SOLID STATE PHYSICS

UNIT III

MAGNETIC PROPERTIES

Presentation by

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WOMEN, NAMAKKAL

CONTENT

- Introduction
- Terms connected with magnetic materials
- Types of magnetic materials
- Langevin’s theory of diamagnetism
- Langevin’s theory of paramagnetism

INTRODUCTION

- Magnetic materials are those materials in which a state of magnetization can be induced.
- Such materials when magnetized create a magnetic field in the surrounding space.
- Magnetic materials are widely used in computers, telephones, tape recorders, electrical meters, transformers, motors, nuclear magnetic resonance equipments, particle accelerators etc. These devices are very important in our modern life.

Terms connected with magnetic materials

- Magnetic flux
- Magnetic flux density
- Intensity of magnetisation
- Magnetic field strength
- Magnetic Permeability
- Relative Permeability
- Magnetic Susceptibility

Magnetic flux (φ):

- Total number of magnetic lines of force passing through a surface is known magnetic flux.
- It is represented by the symbol φ and its unit is weber (Wb)

Magnetic flux density (B):

- Magnetic flux density at any point in a magnetic flux φ passingnormally through unit area of cross section (A) at that

  point.

$$B = \varphi /A$$

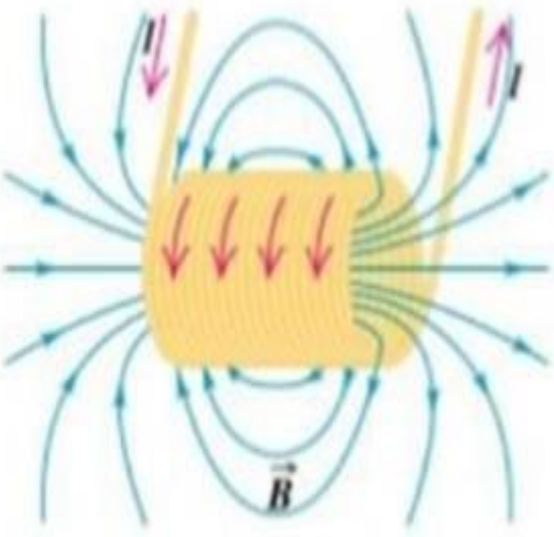
Intensity of magnetisation (I):

- The intensity of magnetisation is the measure of magnetisation of magnetised specimen.

$$I = M/V$$

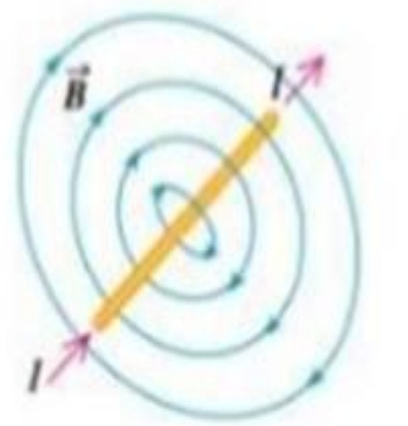
Magnetic field strength(H)

- Magnetic field strength at any point in a magnetic field is the force experienced by a unit north pole placed at that point.



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

$$H = B/\mu_0$$



Magnetic Permeability (μ):

Magnetic Permeability of a substance measures degree to which the magnetic field can penetrate through the substance.

$$\mu = B/H$$

Relative Permeability (μr) of a medium is the ratio between absolute permeability of a medium to permeability of a free space.

$$\mu_r = \mu / \mu_0$$

Magnetic Susceptibility (χ) :

- Magnetic Susceptibility(χ) is the intensity of magnetisation in the substance per unit magnetic field strength.

$$\chi = I/H$$

Relation between Relative Permeability and Magnetic Susceptibility :

Magnetic induction, $B = \mu_0 (H+M)$

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

Relative Permeability, $\mu_r = \mu / \mu_0 = 1 + M/H$

$$\mu_r = 1 + \chi$$

Types of Magnetic Materials

- Diamagnetic
- Paramagnetic
- Ferromagnetic
- Antiferromagnetic

Diamagnetic

- It is a substance which create a magnetic field in opposite to an externally applied field.

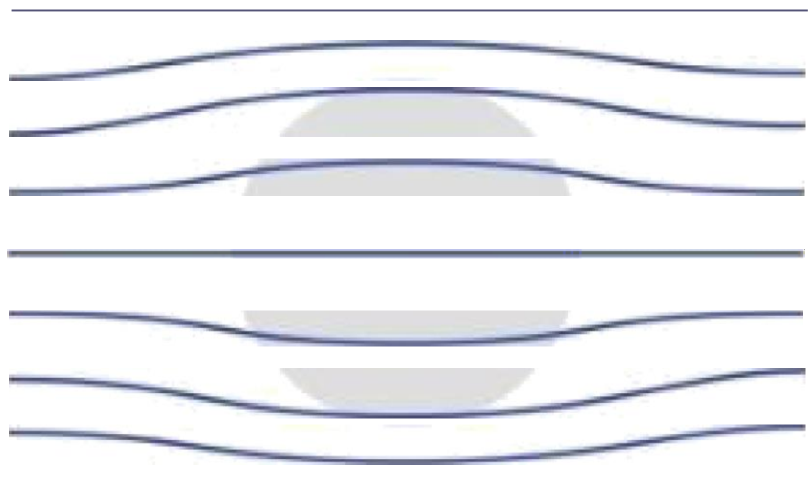
- Susceptibility is negative.

- These have relative permeability slightly less than unity.

