University of Calcutta

Semester 5

PHYSICS

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MAGNETIC PROPERTIES OF MATTER

DIA, PARA, FERRO AND FERRIMAGNETISM

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A quantitative description of magnetism requires the knowledge of quantum mechanics and the electromagnetic theory of multi-atom system.

Magnetic properties of solids

Magnetization is defined as magnetic moment per unit volume. For certain magnetic materials, it is found empirically that the magnetization M is proportional to magnetic field strength H

$$M = \chi H$$

Magnetic susceptibility

$\chi > 0$ -- paramagnetism

$\chi < 0$ -- diamagnetiism

Magnetic properties of solids

Materials may have intrinsic magnetic dipole moments, or they may have magnetic dipole moments induced in them by an applied external magnetic field of induction. In the presence of a magnetic field of induction, the elementary magnetic dipoles, whether permanent or induced, will act to set up a field of induction of their own that will modify the original field. The magnetic dipole moments are the source of **magnetic induction B**

$$B = \mu_o H + \mu_o M$$

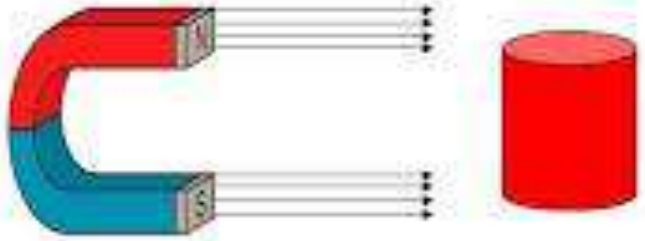
Magnetic field strength

Magnetic constant

Magnetization

Magnetic Materials

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



CONCEPT OF MAGNETIC DOMAIN

MAGNETIC DOMAINS

- A **magnetic domain** is a region within a magnetic material in which the magnetization is in a uniform direction. This means that the individual magnetic moments of the atoms are aligned with one another and they point in the same direction.

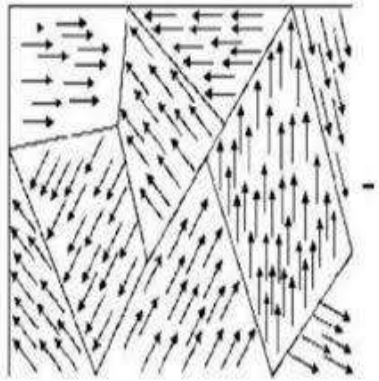


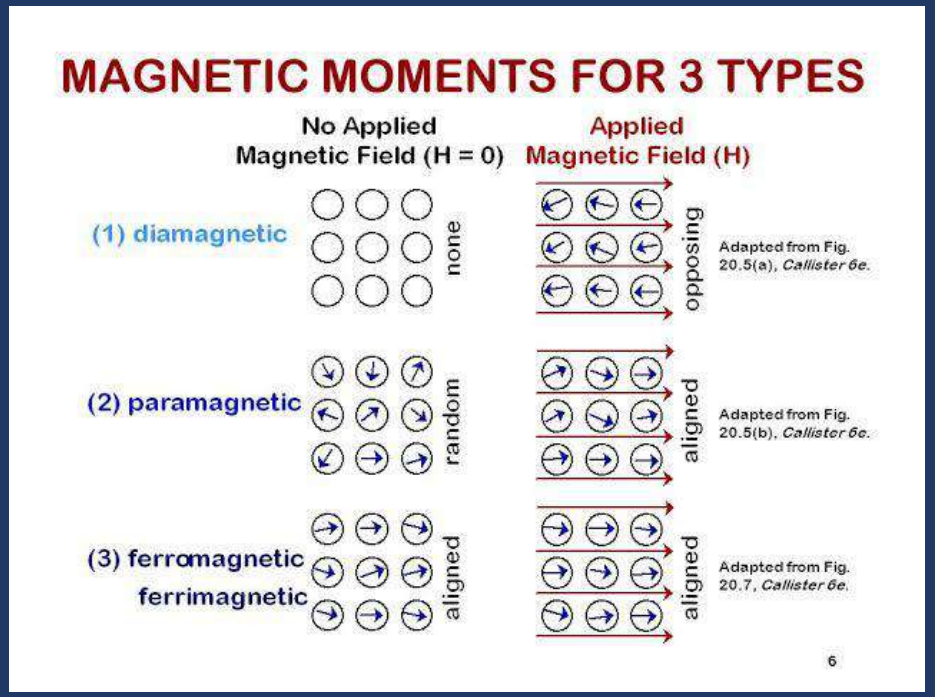
Fig.1.2 Arrangement Magnetic Domains in materials

