SUPERCONDUCTIVITY

LEARNING MATERIAL
PREPARED BY

DR.R.VALLIAMMAL
ASSOCIATER PROFESSOR
APAC W, PALANI

Super Conducting Materials

- Introduction.
- Super conductivity.
- Properties of Super conductors.
- BCS Theory (Qualitative).
- Types of Super conductors.
- High T_C Super conductors.
- Applications of Super conductors.

Introduction:

- ***Superconductors***, materials that have no resistance to the flow of electricity, are one of the last great frontiers of scientific discovery.
- In 1911 superconductivity was first observed in mercury by Dutch physicist Heike Kamerlingh Onnes of Leiden University When he cooled it to the temperature of liquid helium, 4 degrees Kelvin (-452F, -269C), its resistance suddenly disappeared.
- In 1913, he won a Nobel Prize in physics for his research in this area.
- Super conducting materials have extra ordinary.

  electrical and magnetic characteristics.
- Super Conducting materials have many important.

  applications in the field of engineering & technology.

Super conductivity:

- *Definition:* The phenomenon of sudden disappearance of electrical resistance in a material, when it is cooled below a certain temperature is known as ***Super conductivity.***
- The temperature at which a material at normal conducting state changes into super conducting state is known as transition temperature or critical temperature (T_C).

T_C of a super conducting element is in the range of 0K to 9.5K.

S.No	Element	T_C(K)
1.	Indium(In)	3.40
2.	Mercury(Hg)	4.15
3.	Niobium Tin (Nb_3Al)	17.5
4.	Niobium Titanium (NbTi)	10.0

Superconductivity

✓**Superconductivity** is a phenomenon of exactly zero electrical resistance and expulsion of magnetic flux fields occurring in certain materials, called **superconductors,** when cooled below a characteristic critical temperature.

✓It was discovered by Dutch Physicist Heike Kamerlingh Onnes on April 8, 1911.

✓A **superconductor** is an element or metallic alloy which, when cooled below a certain threshold temperature, the material dramatically loses all its electrical resistance.

In principle, **superconductors** can allow electrical current to flow without any energy loss (although, in practice, an ideal **superconductor** is very hard to produce). This type of current is called a supercurrent.

The threshold temperature below which a material transitions into a superconductor state is designated as T_c, which stands for critical temperature. In principle, **superconductors** can allow electrical current to flow without any energy loss (although, in practice, an ideal **superconductor** is very hard to produce). This type of current is called a supercurrent.

The threshold temperature below which a material transitions into a superconductor state is designated as T_c, which stands for critical temperature.

Mercury was historically the first to show **superconductivity**, and it is an **example** of a Type I **superconductor**. Its practical usefulness is limited by the fact that its critical magnetic field is only 0.019 T, so the amount of electric current it can carry is also limited.

In a **superconductor**, the electric resistance is equal to zero. This is why an electric current can circulate forever in a superconducting ring even when the battery has been unplugged! This is how magnetic fields are created in MRIs.

It might seem odd that a battery could create a low voltage electric current at the terminals of a **superconducting** network, since the voltage should be equal to zero because of the absence of electric resistance.

CRITICAL TEMPERATURE or TRANSITION TEMPERATURE

In a **superconductor,** below a temperature called the “critical temperature”, the electric resistance very suddenly falls to zero. At zero resistance, the material conducts current perfectly.

This is incomprehensible because the flaws and vibrations of the atoms should cause resistance in the material when the electrons flow through it.

However, in a **superconductor,** the electric resistance is equal to zero although the flaws and vibrations still exist.