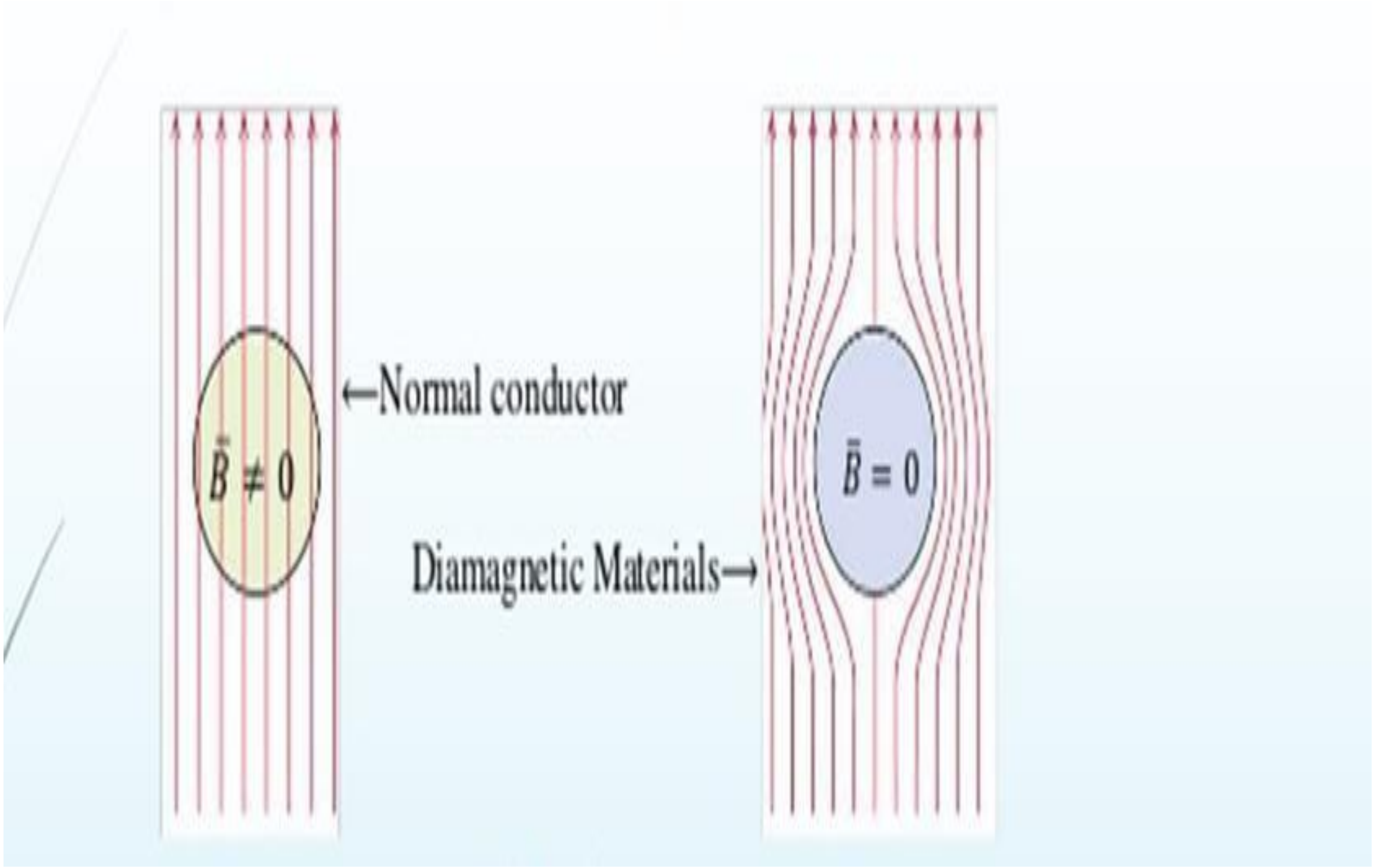
- They reppel the lines of force slightly.

The examples are bismuth silver, copper and hydrogen.

Dlamagn€ttism



Properties of Diamagnetic Materials

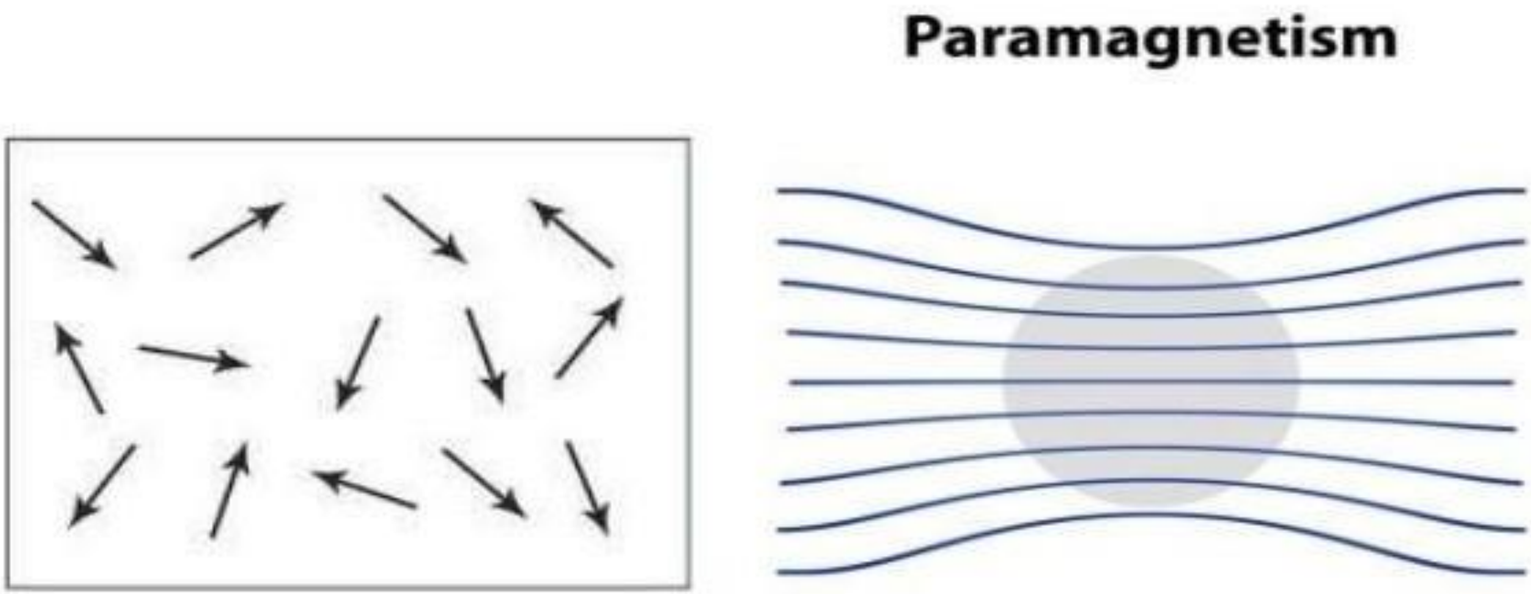


Paramagnetic

- It is a substance or body which very weakly attracted by the poles of a magnet, but not retaining any permanent magnetism.
- These have relative permeability slightly greater than unity and are magnetized slightly.
- They attract the lines of forces weakly.

Properties of Paramagnetic Materials

- Al, Pt, Ca, O_2 are such materials.

