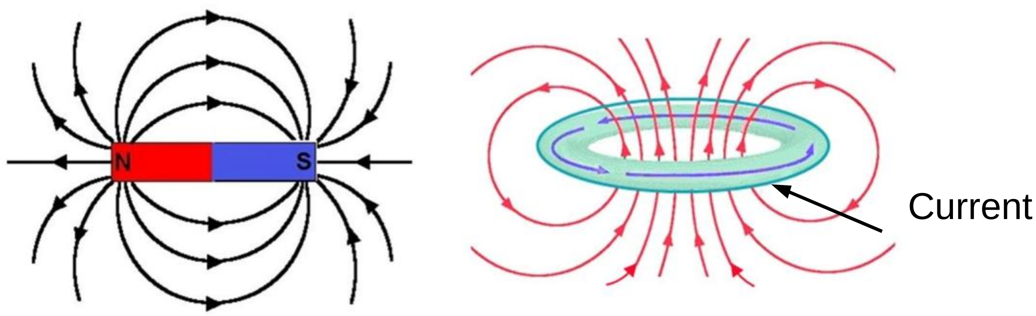
4-1 MAGNETIC PROPERTIES

4-1.1 Magnetic field

- Magnetic field is a force, which is generated due to energy change in a volume of space.
- A magnetic field is produced by an electrical charge in motion e.g. current flowing in a conductor, orbital movement and spin of electrons.

- The magnetic field can be described by imaginary lines as shown in the figure below for a magnet and a current loop.

Magnetic lines of force



4-1.2 Magnetic field Strength

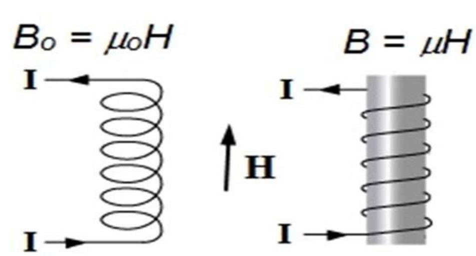
- If a magnetic field, *H*, is generated by a cylindrical coil (solenoid) of *n* turns and length *l*,

$$H = nI/l \text{ (A/m)}$$

- Magnetic flux density, B: It is the magnitude of the field strength within a substance subjected to a field *H* $B = \mu H$ (Tesla or Weber/m^2)

- μ, called the permeability, is the measure of the degree to which a material can be magnetized.

- In vacuum $B = \mu_o H$. μ_o is the permeability of vacuum and is a universal constant. $\mu_o = 4\pi \times 10^{-7}$(H/m). $\mu_r = \mu / \mu_o$ is the relative permeability.

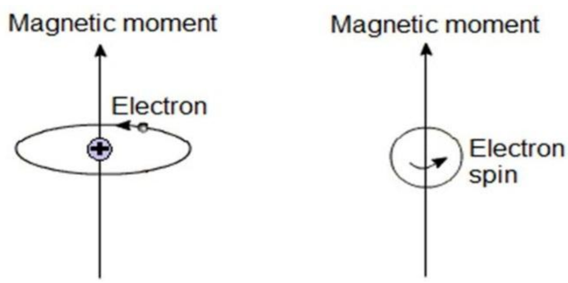


4-1.3 Magnetic moments

- Being a moving charge, electrons produce a small magnetic field having a magnetic moment along the axis of rotation.

- The spin of electrons also produces a magnetic moment along the spin axis.

- Magnetism in a material arises due to alignment of magnetic moments.



4-1.4 Magnetic Dipole and Monopole

- Analogous to electric dipole, a magnetic dipole can be defined as two monopoles of opposite and equal strength separated by a certain distance.

- A magnetic monopole, however, is not observed in nature.

