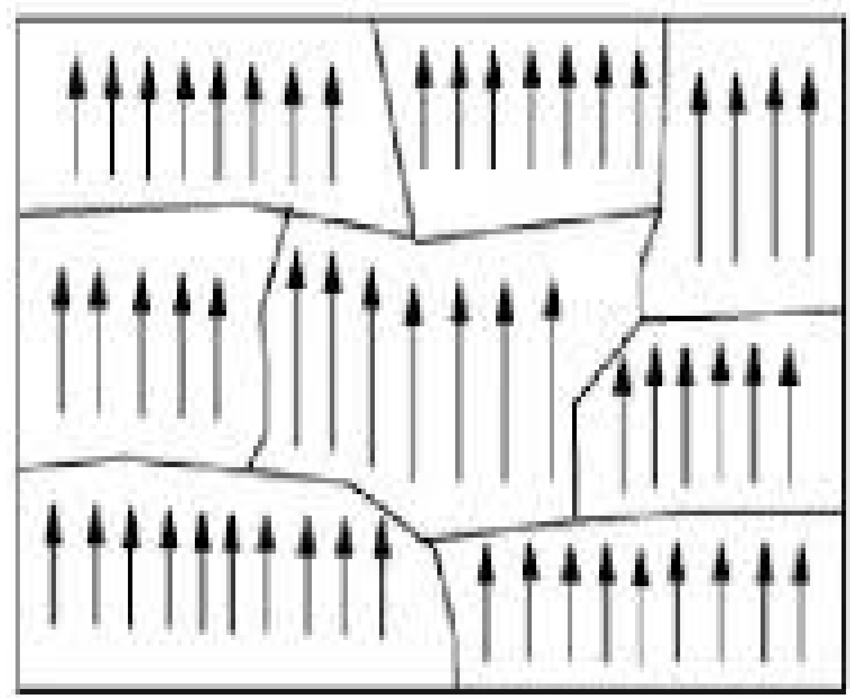
At finite temperature, and in the absence of an external magnetic field, the direction of magnetization of each domain have random orientation in space as shown in Fig.

Because of this randomness, the resultant magnetic moment of the material as a whole (which is the vectorial sum of the magnetic moment of the constituent domains) turn out to be zero.

In Absence of Magnetic field



In Presence of Magnetic field



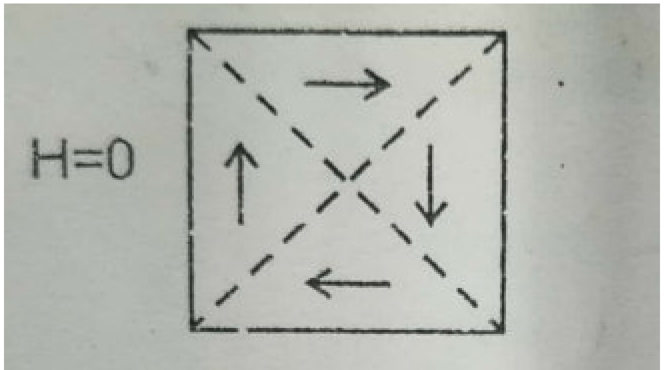
Effect of external magnetic field on the Domains

In the absence of an external magnetic field the relative orientation of the magnetic moments of various domains will be completely random as shown in Fig. (a)

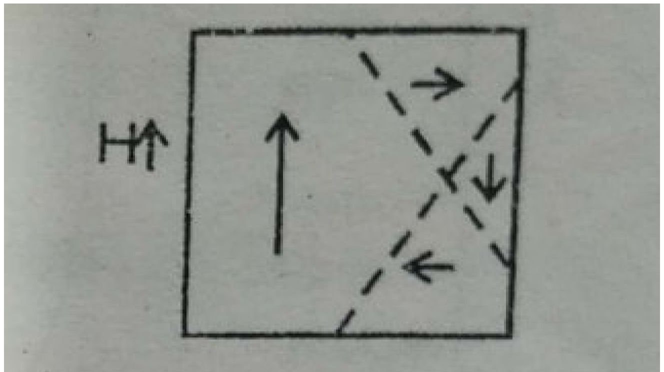
When an external magnetic field is applied, depending on the strength of the applied magnetic field, the magnetization effect may take place in any one of the following three stages.