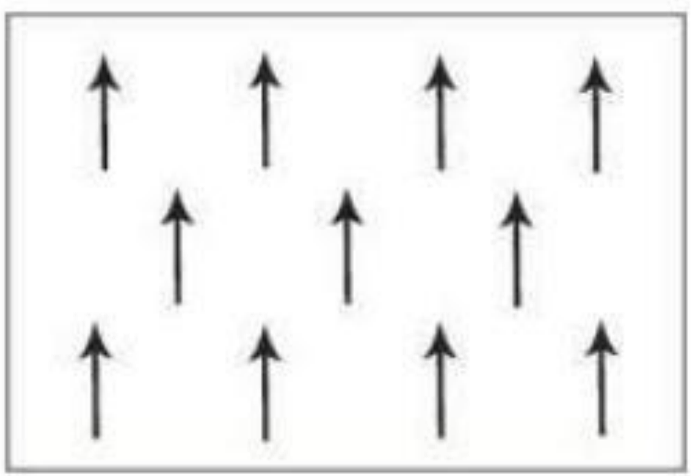


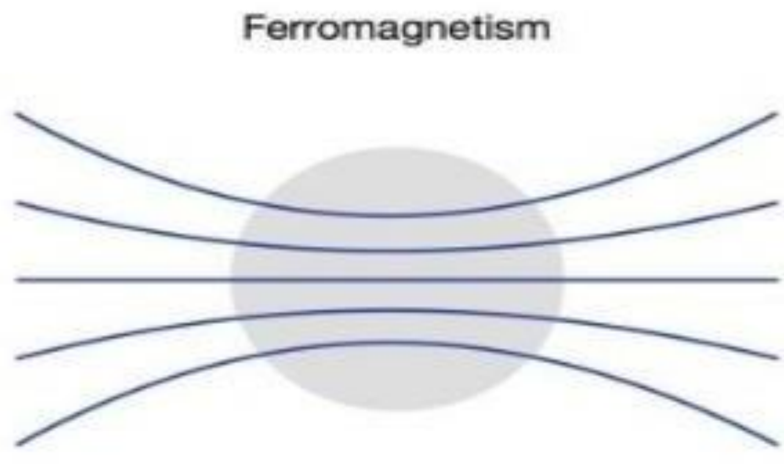
Ferromagnetic

- A type of material that is highly attracted to magnets and can become permanently magnetized is called as ferromagnetic.
- The relative permeability is much greater than unity and are dependent on the field strength.
- These have high susceptibility.

Properties of Ferromagnetic Materials

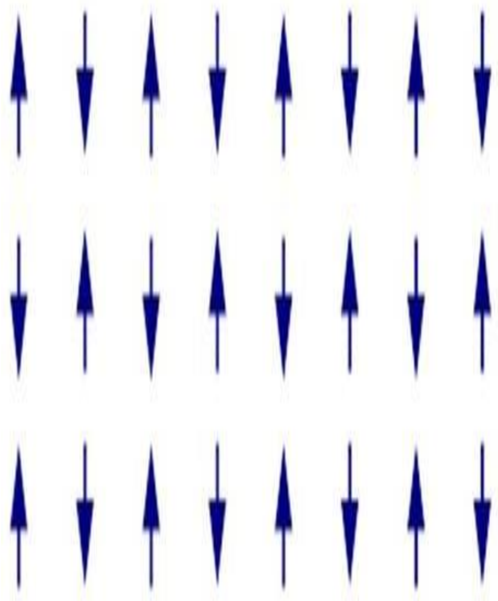
- Fe, Co, Ni, Cr, Mn are such materials.





Antiferromagnetic

- In Antiferromagnetic materials, the magnetic moments of atoms or molecules, usually related to the spins of electrons, align in a regular pattern with neighboring spins pointing in opposite directions. This is, like ferromagnetism and ferrimagnetism, a manifestation of ordered magnetism.
- Generally, antiferromagnetic order may exist at sufficiently low temperatures.



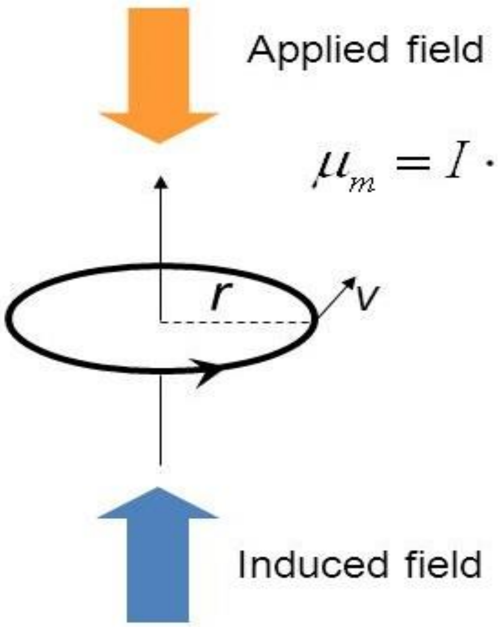
Properties of Antiferromagnetic Materials

- The antiferromagnetism will not produce any magnetisation because of the two opposing spin components.
- When external field is applied, the net magnetisation will be different of zero due to that the maximum spin are in the same direction.
- Examples of antiferromagnetic materials are MnO, FeO, MnF2

Comparative study

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)

Langevin's Theory of Diamagnetism



$$\mu_m = I \cdot A = \frac{e}{t} A = \frac{e}{s/v} A = \frac{ev\pi r^2}{2\pi r} = \frac{evr}{2}$$

e : electron charge

r : radius of the orbit

s : length of the orbit $(= 2\pi r)$

v : velocity of the orbiting electron

t : revolution time

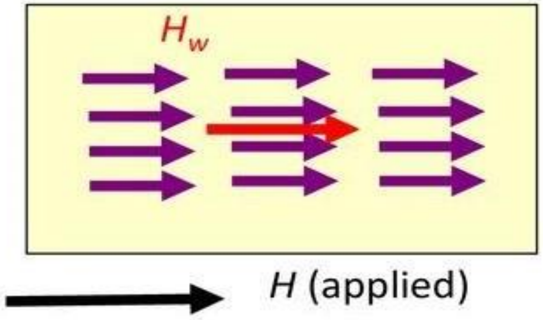
Diamagnetic susceptibility

$$X = M/H = -N\mu0Ze2/6m \langle r2 \rangle$$

This show that the diamagnetic susceptibility is independent of temperature.

Langevin's Theory of Paramagnetism

Magnetic moments (spins*) in paramagnetic material aligned in a internal (Weiss) field:



$H_W = wM$

w=Weiss or molecular field coefficient

Average total magnetization is:

$$M = N\mathcal{M}\frac{\int_0^{\pi}\exp\left(\frac{\mathcal{M}(H+wM)}{kT}\right)\cos\theta\sin\theta d\theta}{\int_0^{\pi}\exp\left(\frac{\mathcal{M}(H+wM)}{kT}\right)\sin\theta d\theta}$$

$\mathcal{M}$ = atomic magnetic dipole moment

*Orbital angular momentum gives negligible contribution to magnetization in solids (quenching)

Paramagnetic susceptibility

$$\chi = \mu_0 M / B = -\mu_0 N \mu^2 / 3kT$$

This shows that the paramagnetic susceptibility is inversely proportional to temperature.

Magnetic Materials

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NAMAKKAL

OUTLINE

- Weiss Theory of Paramagnetism
- Weiss Theory of Ferromagnetism
- Quantum Theory of Ferromagnetism
- Ferrites or Ferrimagnetic Materials
- Superconductors
- Properties of Superconductors
- Type I and Type II Superconductors
- Application of Superconductors

Weiss Theory of

Langevin theory failed to explain some complicated temperature dependence of few compressed and cooled gases, solid salts, crystals etc. Further it does not throw light on relationship between para and ferro magnetism.