- If there are *N* monopoles each located at a point given by a vector $\bar{a}$, then the magnetic dipole moment can be defined as a vector, $\bar{u}$

$$\bar{u} = \sum_{i=1}^{N} \overline{m}_i \bar{a}_i$$

- Two monopoles of strength +m and –m separated by distance ***l***, will give a dipole $\bar{u} = m\bar{a}_1 - m\bar{a}_2 = m(\bar{a}_1 - \bar{a}_2) = m\bar{l}$

- A bar magnet can be thought of consisting of two opposite and equal poles at its two ends.

4-1.5 Magnetization

- With the application of a magnetic field magnetic moments in a material tend to align and thus increase the magnitude of the field strength.

- This increase is given by the parameter called magnetization, M, such that

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

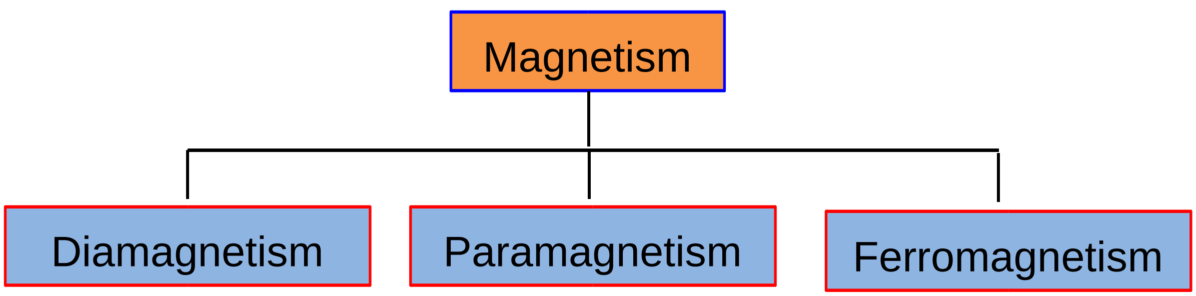
$$M = x_m H.$$

x_m is called magnetic susceptibility.

$$x_m = \mu_r - 1$$

4-2 MAGNETISM

- Depending on the existence and alignment of magnetic moments with or without application of magnetic field, three types of magnetism can be defined.



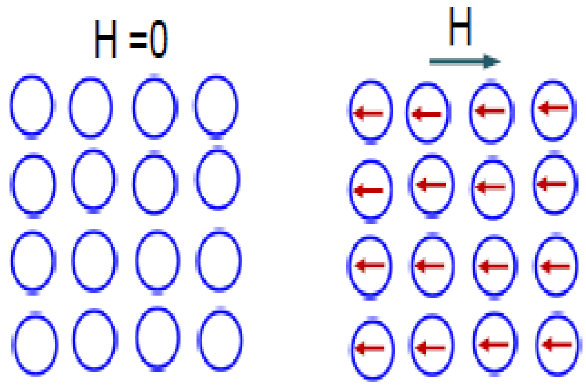
4-2-1 Diamagnetism

- Diamagnetism is a weak form of magnetism which arises only when an external field is applied.

- It arises due to change in the orbital motion of electrons on application of a magnetic field.

- There is no magnetic dipoles in the absence of a magnetic field and when a magnetic field is applied the dipole moments are aligned opposite to field direction.

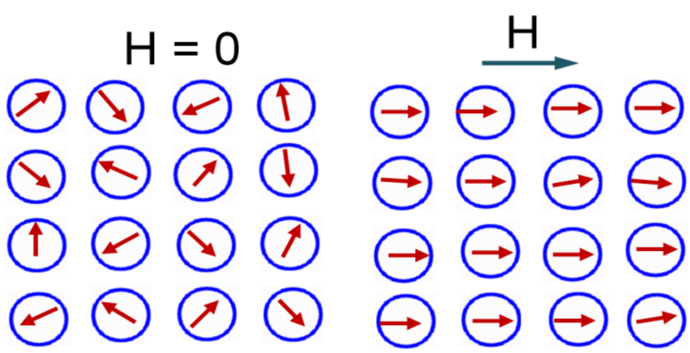
- The magnetic susceptibility, x_m ($\mu_r - 1$) is negative i.e. *B* in a diamagnetic material is less than that of vacuum.