1. **Due to domain wall movement**
2. **Due to the rotation of domains magnetic moments**
3. **Due to both of the above two process**

When the applied filed is weak, the domains which have their resultant magnetic moment in a direction parallel to the direction of the applied field expand their size at the cost of other domains with unfavorably oriented magnetic moments. Thus the domain areas of unfavorably oriented magnetic moments diminish thereby providing a large net magnetization. (Fig. b)



Domain orientation in the absence of magnetic field
(a)

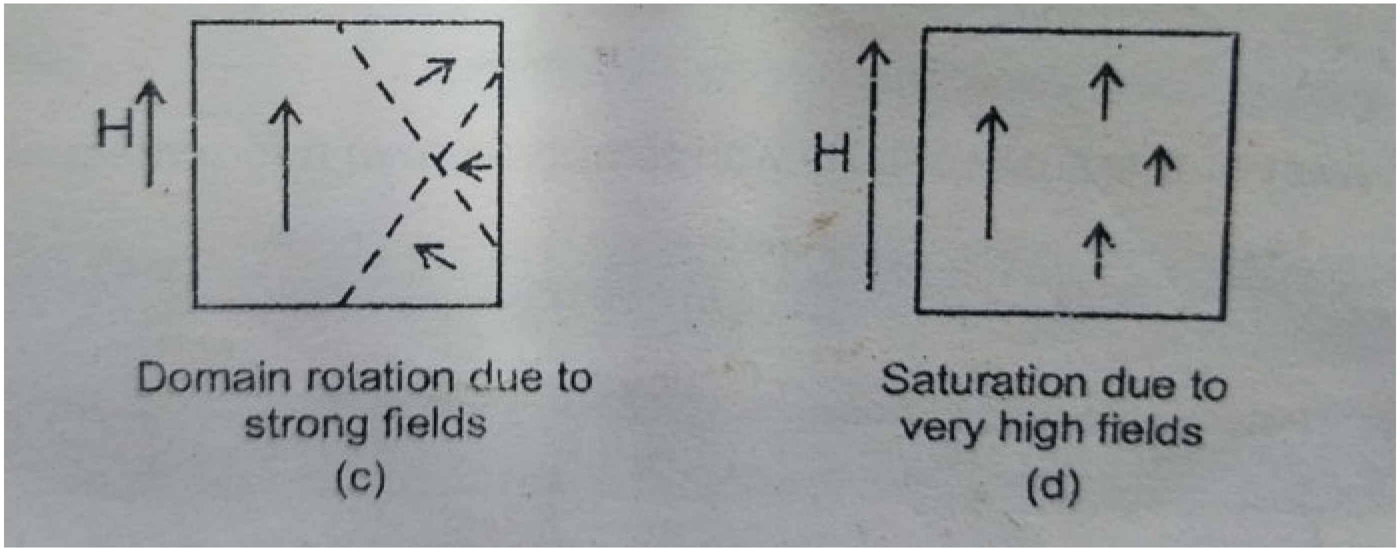


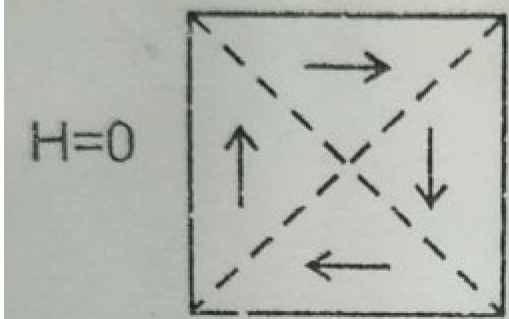
Domain enlargement/ shrinkage due to weak fields
(b)

When the field becomes strong, the domain's magnetic moments rotate partially and tend to align in the direction of the magnetic field. This results in further increase in the magnetization of the material. (Fig. C)