Weiss introduced concept of internal molecular field in order to explain observed discrepancies. According to Weiss, internal molecular field is given as

$H_i = \lambda M$ Where λ is molecular field coefficient.

Therefore the net effective field should be

$$\Rightarrow H_e = H + \lambda M$$

But, we know from classical treatment of paramagnetism that

$M = M_s(\frac{a}{3})$ (For a << 1) $(a = \frac{\mu B}{3kT})$

Paramagnetism

$$M = M_s\left(\frac{a}{3}\right) = \frac{N\mu^2\mu_0 H_e}{3kT} \qquad \Rightarrow M = \frac{N\mu^2\mu_0}{3kT}(H + \lambda M)$$

$$\Rightarrow M\left(1 - \frac{N\mu^2\mu_0}{3kT}\lambda\right) = \frac{N\mu^2\mu_0}{3kT}H \qquad \Rightarrow M = \frac{N\mu^2\mu_0 H}{3kT\left(1 - \lambda\frac{N\mu^2\mu_0}{3kT}\right)}$$

$$\Rightarrow \chi = \frac{M}{H} = \frac{N\mu^2\mu_0}{3kT\left(1 - \lambda\frac{N\mu^2\mu_0}{3kT}\right)} = \frac{N\mu^2\mu_0}{3k\left(T - \lambda\frac{N\mu^2\mu_0}{3k}\right)}$$

$$\Rightarrow \chi = \frac{C}{T - \theta_c}$$

where $\theta_c = \frac{N\mu^2\mu_0}{3k}\lambda$ Paramagnetic curie point

and $C = \frac{N\mu^2\mu_0}{3k}$ Curie constant

Curie-Weiss Law.

Weiss Theory of Ferromagnetism

A molecular field tends to produce a parallel alignment of the atomic dipoles despite effect of thermal energy. This internal magnetic field is, say, H_m is proportional to the magnetization M of a domain i.e.

$$H_m = \lambda M$$

Where λ is constant independent of temperature, called molecular field constant or Weiss constant.

Effective field experienced by each dipole would be then,

$$H_e = H + \lambda M$$

Let us consider a ferromagnetic solid containing N number of atoms/ m^3, then magnetization due to spins (J=1/2) can be given as

$$M = N\mu_B \tanh[\frac{\mu_0 \mu_B H}{kT}]$$

$$\Rightarrow M = N\mu_B \tanh[\frac{\mu_0 \mu_B (H + \lambda M)}{kT}]$$

At sufficiently high temperature,

$$\frac{\mu_0 \mu_B (H + \lambda M)}{kT} << 1$$

Then $$\tanh[\frac{\mu_0 \mu_B (H + \lambda M)}{kT}] \approx \frac{\mu_0 \mu_B (H + \lambda M)}{kT}$$

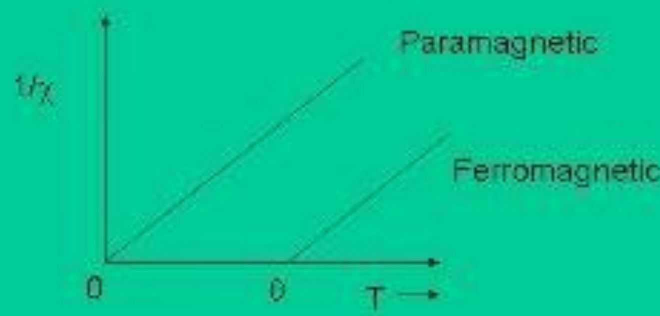
Therefore,

$$M = N\mu_B \tanh\left[\frac{\mu_0\mu_B(H+\lambda M)}{kT}\right] = \frac{N\mu_0\mu_B^{\,2}(H+\lambda M)}{kT}$$

$$\Rightarrow M = \frac{N\mu_0\mu_B^{\,2}H}{kT} + \frac{N\mu_0\mu_B^{\,2}\lambda M}{kT} \Rightarrow M\left(1-\frac{N\mu_0\mu_B^{\,2}\lambda}{kT}\right) = \frac{N\mu_0\mu_B^{\,2}H}{kT}$$

$$\Rightarrow \chi = \frac{M}{H} = \frac{N\mu_0\mu_B^{\,2}}{kT\left(1-\frac{N\mu_0\mu_B^{\,2}\lambda}{kT}\right)} = \frac{N\mu_0\mu_B^{\,2}}{k\left(T-\frac{N\mu_0\mu_B^{\,2}\lambda}{k}\right)}$$

$$\Rightarrow \chi = \frac{C}{(T-\theta)}$$



Where,

$$C = \frac{N\mu_0\mu_B^{\,2}}{k} \text{ and } \theta = \frac{N\mu_0\mu_B^{\,2}\lambda}{k} = \lambda C$$

Now when H = 0, i.e. for spontaneous magnetization

$$M = N\mu_B \tanh[\frac{\mu_0\mu_B(H+\lambda M)}{kT}] \quad = N\mu_B \tanh[\frac{\mu_0\mu_B\lambda M}{kT}]$$

$$\Rightarrow \frac{M}{N\mu_B} = \frac{M}{M_s} = \tanh[\frac{\mu_0\mu_B\lambda M}{kT}]$$

$$\Rightarrow \frac{M}{N\mu_B} = \frac{M}{M_s} = \tanh\alpha$$

Where, $$\alpha = \frac{\mu_0\mu_B\lambda M}{kT}$$

Now let us consider $\alpha = \dfrac{\mu_0 \mu_B \lambda M}{kT}$

It can be written as , $\alpha = \dfrac{N\mu_0 \mu_B{}^2 \lambda M}{N\mu_B kT}$

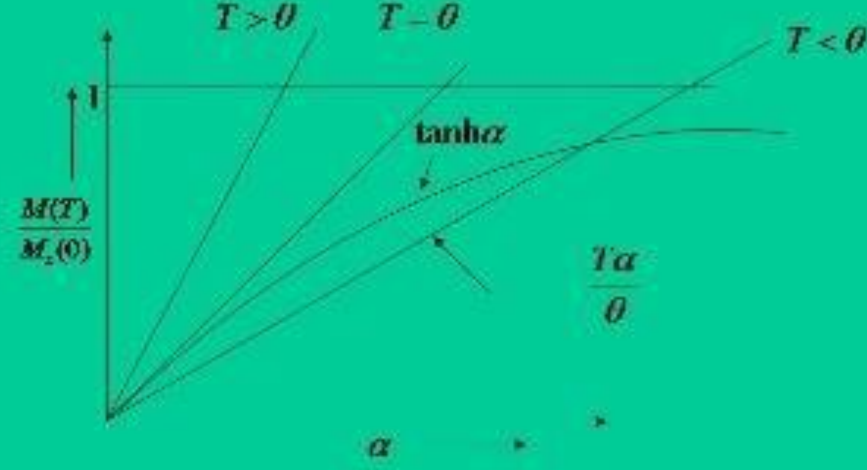
$$\Rightarrow \frac{M}{N\mu_B} = \frac{kT\alpha}{N\mu_0 \mu_B{}^2 \lambda}$$