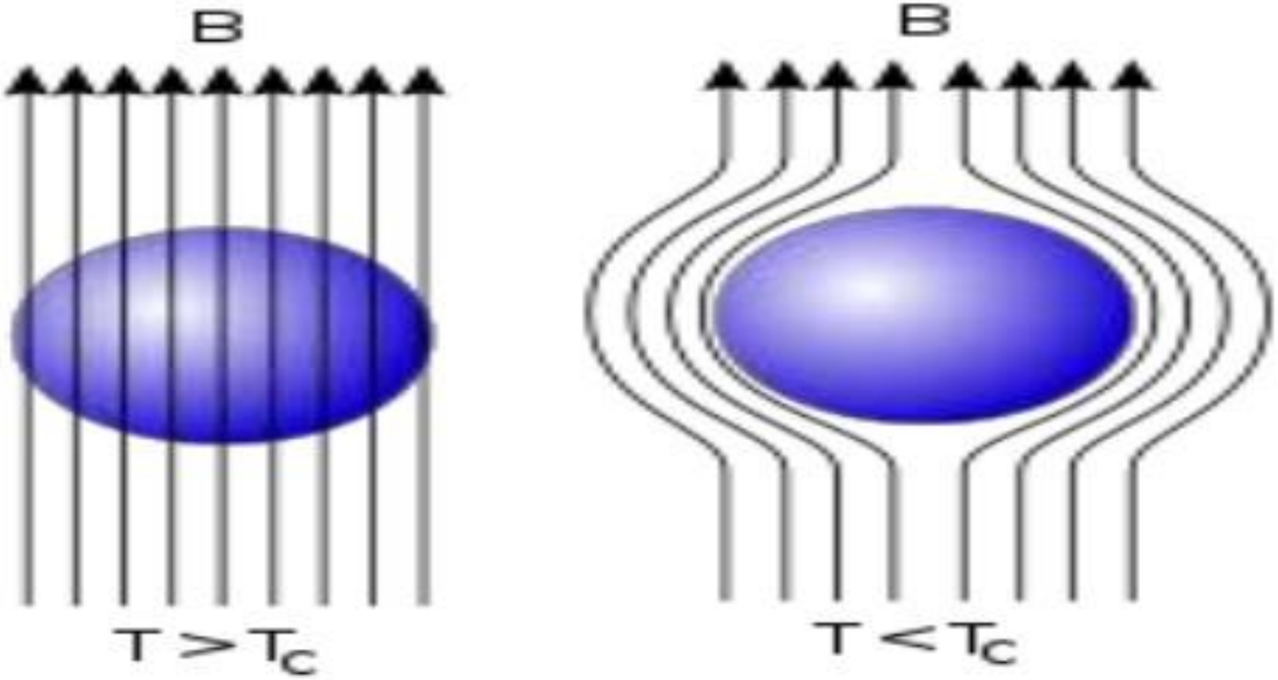
Meissner effect

The German Physicists Walther **Meissner** and Robert Ochsenfeld discovered this phenomenon in 1933 by measuring the magnetic field distribution outside **superconducting** tin and lead samples.

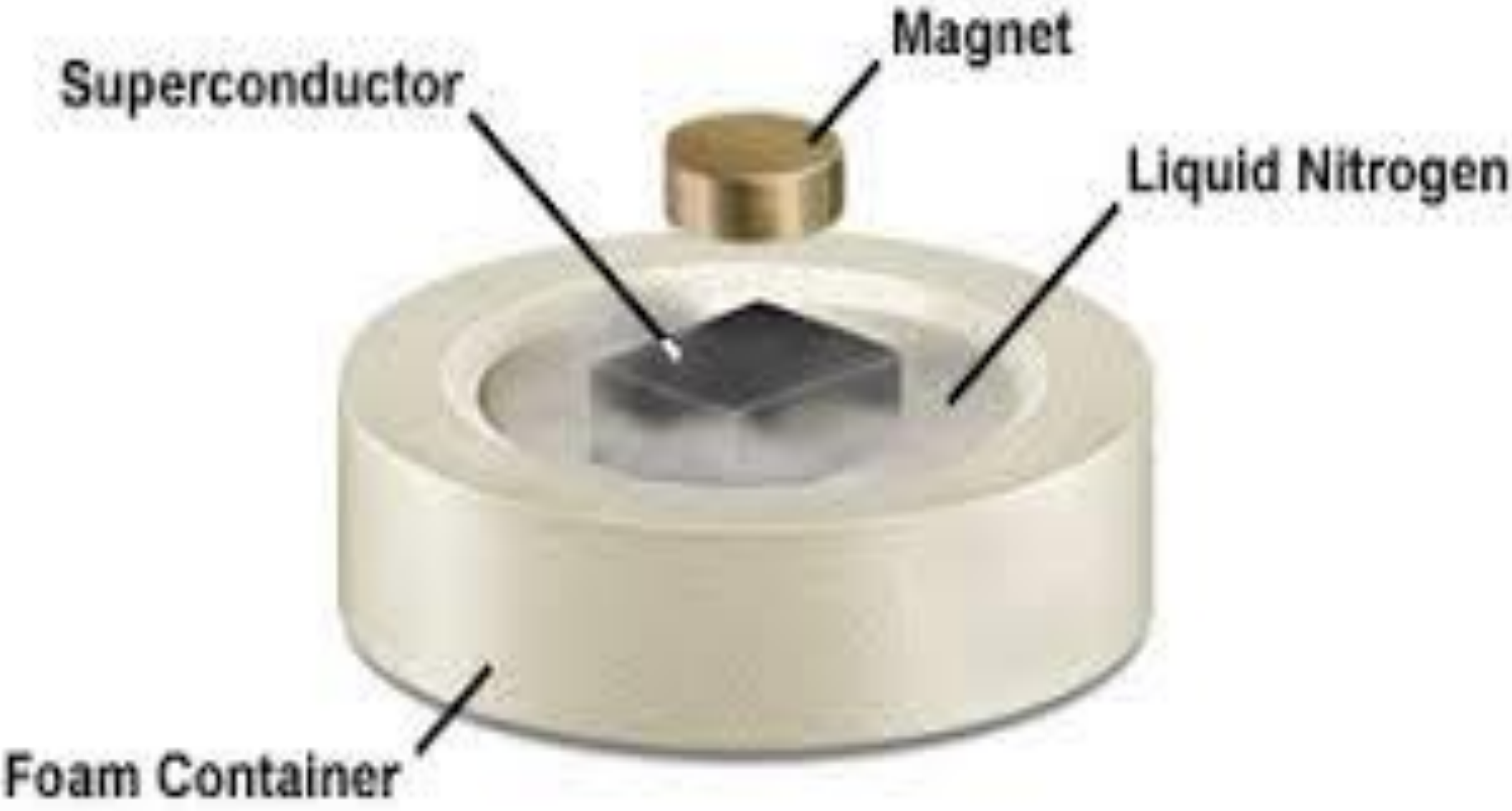
A **superconductor** with little or no magnetic field within it is said to be in the **Meissner** state.