Diamagnetic materials:
Al_2O_3, Cu, Au, Si, Zn

4-2.2 Paramagnetism

- In a paramagnetic material the cancellation of magnetic moments between electron pairs is incomplete and hence magnetic moments exist without any external magnetic field.
- However, the magnetic moments are randomly aligned and hence no net magnetization without any external field.
- When a magnetic field is applied all the dipole moments are aligned in the direction of the field.
- The magnetic susceptibility is small but positive. i.e. *B* in a paramagnetic material is slightly greater than that of vacuum.



Paramagnetic materials:
Al, Cr, Mo, Ti, Zr

4-2.3 Ferromagnetism

- Certain materials posses permanent magnetic moments in the absence of an external magnetic field. This is known as ferromagnetism.

- Permanent magnetic moments in ferromagnetic materials arise due to uncancelled electron spins by virtue of their electron structure.

- The coupling interactions of electron spins of adjacent atoms cause alignment of moments with one another.

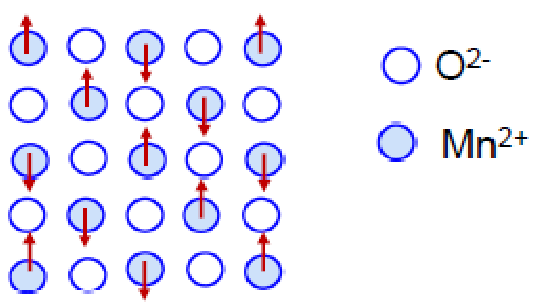
- The origin of this coupling is attributed to the electron structure. Ferromagnetic materials like Fe (26 – [Ar] $4s^2 3d^6$) have incompletely filled *d* orbitals and hence unpaired electron spins.

4-4.6 Antiferromagnetism

- If the coupling of electron spins results in anti parallel alignment then spins will cancel each other and no net magnetic moment will arise.

- This is known as antiferromagnetism. MnO is one such example.

- In MnO, O^{2-} ions have no net magnetic moments and the spin moments of Mn^{2+} ions are aligned anti parallel to each other in adjacent atoms.

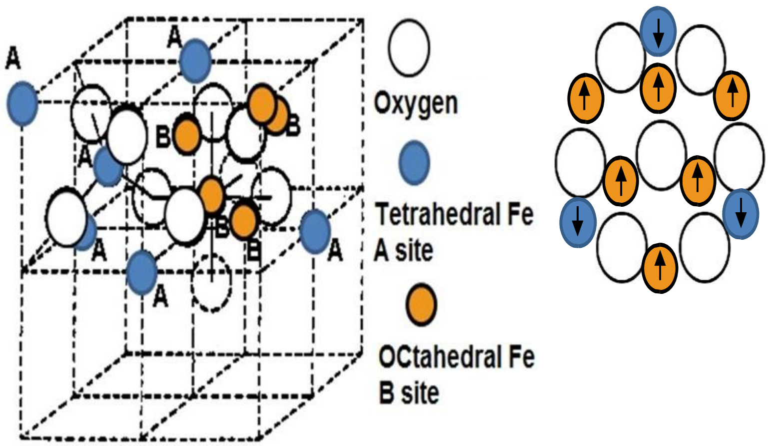


4-2.6 Ferrimagnetism

- Certain ionic solids having a general formula MFe_2O_4, where

M is any metal, show permanent magnetism, termed ferrimagnetism, due to partial cancellation of spin moments.

➢In Fe_3O_4, Fe ions can exist in both 2+ and 3+ states as $Fe^{2+}O^{2-}(Fe^{3+})_2(O^{2-})_3$ in 1:2 ratio. The antiparallel coupling between Fe^{3+} (Half in A sites and half in B) moments cancels each other. Fe^{2+} moments are aligned in same direction and result in a net magnetic moment.