$$\Rightarrow \frac{M(T)}{M_s(0)} = \frac{T\alpha}{\lambda C} = \frac{T\alpha}{\theta} \qquad \text{also } \frac{M}{M_s} = \tanh\alpha$$

where,

$$C = \frac{N\mu_0 \mu_B{}^2}{k}$$

$$\theta = \frac{N\mu_0 \mu_B{}^2 \lambda}{k} = \lambda C$$



Quantum Theory of Ferromagnetism

Exchange interaction: spin dependent coulomb energy

Exchange energy (Exchange Field): If two atoms *i* and *j* have spin angular momentum $S_i h/2\pi$ and $S_j h/2\pi$, respectively, then the exchange energy between them can be described in terms of the exchange integral J_{ex}.

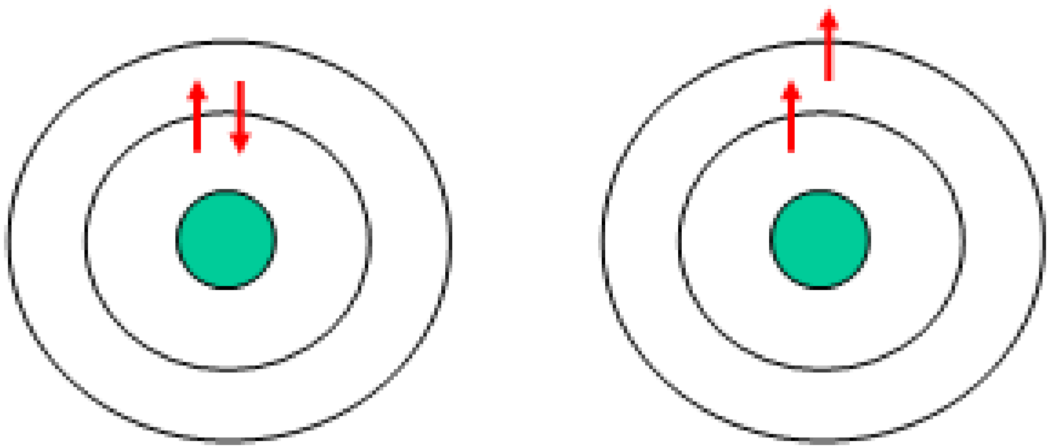
$$E_{ex} = -2J_{ex} S_i \cdot S_j \qquad J_{ex} = 2k - \frac{(e_1 - e_2)^2}{U}$$

Kinetic energy term (antiferromagnetic) and potential energy term (ferromagnetic):

$$J_{AF} = -\frac{(e_1 - e_2)^2}{U} = -\frac{4(\beta + l)^2}{U} \qquad J_F = 2k$$

Exchange Interaction

- Arises from Coulomb electrostatic interaction and the Pauli exclusion principle

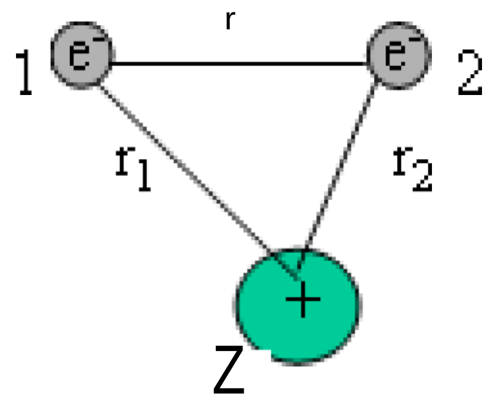


Coulomb repulsion energy high

Coulomb repulsion energy lowered

$$U_c = \frac{e^2}{4\pi\varepsilon_0 r^2} \sim 10^{-18} J \quad (10^5 \text{ K !})$$

Consider two elecaons in an atom:



Hamiltonian:

SF, = A — ______

— 2m 4axgr

g

' 2m, ______

4en r

$\mathcal{H}_{12} =$ -

$4\pi\varepsilon_0 r_{12}$

"y " $\frac{\partial^2}{\partial x_j^2} + \frac{\partial^2}{\partial y_j^2} + \frac{\partial^2}{\partial z_j^2}$

Using one electron approximation

$$\Psi_s(r_1,r_2)=\frac{1}{\sqrt{2}}\left[\phi_1(r_1)\phi_2(r_2)+\phi_2(r_1)\phi_1(r_2)\right]$$ **singlet** ↓ ↑

$$\Psi_A(r_1,r_2)=\frac{1}{\sqrt{2}}\left[\phi_1(r_1)\phi_2(r_2)-\phi_2(r_1)\phi_1(r_2)\right]$$ **triplet** ↑ ↑

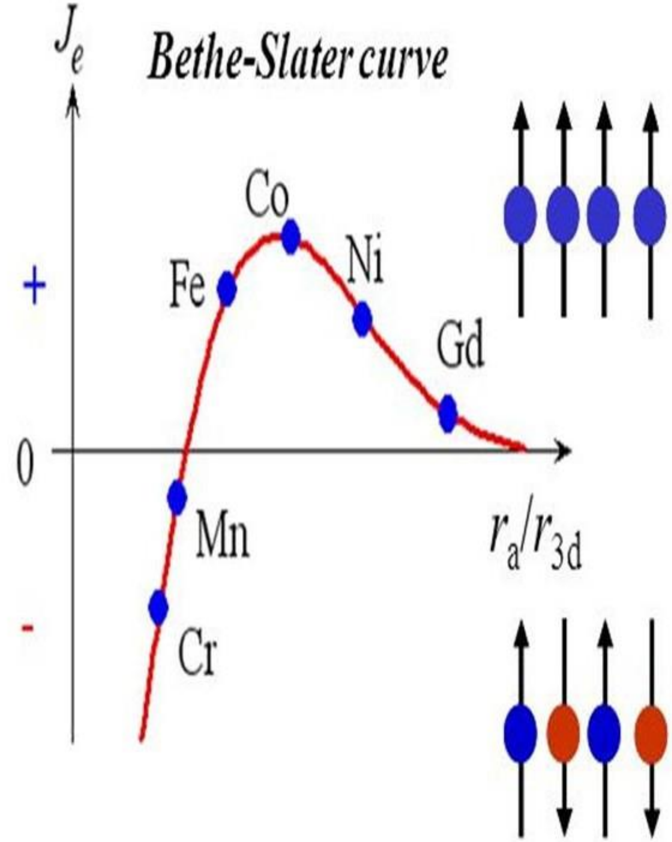
ϕ_1, ϕ_2 are normalized spatial one-electron wavefunctions

Relative orientation of two spins

determines the energy states

(1) If J_{ex} is positive, E_{ex} is a minimum when the spins are parallel, leading to **ferromagnetism**

(2) If J_{ex} is negative, E_{ex} is a minimum when the spins are antiparallel, leading to **antiferromagnetism**.