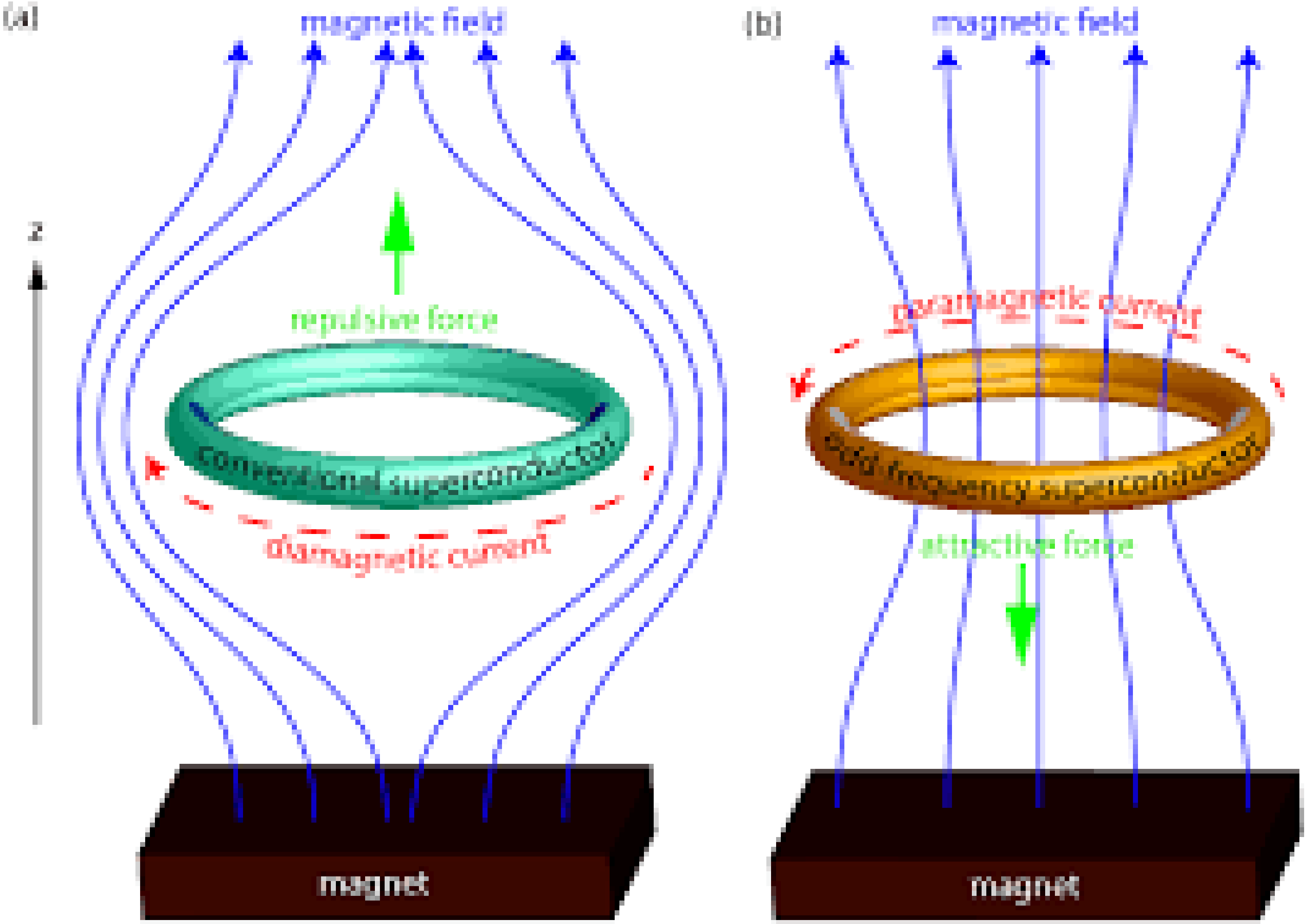
MEISSNER EFFECT

- The phenomenon of exclusion of magnetic flux or ejection of lines of magnetic induction from the interior of bulk superconductors, when they are cooled below the transition temperature is called Meissner's effect.