When the field become very strong, the magnetic moments of each and every domain undergo required amount of rotation so as to align perfectly along the direction of the field. (Fig. D)

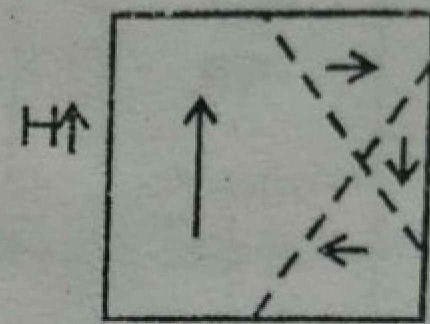
This indicates the ultimate stage of magnetization, further increase in magnetization is impossible no matter how strong the field is.





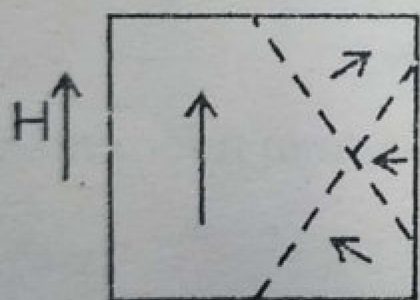
Domain orientation in the absence of magnetic field

(a)



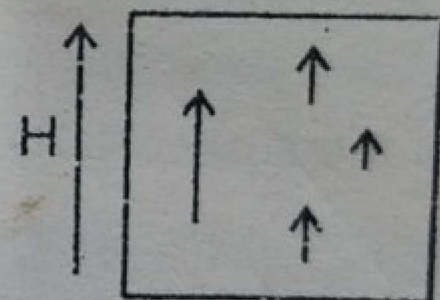
Domain enlargement/ shrinkage due to weak fields

(b)



Domain rotation due to strong fields

(c)