Ferrites or Ferrimagnetic Materials

- Ferrites are ceramic compounds consisting of a mixed oxide of iron and one or more other metals which has ferrimagnetic properties and is used in high-frequency electrical components such as aerials.

Classification of Ferrites

- ***Soft Ferrite:*** Ferrites with low coercive force are called soft ferrites.

eg. Nickel-zinc ferrite, Manganese-zinc ferrite etc.

- ***Hard Ferrite:*** Ferrites with high coercive force are called hard ferrite.

eg. Barrium ferrite , Stonsium ferrite etc.

Properties of ferrimagnetic materials

- Ferrimagnetic materials have a large, positive susceptibility to an external magnetic field.
- They exhibit a strong attraction to magnetic fields and are able to retain their magnetic properties after the external field has been removed.
- They have high magnetic permeability coupled with low electrical conductivity (which helps prevent eddy currents).
- Above Curie temperature ferrimagnetic material becomes paramagnetic while below

it behaves as ferrimagnetic material.

Uses of Ferrites

❖Ferrites are used in digital computers and data processing circuits. Ferrites are used to produce low frequency ultra sonic waves by magnetostriction principle.

❖ Ferrites are widely used in non-reciprocal microwave devices. Examples for non-reciprocal microwave devices are Gyrator, Isolator and Circulator.

❖ Ferrites are also used in power limiting devices.

❖Ferrites can also be used in the design of ferromagnetic amplifiers of microwave signals.

❖ Ferrite core can be used as a bit-able element.

❖The rectangular shape ferrite cores can be used as a magnetic shift register.

❖Hard ferrites are used to make permanent magnets.

❖ The permanent magnets (hard ferrites) are used in instruments like galvanometers, ammeter, voltmeter, flux meters, speedometers, wattmeter, compasses and recorders.

Superconductors

- *Superconductors are the material having almost zero resistivity and behave as diamagnetic below the superconducting transiting temperature*
- *Superconductivity* is the flow of electric current without resistance in certain metals, alloys, and ceramics at temperatures near absolute zero, and in some cases at temperatures hundreds of degrees above absolute zero = $-273^{o}K$.

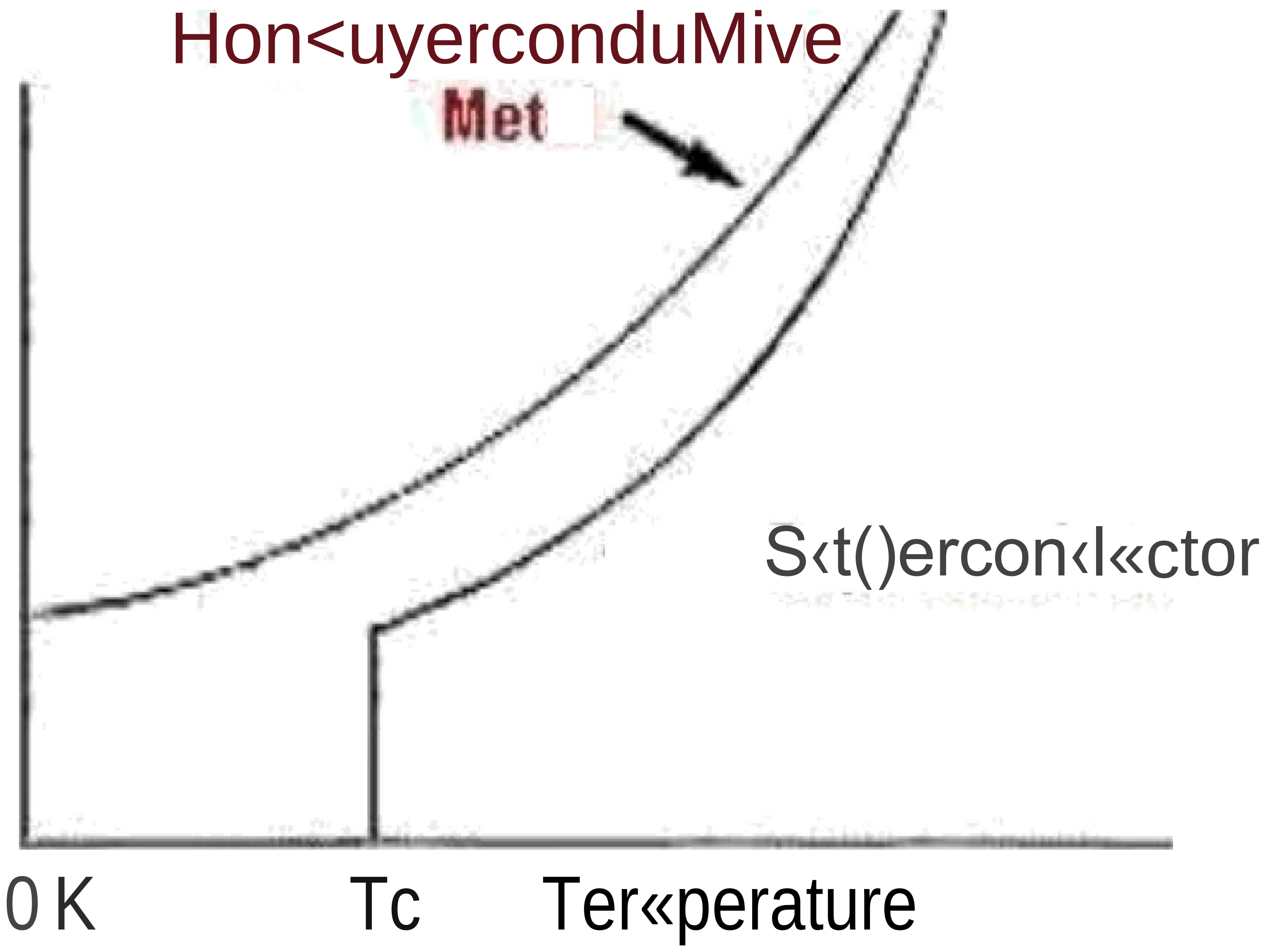
Discoverer of supercondunivity

- Superconductivity was first discovered in 1911 by the

Critical Temperature

- ✓The temperature at which electrical resistance is zero is called the Critical temperature (T_c)

- ✓The cooling of the material can be achieved using liquid nitrogen or liquid helium for even more lower temperature.


Hon<uyerconduMive
Met
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0 K
Tc
Ter«perature

General properties of Super conductors

- **Electrical resistance**: Virtually zero electrical resistance.