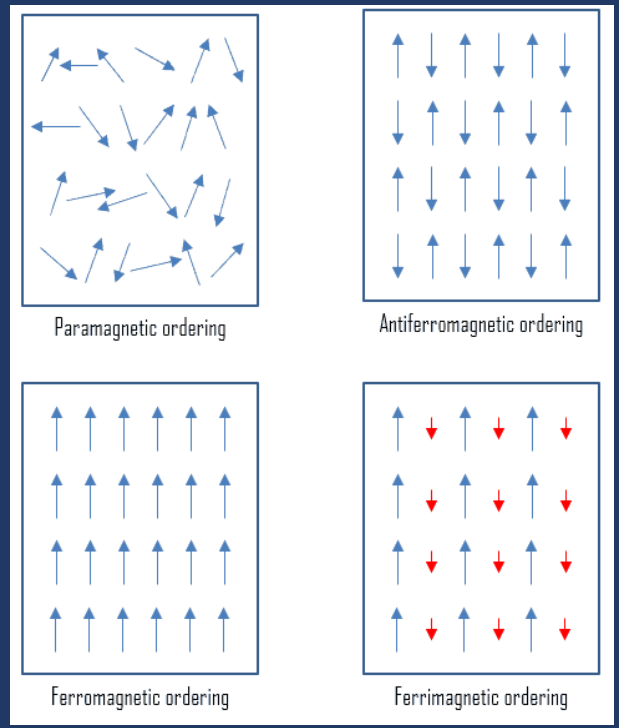
What are Magnetic Domains?

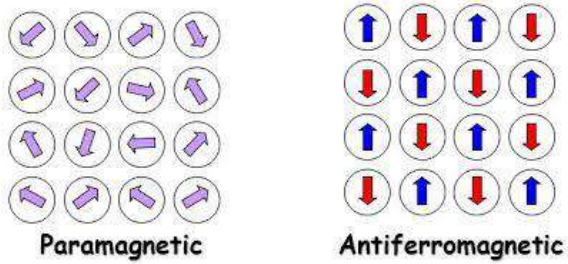
- The orbiting motion of electrons in a magnetic material makes each atom an *atomic magnet*.
- A group of atomic magnets pointing in the same direction is called a magnetic domain.
- In an unmagnetised bar, the magnetic domains point in random directions.
- The magnetic effects of the atomic magnets cancel out so there is no resultant magnetic effect.

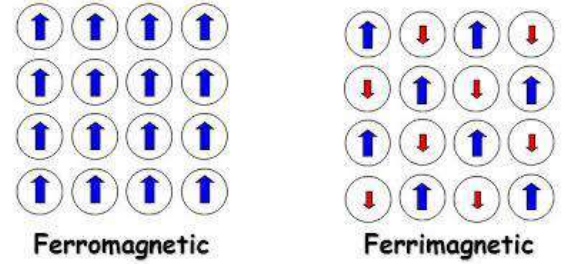
An unmagnetised bar – the magnetic domains point in random directions.

- Susceptibility (χ) = internal magnetization
  - Diamagnetic ($\chi < 0$) opposes applied field
  - Paramagnetic ($\chi > 0$) reinforces applied field
  - Superparamagnetic and ferromagnetic ($\chi >> 0$)
- Most biological tissues are weakly diamagnetic





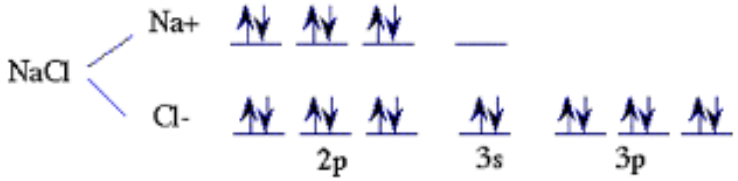




Magnetic Ordering

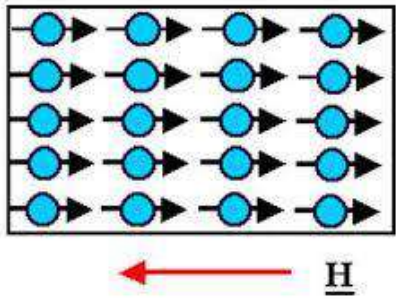
DIAMAGNETISM AND DIAMAGNETIC MATERIAL

Diamagnetic: all spins are paired
(nonmagnetic)