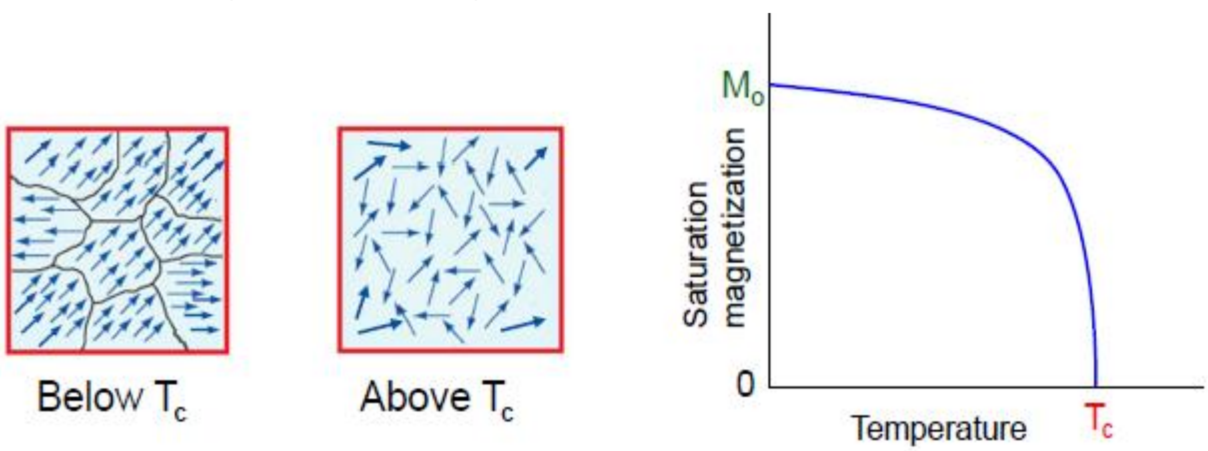


	Octahedral	Tetrahedral
Fe^{3+}	↑↑↑↑ ↑↑↑↑	↓↓↓↓ ↓↓↓↓
Fe^{2+}	↑↑↑↑ ↑↑↑↑	

Effect of Temperature

➢The atomic vibration increases with increasing temperature and this leads to misalignment of magnetic moments. Above a certain temperature all the moments are misaligned and the magnetism is lost. This temperature is known as Curie temperature, Tc.

➢Ferro and ferrimagnetic materials turn paramagnetic above curie point. For Fe Tc = 768 °C, Co – 1120 °C, Ni – 335 °C.



Above the Neel temperature(TN), (or magnetic ordering temperature is the temperature above which an antiferromagnetic material becomes paramagnetic that is, the thermal energy becomes large enough to destroy the macroscopic magnetic ordering within the material),thermal energy is sufficient to cause the equal and oppositely aligned atomic moments randomly fluctuate leading to a disappearance of their long-range order. In this state, the material exhibits paramagnetic behavior. Ferrimagnetism is a property exhibited by materials whose atoms or ions tend to assume an ordered but non-parallel arrangement in zero applied field below a Neel temperature (e.g., Fe_3O_4 and Fe_3S_4). In the usual case, within a magnetic domain, a substantial net magnetization results from the antiparallel alignment of neighboring non-equivalent sublattices.

Above the Neel temperature, the substance becomes paramagnetic. Size reduction in magnetic materials resulting in the formation of single domain particles also gives rise to the phenomenon of superparamagnetism. Briefly, superparamagnetism occurs when thermal fluctuations or an applied field can easily move the magnetic moments of the nanoparticle away from the easy axis, the preferred crystallographic axes for the magnetic moment to point along. Each particle behaves like a paramagnetic atom, but with a giant magnetic moment, as there is still a well-defined magnetic order in each nanoparticle.