- **Effect of impurities**: When impurities are added to superconducting elements, the superconductivity is not loss but the T_c is lowered.

- **Effects of pressures and stress**: certain materials exhibits superconductivity on increasing the pressure in superconductors, the increase in stress results in increase of the T_c value.

- Isotope effect: The critical or eansitlon temperature Tc value of a superconductors is found to vary wit its isotopic mass. i,e. *"the transition temperature is inversely pmportional tO* féc *squaee eoot* oj£f. *ofopic* rna.ss *ofsingle supeiz:onductoes,"*

$$T_c \;\alpha\; 1/\,{}^{2}\sqrt{M}$$

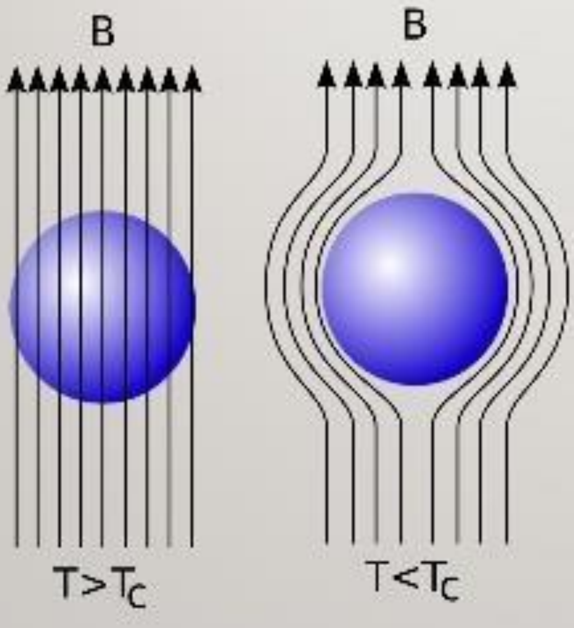
- Magnetic field effect: If Soong magnetic field applied to a superconductors below ie T , ie superconductors

undergoes a Oansition horn superconducting stare io nomial

state.

Meissner Effect

THE COMPLETE EXPULSION OF ALL MAGNETIC FIELD BY A SUPERCONDUCTING MATERIAL IS CALLED "MEISSNER EFFECT"



- Normal state: $T > T_c$
- Superconducting state : $T < T_c$
- The Meissner effect is a distinct characteristics of a superconducting from a normal perfect conductor. In addition, this effect is exhibited by the superconducting materials only when the applied field is less then the critical field Hc.

Types of Superconductors

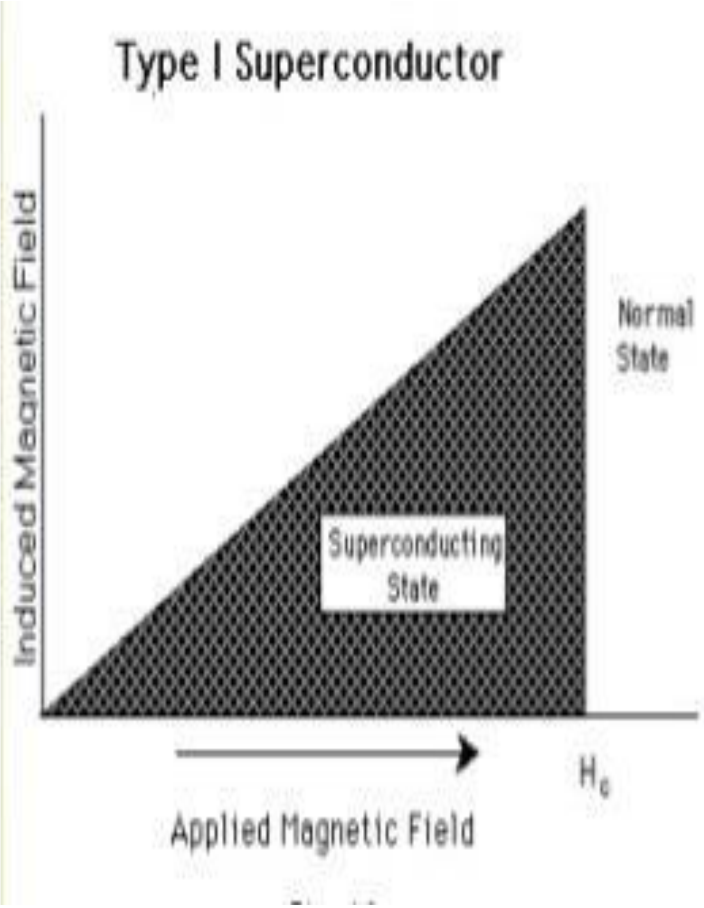
TYPE I

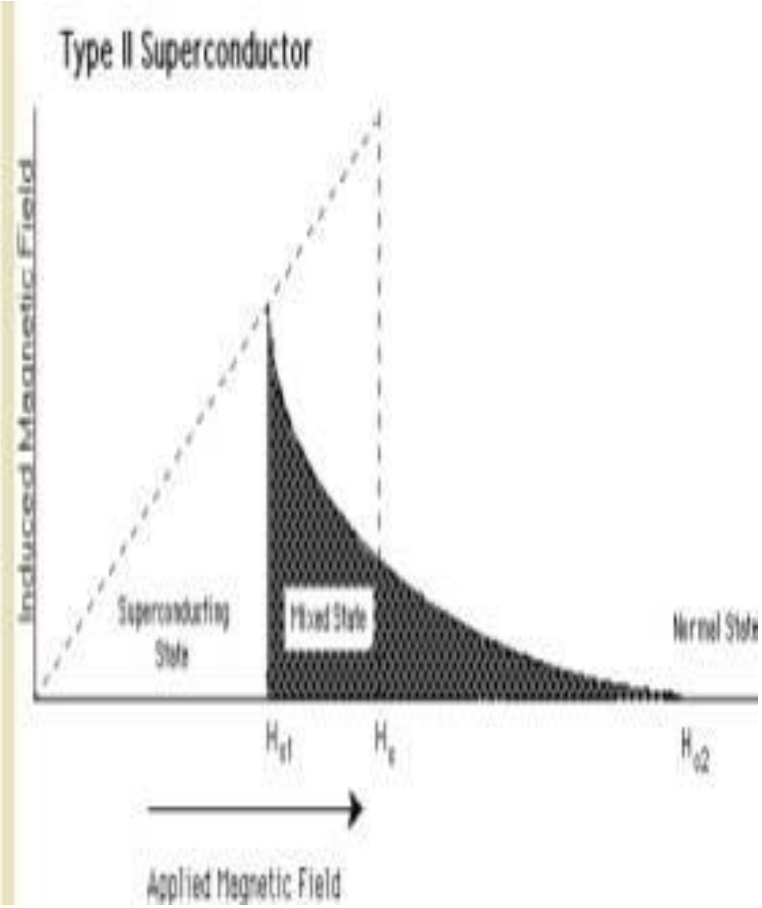
- Soft superconductors are those which can tolerate impurities without affecting the superconducting properties.
- Also called SOFT SUPERCONDUCTORS.
- Critical field value is very low.
- Exhibits perfect and complete Meissner effect.
- The current flows through the surface only.
- These materials have limited technical applications because of very low field strength value

TYPE II

- Hard superconductors are those which cannot tolerate impurities, i.e., the impurity affects the superconducting property
- Also called HARD SUPERCONDUCTORS.
- Critical field value is very high.
- Don't exhibit perfect and complete Meissner effect.
- It is found that current flows throughout the material.
- These materials have wider technology of very high field strength value.