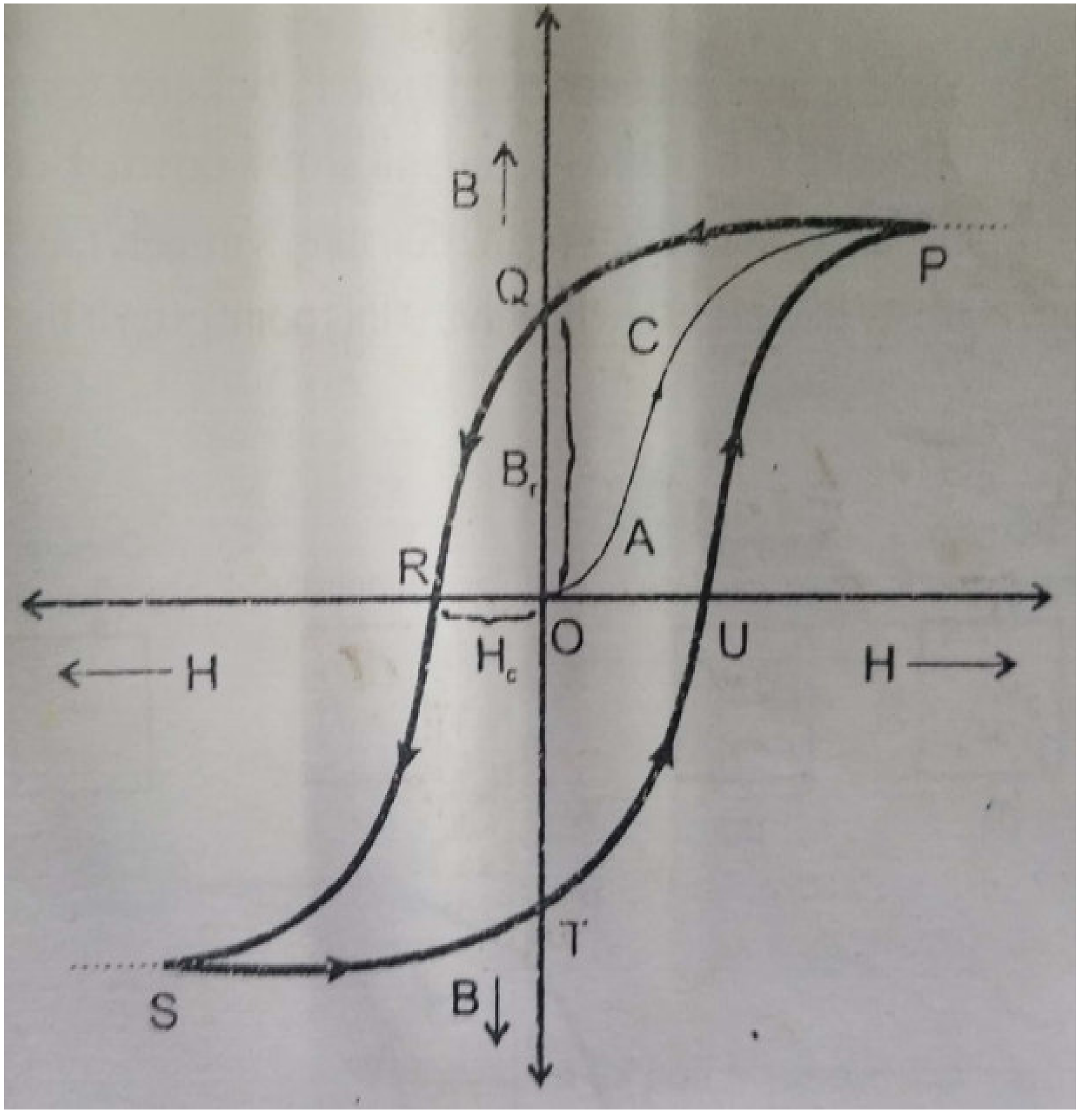
Saturation due to very high fields

(d)

Hysteresis

Hysteresis is the lagging (i.e., the phase lagging) of magnetic induction (B) in ferromagnetic and ferromagnetic materials with respect to cyclic variation of an applied magnetic field (H), when the specimen is at temperature below its Curie temperature.

When a ferromagnetic material is taken through a cycle of magnetization, the variation **B** with respect to the applied field **H** is shown in Fig.



From the figure we can observed that, when the magnetic field H is increased from value in the positive direction shown along OH, the value of B also increases and the curve develops along OP.

After the point P, B remains constant, in spite of continuous increase in H. This value of B at P is called the **saturation value** and the specimen is said to be in the **saturation magnetization state.**

Now, when the value H is decreased, B starts decreasing from the point P but fails to retrace the same path which it had while H was increasing. Thus the new path is PQ. When H becomes zero, the value of B retains a value equal to OQ. This residual value of magnetization equal to OQ is called **remnant induction** or **residual magnetism** or **retentivity Br.**

When the value of applied magnetic field H is reserved and increased gradually till the point R is reached, the magnetic induction B becomes zero at point R and the specimen gets completely demagnetized. This value of H =OR is called coercive field Hc, and the effect is called **coercivity**.
Further increase in H causes the specimen to get magnetized in the opposite direction. This makes B also to increase in the opposite direction and reaches a saturation value again at S. Now also when the filed is decreased the curve trace the path ST instead of SR.

Again the specimen gets completely demagnetized at U, when the direction of h is reversed and increased along OH. The curve traces the path up as H is increased further.