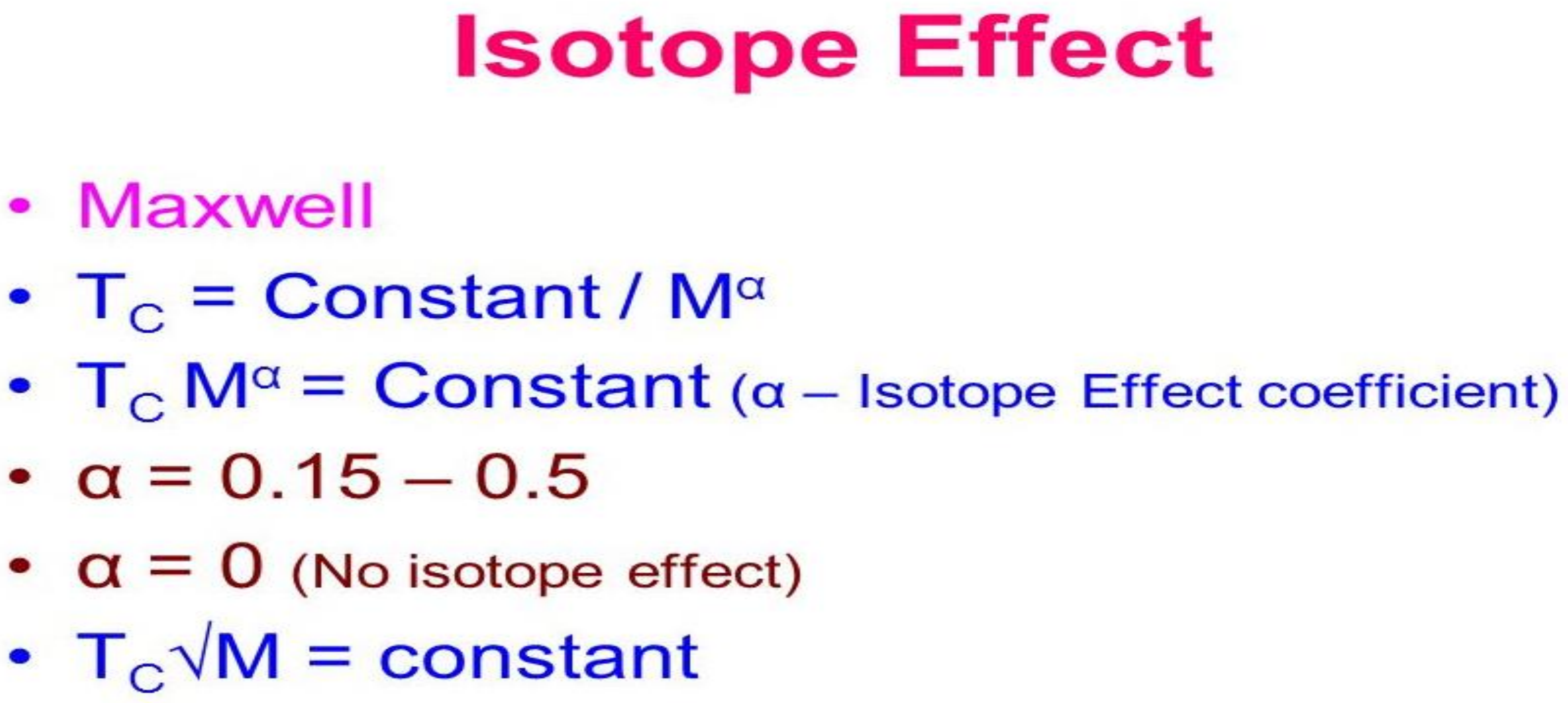
The Meissner Effect




(a)
magnetic field
z
repulsive force
conventional superconductor
diamagnetic current
magnet
(b)
magnetic field
paramagnetic current
odd-frequency superconductor
attractive force
magnet

The BCS theory reproduces the isotope effect, which is the experimental observation that for a given superconducting material, **the critical temperature is inversely proportional to the mass of the isotope used in the material**.

The isotope effect has played an important role in establishing **electron–phonon interaction** as the dominant interaction in conventional superconductors



Isotope Effect

- Maxwell
- T_C = Constant / M^α
- $T_C M^\alpha$ = Constant (α – Isotope Effect coefficient)
- $\alpha = 0.15 – 0.5$
- $\alpha = 0$ (No isotope effect)
- $T_C\sqrt{M}$ = constant

Properties of Super conductors:

- Isotope Effect:

  - In most of the cases, the isotope of a super conducting element is also a super conductor.

  - T_C of a heavier isotope is lower than that of a lighter isotope.

  - Maxwell found that T_C are inversely proportional to tha atomic masses of the isotopes of a single super conductor.

Types of Super conductors.

- Based on the magnetization behavior of super conductors in an external magnetic field, they are classified into two types,

  (i) Type – I super conductors.

  (ii) Type – II super conductors.

(i)Type – I super conductors: In this super conductor, the magnetic field is totally expelled from the interior of the material below a certain magnetising field H_C. At H_C, the material loses its superconductivity abruptly and the magnetic field penetrates fully(Soft super conductors).

(ii)Type – I super conductors: In which the material losses its magnetisation gradually rather than suddenly (Hard super conductors).

- Based on the super conducting transition temperatures, the super conductors are classified into two types,

  (i) Low – temperature super conductor.

  If T_C is low, less than 20K such super conductors are called as Low – Temperature super conductors. They are also known as elemental super conductors. It is not in practical use due to ultra-low transition temperature.

  (ii) High – temperature super conductor.

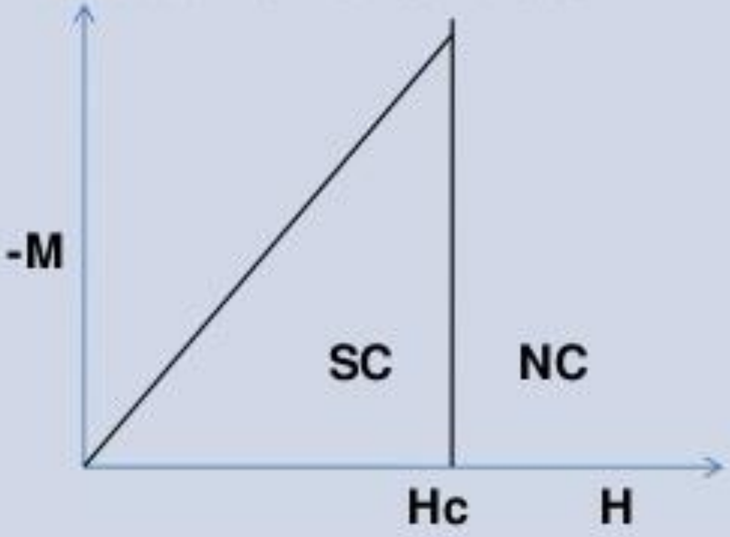
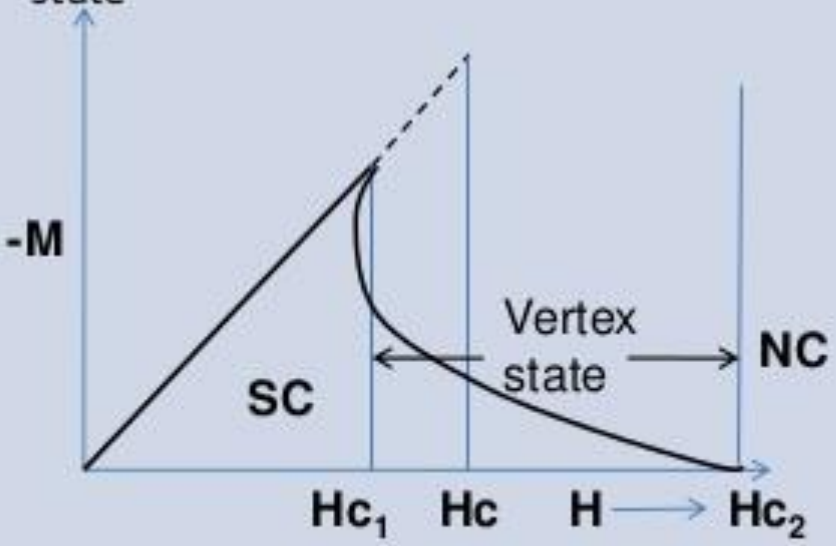
TYPES OF SUPERCONDUCTORS