- Diamagnetic materials repel magnetic lines of force.
- There are no permanent dipoles; consequently magnetic effects are very small.
- Generally the value of diamagnetic susceptibility is independent of temperature and applied magnetic field strength

Examples : Organic materials, light elements, Alkali earths, Bismuth, Niobium and its compounds in the superconducting state, etc.



Diamagnetic Materials

In the presence of a field, dipoles are induced and aligned opposite to the field direction Fig. 1.

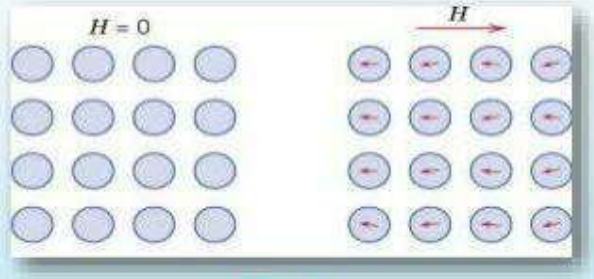
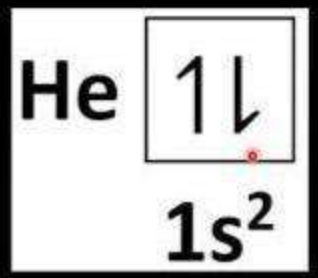
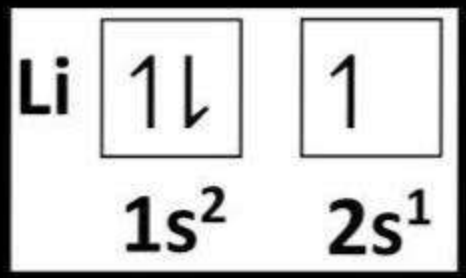


Fig. 1.

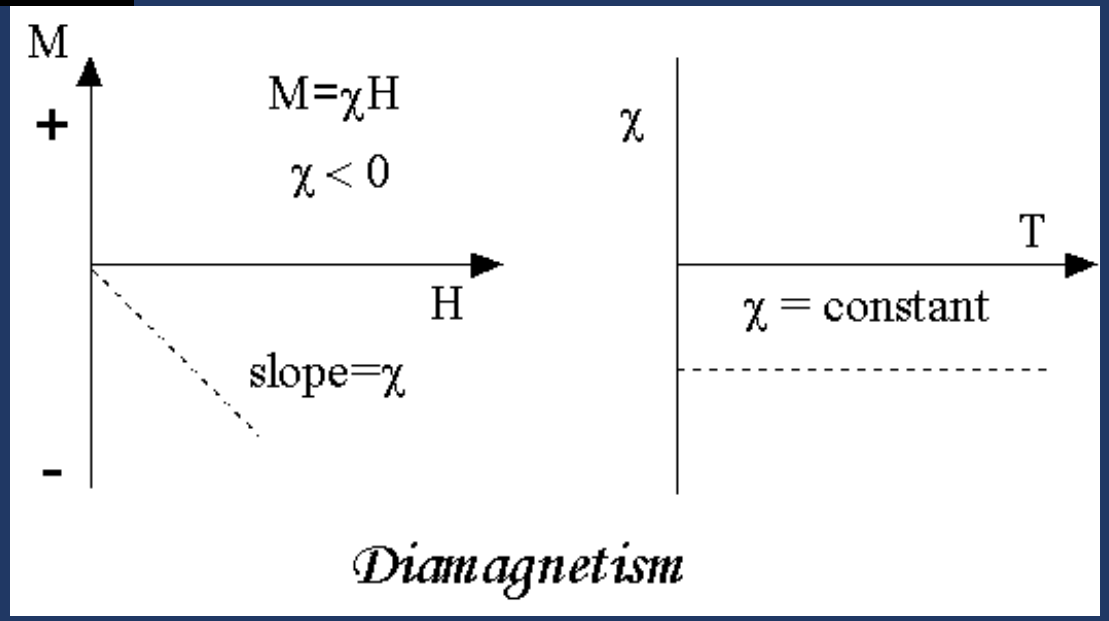
Diamagnetic materials have no unpaired electrons and are weakly repelled by a magnetic field.
Paramagnetic materials have unpaired electrons and are attracted by a magnetic field.