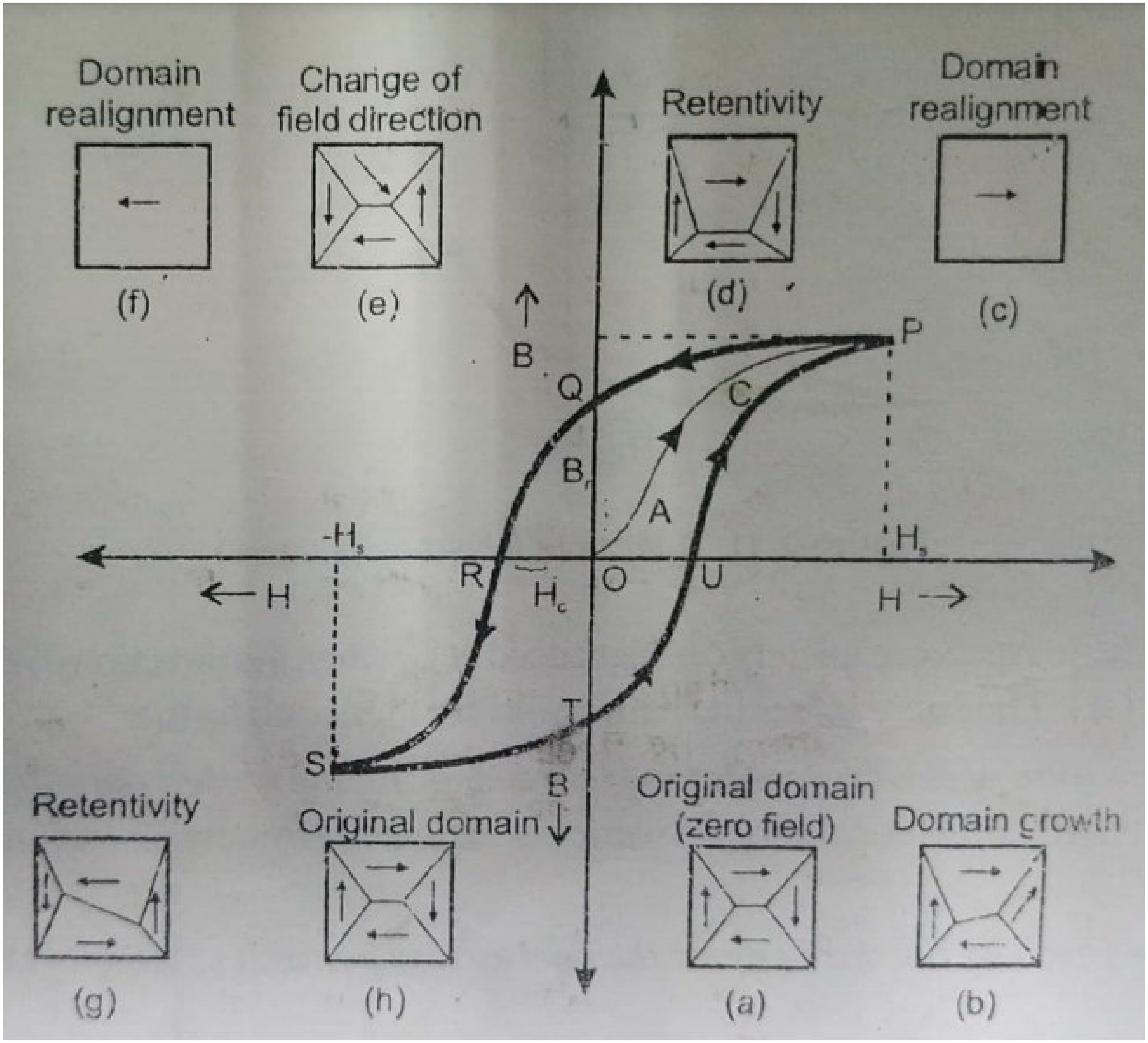
Thus the variation of B with respect to H traced along the closed path PQRSTUP in one full cycle of magnetization and demagnetization is called the **hysteresis loop** or the **hysteresis curve**.

The area enclosed by the curve gives the **energy loss per unit volume of the materials per cycle**.