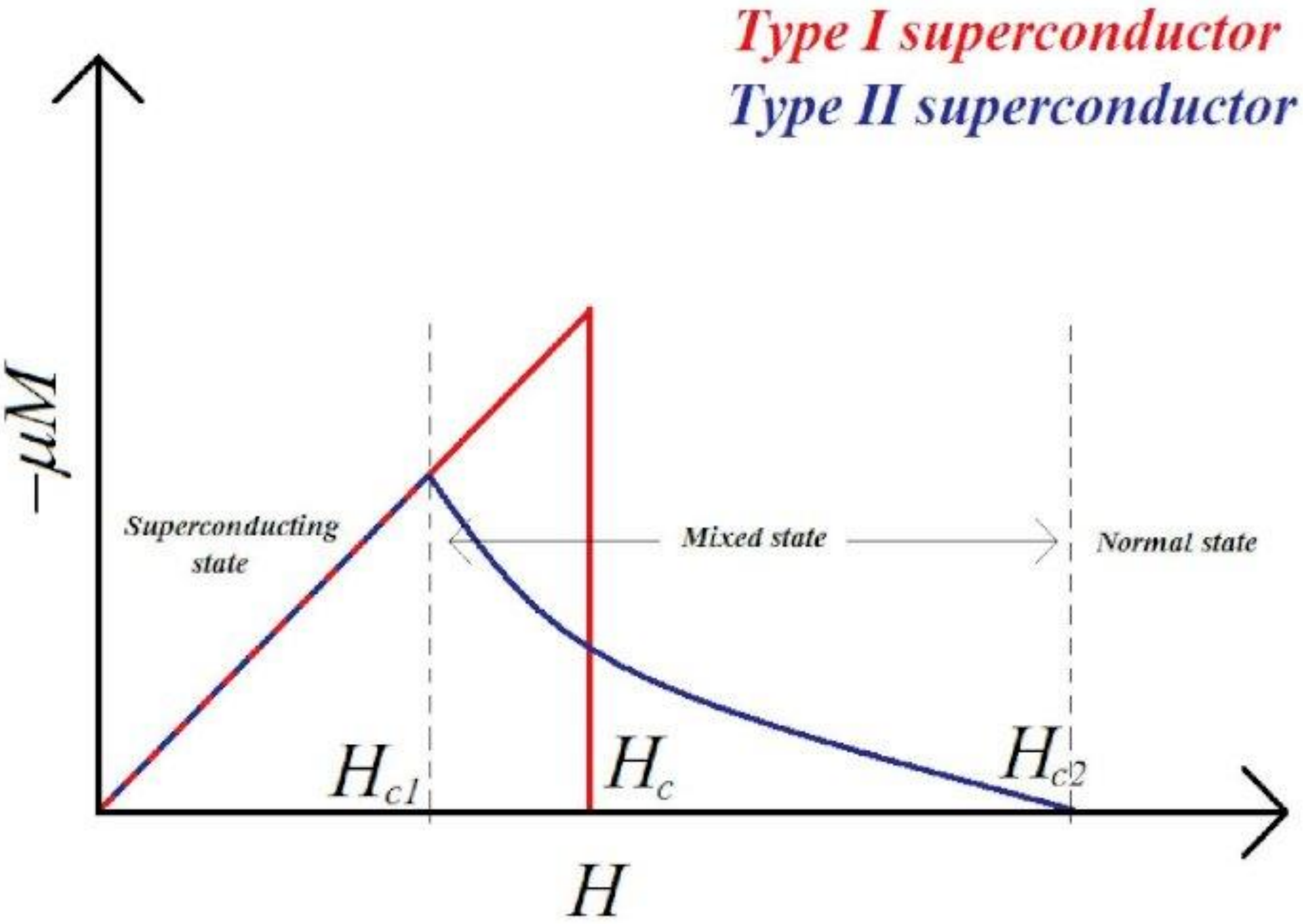
Type I **superconductors** act as conductors at room temperature, but when cooled below T_c, the molecular motion within the material reduces enough that the flow of current can move unimpeded.

Type 2 **superconductors** are not particularly good conductors at room temperature, the transition to a **superconductor** state is more gradual than Type 1 **superconductors.**

The mechanism and physical basis for this change in state is not, at present, fully understood. Type 2 **superconductors** are typically metallic compounds and alloys.

Classification of Superconductors:

Type-I or Soft superconductor	Type-II or Hard superconductor
1. Meissner effect is complete.	1. Meissner effect is incomplete.
2. At a sharp value of critical magnetic field, transition from SC to NC occur	2. Two values of critical magnetic field, at Hc_1 penetration of magnetic lines start and at Hc_2 penetration is completed. In between these two values the SC remains in a vertex state
	
3. Low value of Critical magnetic field, hence can be destroyed easily	3. SC property stays for a longer time large value of critical field , Hc2=100 Hc1
4. Not fit for practical application	4. Useful for practical application
5. Coherence length large, penetration depth less	5. Coherence length small, penetration depth large
Ex; **Pb, Sn, Hg, Cr, Al**	


Type I superconductor
Type II superconductor
$-\mu M$
Superconducting state
Mixed state
Normal state
H_{c1}
H_c
H_{c2}
H

The **London equations**, developed by brothers Fritz and Heinz **London** in 1935, relate current to electromagnetic fields in and around a **superconductor.** Arguably the simplest meaningful description of superconducting phenomena, they form the genesis of almost any modern introductory text on the subject.