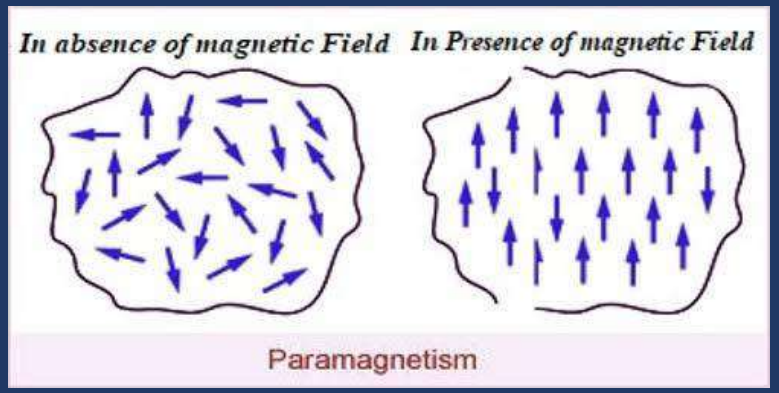
He - paired electrons
diamagnetic



Li - unpaired electrons
paramagnetic



PARAMAGNETISM AND PARAMAGNETIC MATERIAL



Paramagnetic Materials

In the paramagnetic materials, the magnetic moments do not interact with each other and they are randomly arranged in the absence of a magnetic field .

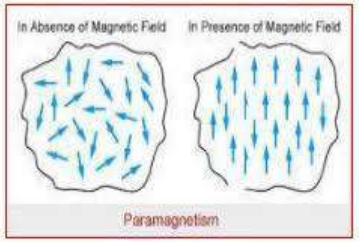


Figure 3: Spin orientation in paramagnetic materials before and after applying magnetic field

When a field is applied, the atomic magnetic moments are aligned in the direction of the field and that will induce a net positive magnetization and positive susceptibility.

PARAMAGNETIC SUBSTANCES

- These are the substances which when placed in a strong magnetic field acquire a feeble magnetism in the same direction as the applied magnetic field
- Attracted feebly by the magnet.
- Unpaired electrons are present in them.
- They follow Curie`s Law- $\chi_m = C/T$
- M has slightly positive value.
- χ_m is slightly positive.
- Relative permeability(μ_r) is slightly positive.
- Examples of paramagnetic substances are:- Aluminium(Al), Sodium(Na), Platinum(Pt) Manganese(Mn), etc

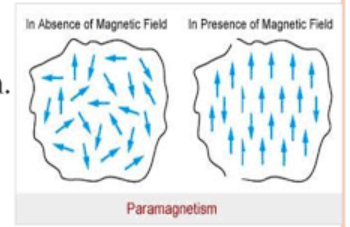


Fig1.4. Alignment of Domains in Paramagnetic on Applying B

FERROMAGNETISM AND FERROMAGNETIC MATERIAL

- On a small scale, ferromagnetic materials are actually made up of tiny regions known as domains. Each domain behaves like a tiny magnet with a North and South pole.
- In an unmagnetized piece of iron, these domains are arranged randomly pointing in all directions. The magnetic effects end up cancelling each other out.

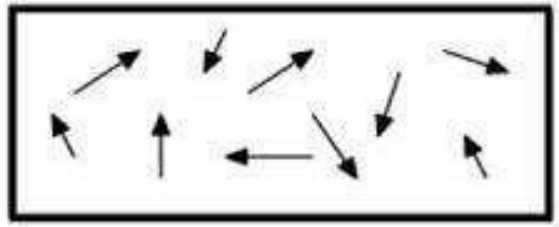


Figure 18: Unmagnetized Ferromagnetic Material

Ferromagnetic theory (Weiss Theory)