The energy loss in the form of heat that occurs during the full cycle of magnetization and demagnetization processes in a ferromagnetic materials is called the **hysteresis loss.**

The coercive field is the main parameter in distinguishing two types of magnetic materials namely,

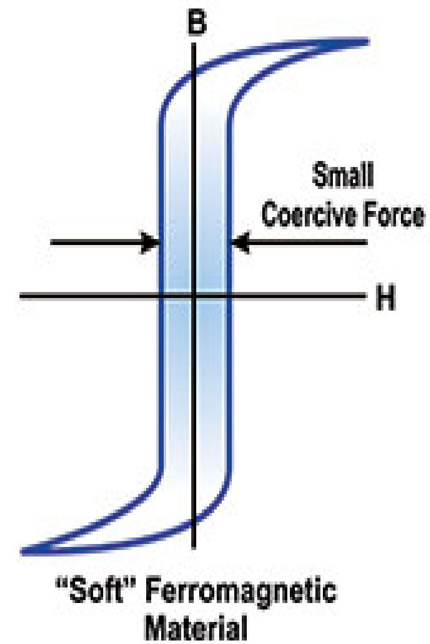
1. **Soft magnetic materials**
2. **Hard magnetic materials**



Domain realignment
(f)
Change of field direction
(e)
Retentivity
(d)
Domain realignment
(c)
B
P
Q
C
B_r
A
$-H_s$
H_s
R
O
U
H_c
← H
H →
T
S
B
Retentivity
(g)
Original domain
(h)
Original domain (zero field)
(a)
Domain growth
(b)

Soft magnetic materials

Soft magnetic materials are characterized by small hysteresis are and easy domain wall movement in the presences of an external magnetic field. These magnetic materials can be easily magnetized and demagnetized. But the can not be permanently magnetized.



Properties

1. Low coercivity and low remnant magnetization
2. Low hysteresis energy loss
3. High permeability and susceptibility

The soft magnetic materials are prepared by heating the pure materials to a temperature at which sufficient movement of the atoms is possible for them to settle down into an ordered lattice followed by slow cooling (annealing process)

Soft magnetic materials are classified into two categories.
(1) Metallic and (2) Ceramic

Examples: Iron-Silicon alloy, Iron-Nickel alloys, Iron- Cobalt alloys, Ferrite and garnets, etc.

Application of Soft Magnetic Materials

1. For audio frequency application

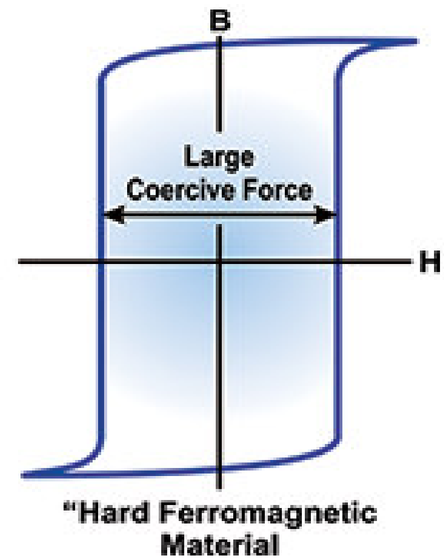
2. Used as core materials in inductor coils and transformer

3. Used in digital computers and data processing circuits

4. Used as memory storage device

Hard magnetic materials

A hard magnetic materials is characterized by a large hysteresis area and less mobile domain wall. The magnetic materials cannot be easily magnetized and demagnetized . But they can be permanently magnetized.



Properties

1. High coercivity and High remnant magnetization
2. Relatively low permeability and susceptibility
3. High energy product (BrHc) or high power
4. High hysteresis energy loss due to large hysteresis area