BCS theory. ... The **theory** describes superconductivity as a microscopic effect caused by a condensation of Cooper pairs into a boson-like state. The **theory** is also used in nuclear physics to describe the pairing interaction between nucleons in an atomic nucleus.

The **Josephson effect** is the phenomenon of supercurrent—i.e. a current that flows indefinitely long without any voltage applied—across a device known as a **Josephson junction** (JJ), which consists of two **superconductors** coupled by a weak link. ... The **Josephson effect** is an example of a macroscopic quantum phenomenon.

Magnetic levitation (maglev) is a relatively new transportation technology in which non-contacting vehicles travel safely at speeds of 250 to 300 miles-per-hour or higher while suspended, guided, and propelled above a guideway by magnetic fields.

The guideway is the physical structure along which maglev vehicles are levitated. Various guideway configurations, e.g., T-shaped, U-shaped, Y-shaped, and box-beam, made of steel, concrete, or aluminum, have been proposed.

There are three primary functions basic to maglev technology: (1) levitation or suspension; (2) propulsion; and (3) guidance.

In most current designs, magnetic forces are used to perform all three functions, although a nonmagnetic source of propulsion could be used. No consensus exists on an optimum design to perform each of the primary functions.

The isotope effect in superconductors is usually summarized by giving the observed values of p in the equation MpTc=constant, where M is the isotopic mass and Tc the superconducting transition temperature. Fröhlich predicted the value p=12, but the measurements in some instances show deviations from this prediction. An explanation of the deviation of p from ½ is offered based on an analog of Wien's displacement law applicable to the vibration spectrum of real crystal lattices. The departure of p from the value ½ is attributed to the departure of the frequency spectrum from a simple power law.

For many superconducting elements, p may be estimated from specific heat data, when such data are available to the desired degree of accuracy. A value of p is calculated for Sn which is in good agreement with some of the experiments. The large value 0.73 observed for Pb is shown to be reasonable. The values of p for the other superconducting elements are discussed. It is concluded that the observed deviations of p from ½ are not necessarily in conflict with the theories of Fröhlich and Bardeen.


MT
1
Shanghai Transrapid

Properties of Super conductors:

- Zero electrical resistance:

  - The electrical resistance of the superconductors of the superconductor is zero below the transition temperature (T_C).

  - This property of Zero electrical resistance is known as

  'defining property' of a super conductor.

- Effect of Magnetic Field:

  - Below T_C superconductivity can be destroyed by the application of a strong magnetic field.

  - Minimum magnetic field strength required to destroy the super conducting property at any temperature is known as Critical magnetic field (H_C),

ield at 0K.

T_C

tem

T is

$$H_C = H_0 \left[1 - \left(\frac{T}{T_c} \right) \right]$$

Applications of Super conductors:

- Cryotron:

  - Cryotron is a magnetically operated current switch.

- Magnetic levitation:

  - When a super conducting material shows the Meissner effect. Due to this effect, super conducting materials strongly repel external magnets. This leads to a levitation effect.

  - When a magnet is placed over a super conductor, it floats. This phenomenon is known as Magnetic Levitation.

  - Magnetic levitated Train(Maglev train)

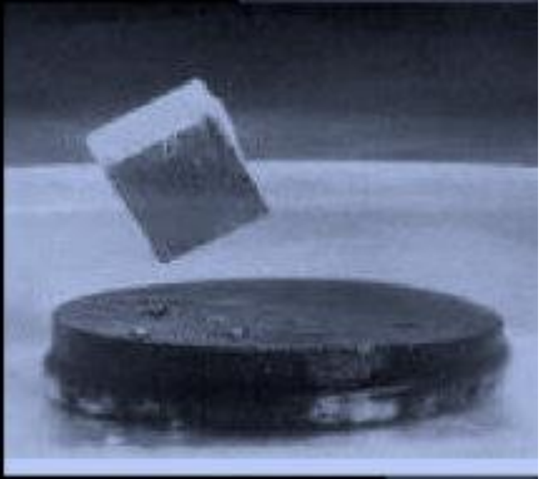
- Additional applications:

  - Super conducting Magnets.

  - Electrical Machines.

  - Power cables.

  - Computer memory devices.

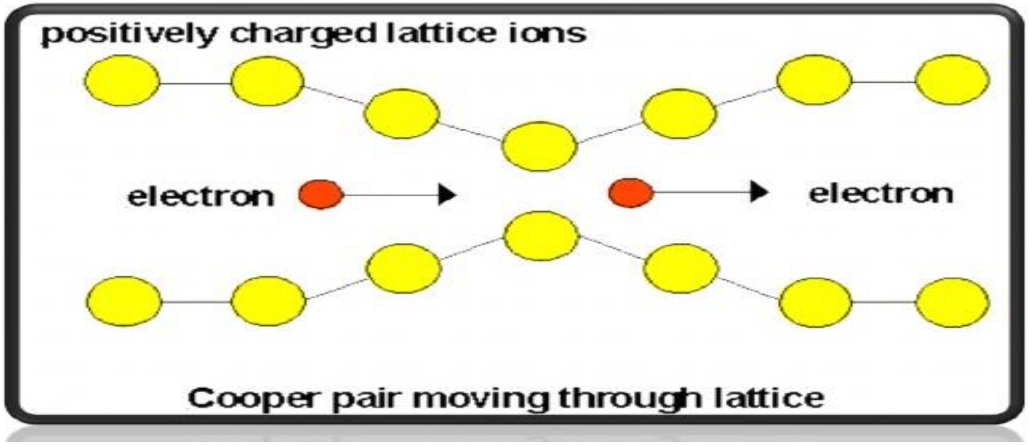


In conductors current flows by the movement of individual electrons. In superconductive materials current flows by the movement of pair or electron.