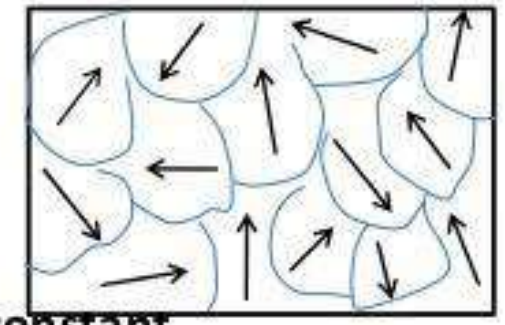
- **Weiss** predicted that, in ferromagnetic materials **Spontaneous magnetization** is observed, which is due to a **strong internal field** arising from an **exchange interaction** between the magnetic moments in the neighborhood **domains**

- exchange interaction

between two atoms 'I' and 'j'

- = $\mathbf{U = -2 J S_i S_j}$

'J' is called the exchange integral



- $\mathbf{H_{int} = \lambda M}$, **where 'λ' is called Weiss constant**
- $\mathbf{H_{tot} = H_{appl} + H_{int}}$
- $\mathbf{H_{tot} = H_{appl} + \lambda M}$

FERRIMAGNETISM AND FERRIMAGNETIC MATERIAL

Properties of Ferrimagnetic Materials

- The dipoles are antiparallel as shown in Fig. 8. However, the dipoles are not equal in magnitude.

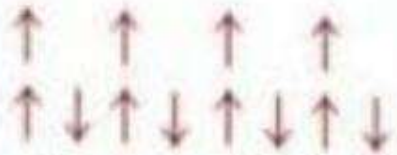


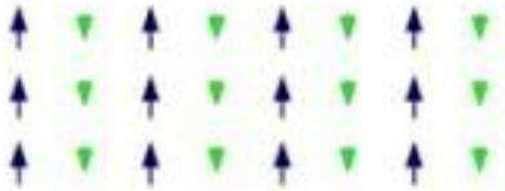
Fig. 8.

- Net magnetization is larger even for a small external field.
- The susceptibility is positive and vary large when the temperature is higher than T_N.

$$\chi = \frac{C}{T \pm \theta}$$

- They behave as paramagnetic and ferromagnetic materials respectively above and below Curie temperature.

Ferrimagnetism



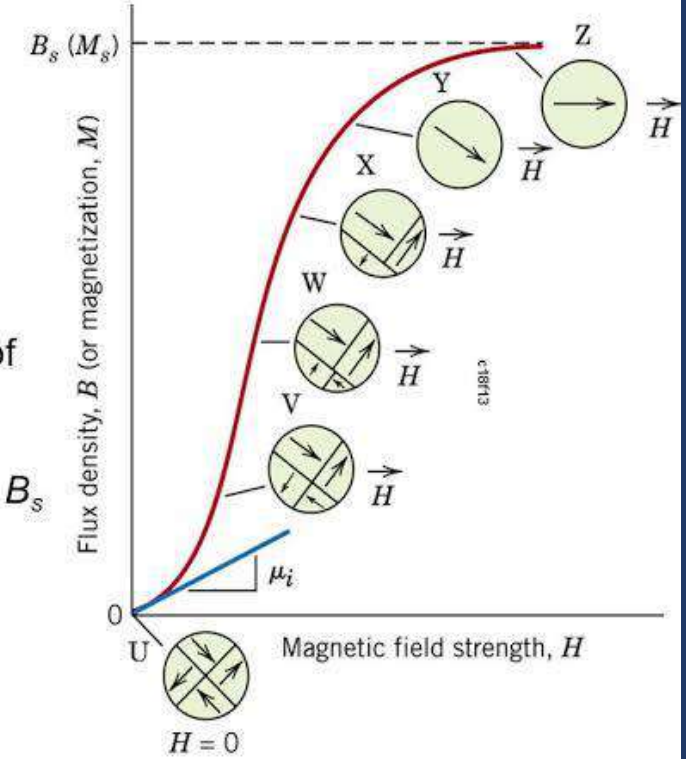
➢In physics, a **ferrimagnetic material** is one that has populations of atoms with opposing magnetic moments, as in antiferromagnetism; however, in **ferrimagnetic materials**, the opposing moments are unequal and a spontaneous magnetization remains.**Ferrimagnetism** is exhibited by ferrites and magnetic garnets.