Types of Superconductos





High Tc Superconductors

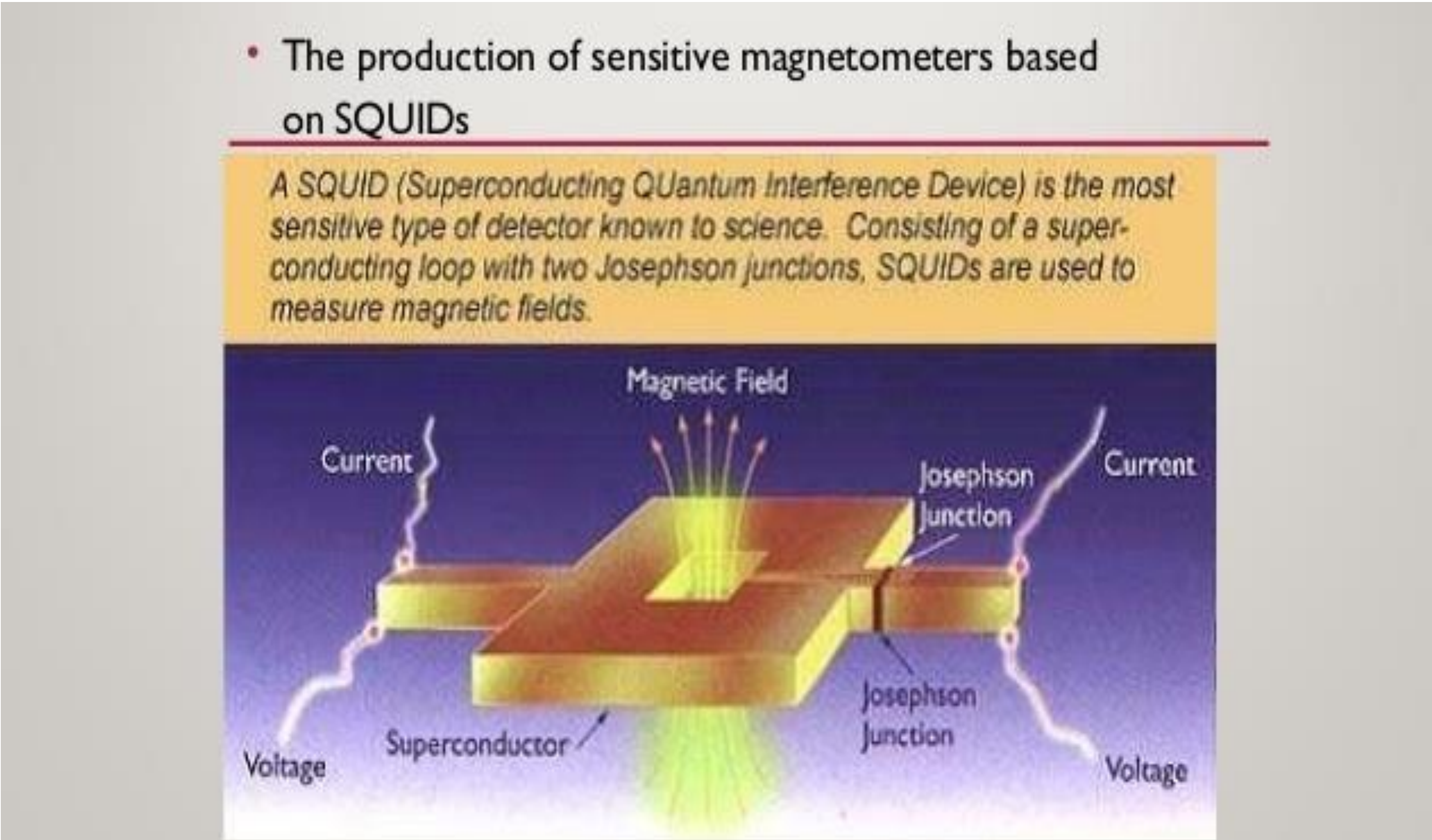
LOW Tc SUPERCONDUCTORS	HIGH Tc SUPERCONDUCTORS
• Superconductors that require liquid helium coolant are called low temperature superconductors. • Liquid helium temperature is 4.2K above absolute zero	• Superconductors having their Tc values above the temperature of liquid nitrogen (77K) are called the high temperature superconductors.

Applications

- Maglev trains:
- Based on two techniques:
  1)Electromagnetic suspension
  2)Electrodynamic suspension
- In EMS, the electromagnets installed on the train bogies attract the iron rails. The magnets wrap around the iron & the attractive upward force is lift the train.
- In EDS levitation is achieved by creating a repulsive force between the train and guide ways.
- The basic idea of this is to levitate it with magnetic fields so that there is no physical contact between the trains and guideways.
  Consequently the maglev train can travel at high speed of 500 km/h.

APPLICATIONS MAGLEV VEHICLES

SQUIDS



The production of sensitive magnetometers based on SQUIDs
A SQUID (Superconducting QUantum Interference Device) is the most sensitive type of detector known to science. Consisting of a super-conducting loop with two Josephson junctions, SQUIDs are used to measure magnetic fields.
Magnetic Field
Current
Current
Josephson Junction
Josephson Junction
Superconductor
Voltage
Voltage

• Powerful superconducting eleceomagnets used in maglev oains, MagnWlC Resonance ImaQlllQ @RI) and Nuclear magnehc resonance (NMR) macEnes, magnetic conflnement k sion reactors (e.g. tokomaks), and ie beam- sieering and focusing magnes used in particle accelerators.

• Superconduttlng generators has 4e beneflt Of small size and low crier[illegible] consumption than 4e conventional generators.

• Very fasi aid accurate computers car be constructed using supercond uctors and ae p›wer consum tlon is also very low. Superconductors can be used to transmit electrical power over very long distances without any power or any voltage Aop

Examples

1)Elemental Superconductor:

Hg=4.15k, Pb=7.19k

2) Compound Superconductor

Nb3Al=19k, Nb3Ge= 23k

3) Ceramic Superconductor

HgBa2Ca2Cu2o8=133k, Ti2Ba2Ca2Cu2O11=125k

Thank you