This electron pair is named as COOPERPAIR

A Cooper pair is two electrons that are bound together at low temperatures in a certain manner. First described in 1956 by American physicist **Leon Cooper.**

When electrons are passing through the superconductive material its atoms experiences the deformation. This deformation helps the electrons to form pair and move through the lattice.



Applications of Superconductors

MEDICAL:

Biotechnical engineering

Nuclear Magnetic Resonance (NMR)

Diagnosis of brain tumo

INDUSTRIAL:

Separation

Magnets

Sensors & Transducers

Magnetic Shielding

ELECTRONICS:

SQUIDs

Transistors

Josephson Junction Devices

Circuitry Connections

Particle Accelerators

Sensors

Memory Storage Element inComputers

Transportation:

Magnetically Levitated Vehicles

Marine Propulsion

Power Generation:

Motors

Generators

Energy Storage

Transmission

Fusion

Transformers and Inductors

Applications of Super conductors:

- SQUID :

  -SQUID stands for Super conducting QUantum Interference Device.

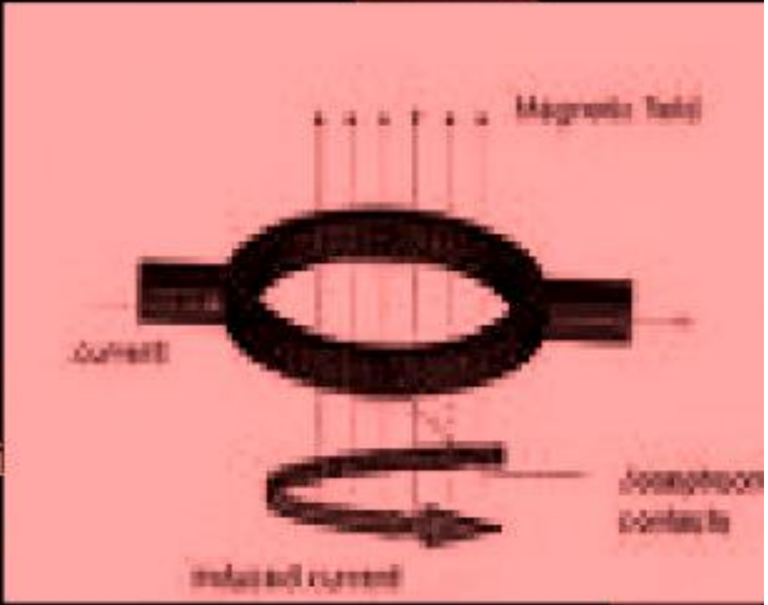
  -It is an ultra-sensitive instrument used to measure very weak magnetic field of the order of 10^{-14} tesla

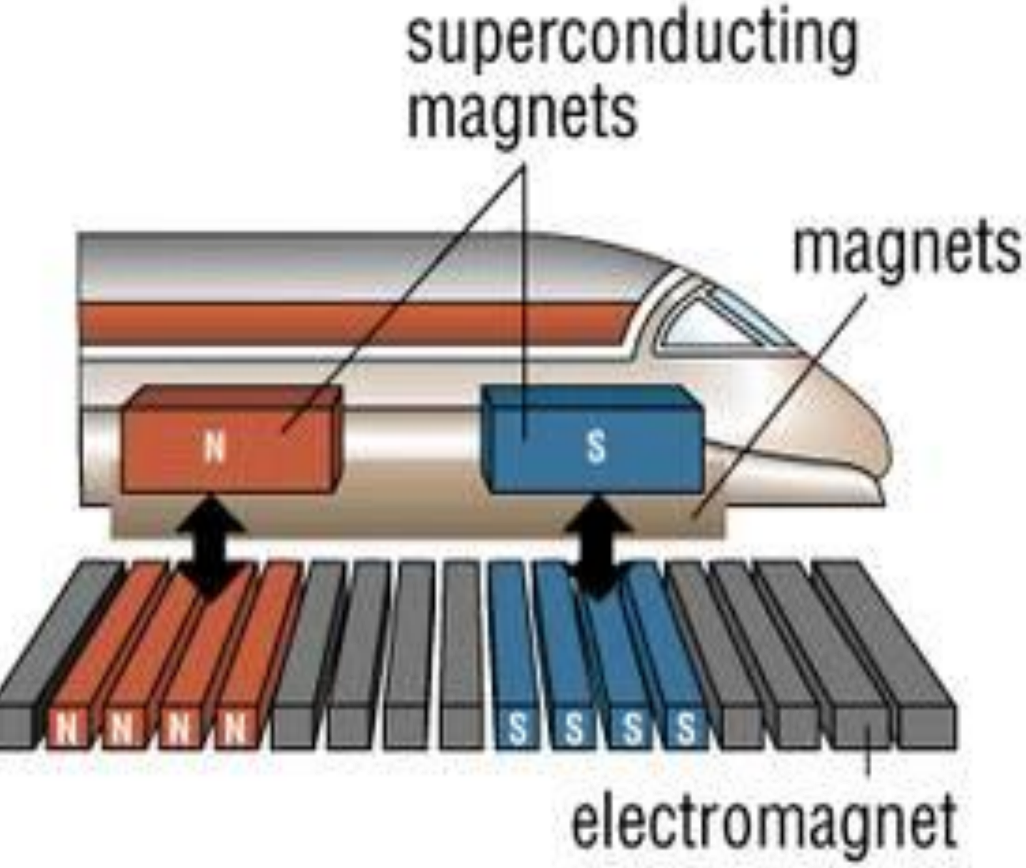
Application:

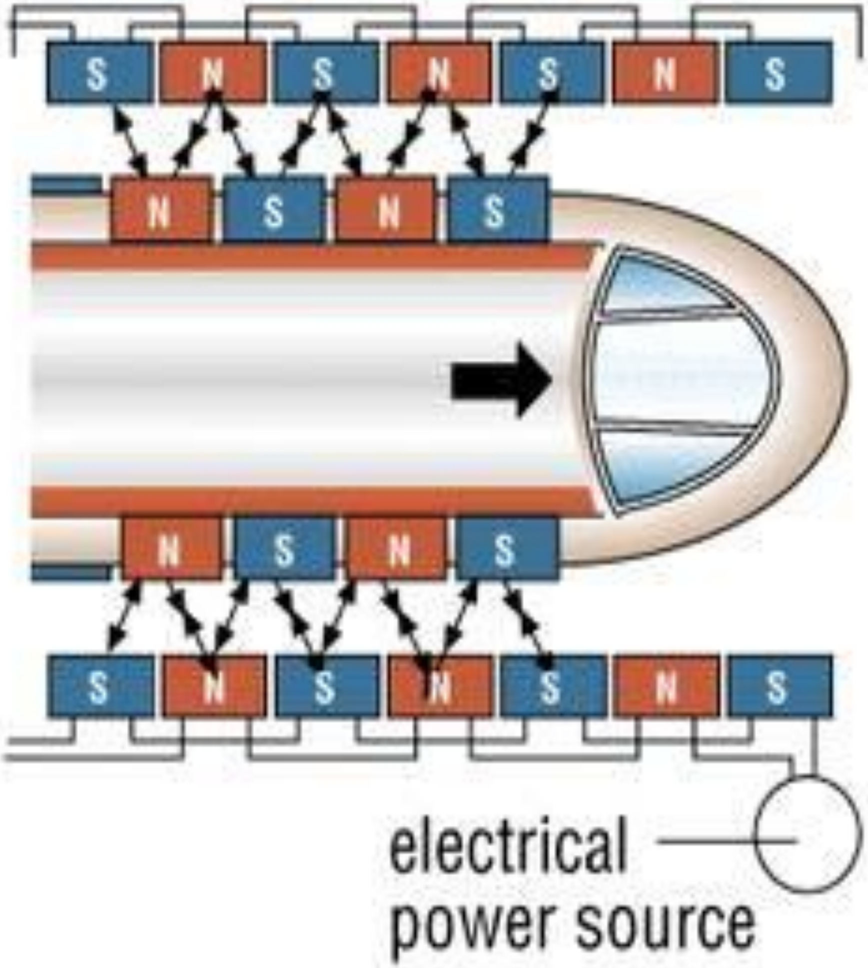
- SQUID can be used to detect the variation of very minute signals in terms of quantum flux.

- It can also be used as storage device for magnetic flux.

-SQUID is useful in the study of earth quakes, removing paramagnetic impuri detection of magnetic signals from the brain and heart.




superconducting magnets
magnets
N
S
N N N N
S S S S
electromagnet


S N S N S N S
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electrical power source

Example 7.1

The superconducting transition temperature of Lead is 7.26 K. The magnetic field at O K is 64 × 10^3 A/m. Determine the critical field at 5 K

$$H = H_o \left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

$$= 64 \times 10^3 \left[1 - \left(\frac{5}{7.26}\right)^2\right]$$

$$= 33.64 \times 10^3 \text{ A/m}$$

Example 7.2

The transition temperature of mercury with an atomic mass of 200.59 amu is 4.153 K. Determine the transition temperature of are of its isotopes $80^{\mathrm{Hg}^{204}}$ The transition temperature of superconducter is related to its isotopic mass as $T_C \infty \frac{1}{\sqrt{M}}$

Which gives, $$\frac{T_{c2}}{T_{c1}} = \sqrt{\frac{M_1}{M_2}}$$

$$T_{c2} = T_{c1} \cdot \sqrt{\frac{M_1}{M_2}} = 4.153 \sqrt{\frac{200.59}{204}} = 4.118 \text{ K.}$$

Example 7.3

Prove that superconductors are perfect diamagnetic in nature.

For a magnetic material, the flux density is given by $B = \mu_0 (M + H)$

For a superconducting material, $B = 0$, (ie) $0 = \mu_0 (M + H)$

$$M + H = 0$$

$$M = -H$$

Susceptibility $$\chi = \frac{M}{H} = -1$$

For a diamagnetic material, the susceptibility is negative. So superconductors are perfect diamagnetic in nature.

Example 7.4

The critical temperature of mercury is 4.2 K. Calculate the energy gap in electron volts at T = 0 K.

The Cooper pair binding energy or energy gap $E_g = 3\, k_B\, T_C$

$$= 3 \times 1.38 \times 10^{-23} \times 4.2$$

$$= 1.7388 \times 10^{-22} \text{ J}$$

$$= 1.0867 \times 10^{-3} \text{ eV}$$

Example 7.5

Example 7.5

Calculate the temperature of a proton whose energy $E_g = 1.8 \times 10^{-22}$ J is just sufficient to break up Cooper pairs in mercury of $T = 0$ K. In what region of the electromagnetic spectrum are such photon found?

The Cooper pair binding energy or energy gap $E_g = 1.8 \times 10^{-22}$ J

$$E_g = hv = nc/\lambda$$

$$\lambda = \frac{hc}{E_g} = \frac{6.6\times10^{-34}\times3\times10^{8}}{1.8\times10^{-22}} = 1.1\times10^{-3}m$$

Obviously there protons are in a short wavelength which is part of microwave region.