B versus H

ferromagnetic or ferrimagnetic material initially unmagnetized

Domain configurations during several stages of magnetization

Saturation flux density, B_s
Magnetization, M_s,
initial permeability μ_i

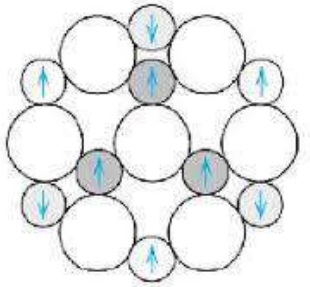


Ferrimagnetic substances In ferrimagnetic substances there are unequal number of parallel and antiparallel magnetic momenta which leads to some resulting magnetic moment, for example, Fe_3O_4, ferrites.

↑↓↓↓↑↓

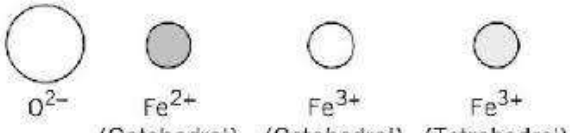
The ferromagnetic, anti-ferromagnetic and ferrimagnetic solids change into paramagnetic at a particular temperature, for example, Ferrimagnetic Fe_3O_4 on heating to 850 K becomes paramagnetic. This is due to alignment of spins in one direction on heating.

Ferrimagnetism

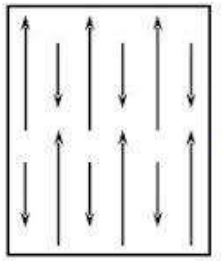


All Fe^{2+} have a spin magnetic moment.

Half of Fe^{3+} have a spin moment in on direction, **the other half in the other** (decreasing the overall moment to just that contributed by the Fe^{2+} ions).



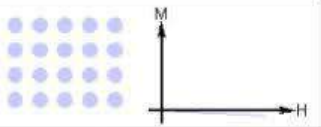
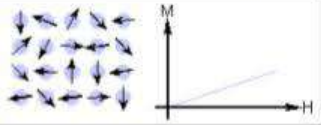
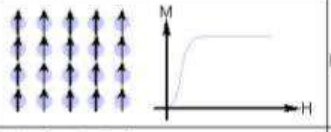
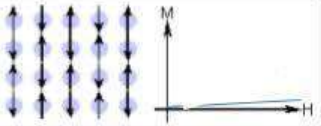
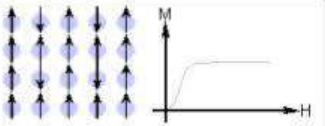
Common for **inverse spinel** materials and **garnets**. Usually, $^{2+}$ ions of Ni, Mn, Co, and Cu are the active ones.

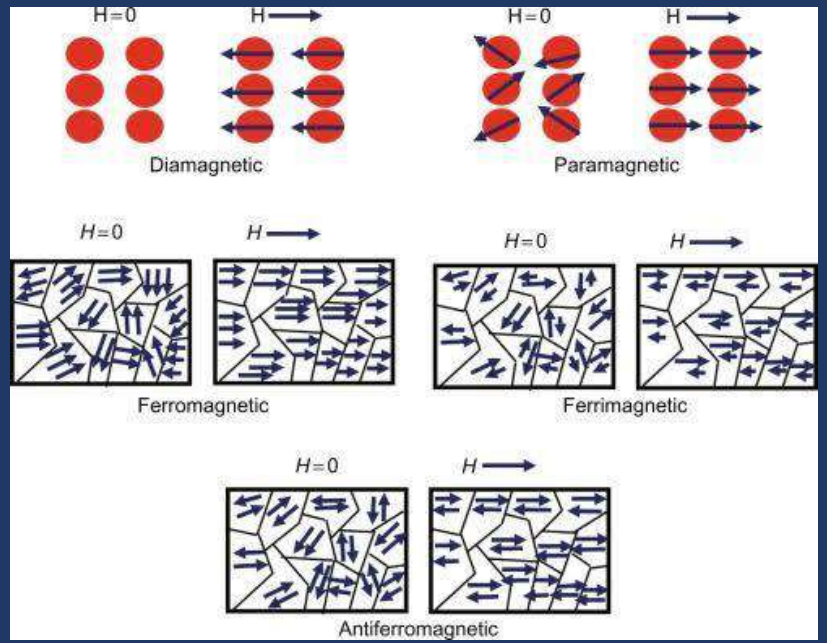


Simpler picture showing a net magnetic moment.