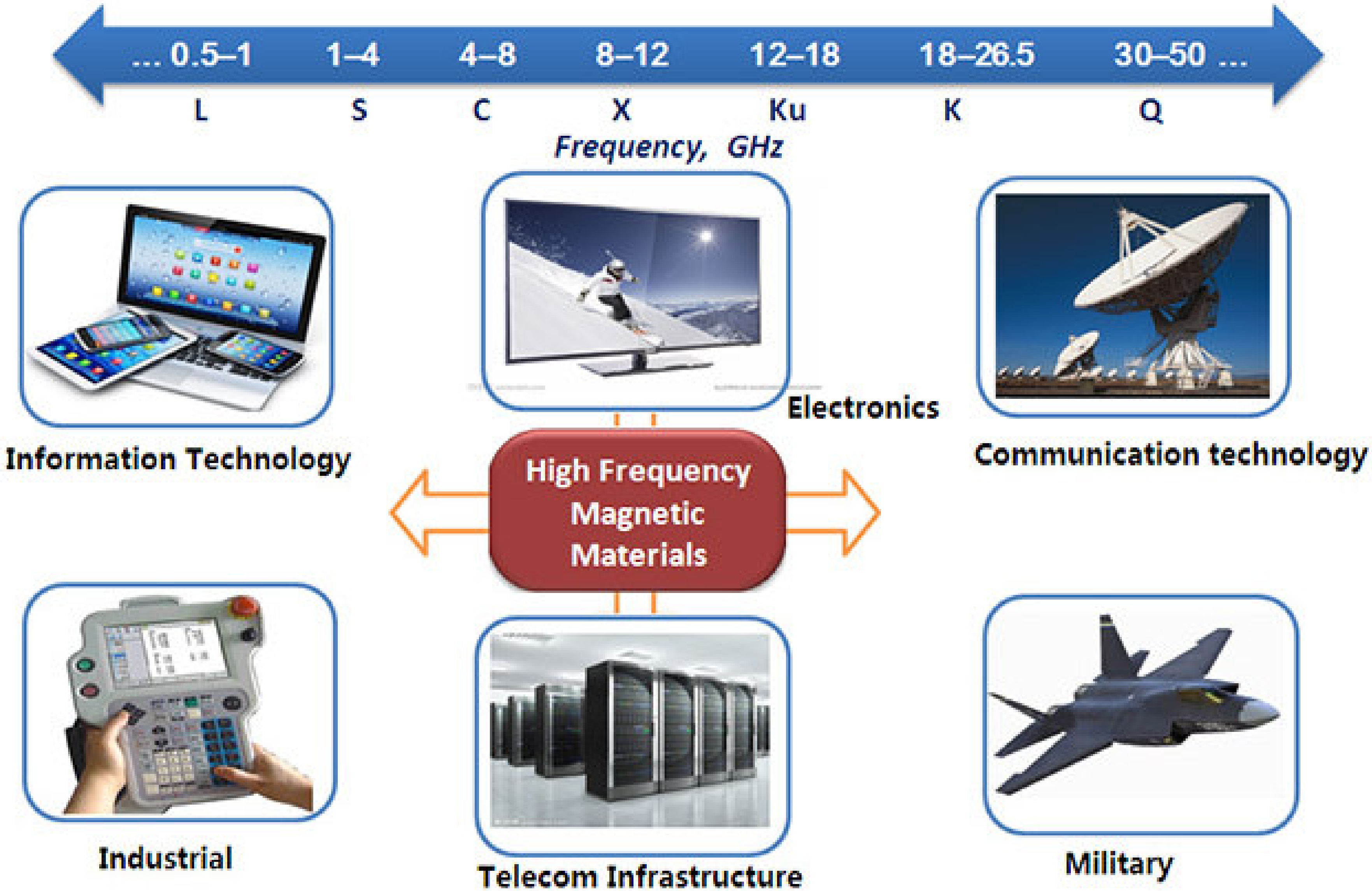
These materials are prepared by heating the material to a required temperature and then suddenly cooling them (quenching process) by dipping in cold liquid which sets up internal stresses. The mechanical strains are purposely introduced to make the magnetic materials hard.

Metallic and Ceramic type hard magnetic materials

Example: Pletinum Cobalt alloy, Tungsten steel alloy, CuNiFe alloy, CuNiCo alloy.

Application of Hard Magnetic Materials

1. Used for making permanent magnets.
2. Used as magnetic separators,
3. Magnetic detectors
4. Loudspeakers of audio system
5. Microphones, dc motors.
6. Used in making magnets for toys



... 0.5–1
1–4
4–8
8–12
12–18
18–26.5
30–50 ...
L
S
C
X
Ku
K
Q
Frequency, GHz
Information Technology
Electronics
Communication technology
High Frequency Magnetic Materials
Industrial
Telecom Infrastructure
Military