COMPARISON BETWEEN MAGNETIC SUBSTANCE

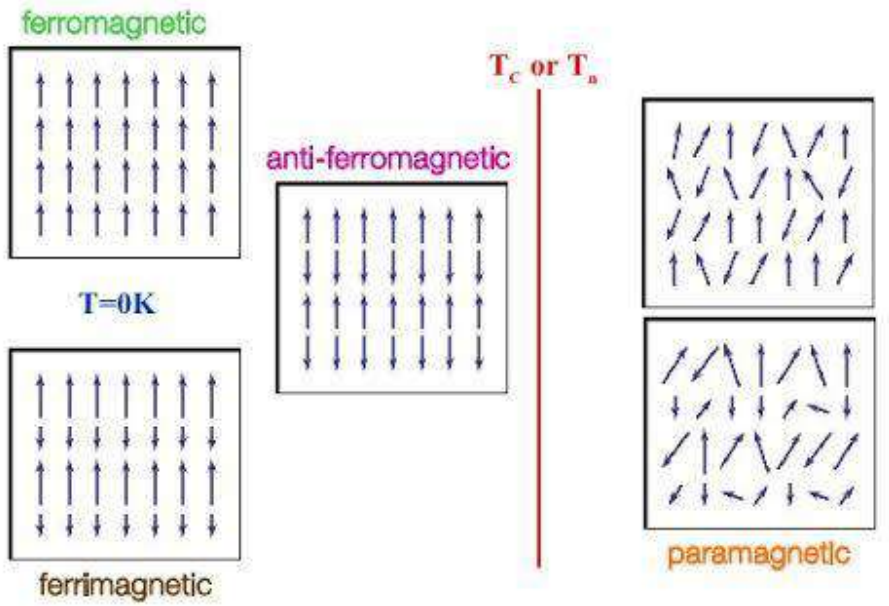
S. N	Properties	Diamagnetic	Paramagnetic	Ferromagnetic
1	Definition	It is a material in which there is no permanent magnetic moment.	It has permanent magnetic moment.	It has enormous (more) permanent magnetic moment.
2	Spin or magnetic moment or dipole alignment.	No spin alignment.	Random alignment	Parallel and orderly alignment.
3	Behavior	Repulsion of magnetic lines of force from the centre of the material.	Attraction of magnetic lines towards the centre.	Heavy attraction of lines of force towards the centre.
4	Magnetized direction	Opposite to the External magnetic field.	Same direction as the External magnetic field.	Same direction as the External magnetic field.
5	Permeability	It is very less	It is high	It is very high
6	Relativity permeability	$\mu_r < 1$	$\mu_r > 1$	$\mu_r >> 1$
7	Susceptibility	Negative	Low positive	High positive
8	Magnetic phase transition	At 0 K, diamagnetic material is Superconductor. When we increase its temperature it becomes a normal conductor.	When temperature is less than the curie temp, it is converted in to Diamagnetic.	When temperature of the material is greater than it Curie temperature it is converted into Paramagnet.

Type of Magnetism	Susceptibility	Atomic / Magnetic Behaviour		Example / Susceptibility	
Diamagnetism	Small & negative.	Atoms have no magnetic moment		Au Cu	-2.74×10^{-6} -0.77×10^{-6}
Paramagnetism	Small & positive.	Atoms have randomly oriented magnetic moments		β-Sn Pt Mn	0.19×10^{-6} 21.04×10^{-6} 66.10×10^{-6}
Ferromagnetism	Large & positive, function of applied field, microstructure dependent.	Atoms have parallel aligned magnetic moments		Fe	~100,000
Antiferromagnetism	Small & positive.	Atoms have mixed parallel and anti-parallel aligned magnetic moments		Cr	3.6×10^{-6}
Ferrimagnetism	Large & positive, function of applied field, microstructure dependent	Atoms have anti-parallel aligned magnetic moments		Ba ferrite	~3



Ferromagnetic 	Below T_C, spins are aligned parallel in magnetic domains
Antiferromagnetic 	Below T_N, spins are aligned antiparallel in magnetic domains
Ferrimagnetic 	Below T_C, spins are aligned antiparallel but do not cancel
Paramagnetic 	Spins are randomly oriented (any of the others above T_C or T_N)

Temperature dependence



Above a critical temperature called the Curie point (TC), ferro- and ferrimagnetic materials no longer possess a spontaneous magnetization. They become PARAMAGNETIC. So do anti-ferromagnetic materials.