UNIT IV

Chapter 2

Superconductivity

Introduction:

Superconductivity is the phenomenon in which the electrical resistance of certain materials becomes zero at very low temperatures.

For example, the electrical resistance of pure mercury suddenly drops to zero, when it is cooled below 4.2 Kelvin and becomes a superconductor. This was first observed by the Dutch physicist, Heike KammerlinghOnnes on April 8, 1911. Further, the theory of super conductivity was developed in 1957 by three American physicists-John Bardeen, Leon Cooper, and John Schrieffer, through their Theories of Superconductivity, known as the **BCS Theory.**

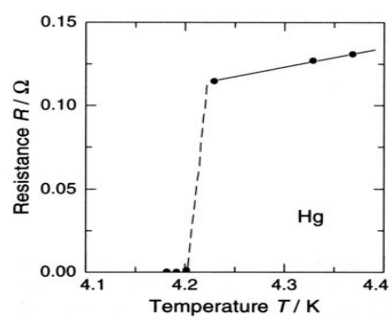


Figure: The resistance of mercury measured by Onnnes.

Superconductors:

A Superconductor is a material that loses all its resistance to flow of electric current when it is cooled below a certain low temperature.

Examples:

Material	Type
Tungsten	Metal
Zinc	Metal
Aluminum	Metal
Tin	Metal
Mercury	Metal
Lead	Metal
NbTi	Inter metallic compound
Nb_3Sn	Inter metallic compound
Nb_3Ge	Inter metallic compound
$YBa_2Cu_3O_7$	Ceramic
TlBaCaCuO	Ceramic

General properties of a superconductor:

- Superconductivity is the physics of the Cooper Pairs. It occurs due to the movement of electron pairs called cooper pairs through the lattice points. These copper pairs are formed due to the **electron–lattice–electron interaction.**
- Superconductivity is a low-temperature phenomenon.
- The electrical resistivity of a superconducting material is very low and is the order of 10^{-5} Ωcm.
- The temperature at which a normal conductor loses its resistivity and becomes a superconductor is known as transition temperature or critical temperature (T_C). Different materials will have different critical temperatures.
- When impurities are added to superconducting elements, the superconducting property is not lost, but the T_c value is lowered.
- The critical temperature(Tc) decreases with increasing isotopic mass **M**. This effect is known as the isotope effect.

$$\text{i.e.,} T_c \,\alpha\, M^{\frac{-1}{2}}$$

- The magnetic field at which super conductor loses its super conductivity and becomes normal conductor is known as critical magnetic field H_c. Different materials will have different Hc values.
- Super conductors do not allow magnetic flux through them and behave as a diamagnetic. This property of expulsion of magnetic flux is known as meissner effect.
- Ferromagnetic materials like Fe,Co,Ni do not show superconductivity.
- The magnetic flux (Φ) lines passing through a super conducting ring due to persistent current is quantized in terms of integral multiples of $\frac{h}{2e}$

$$\Phi = \frac{nh}{2e}$$

Where n = 1, 2, 3………

Where $\frac{h}{2e}$ is known as fluxion (or) fluxiod. = 2.07 X 10^{-15} Weber's.

Effect of temperature-Critical temperature:

In the year 1911, kammerlighOnnes observed that the electrical resistance of pure mercury suddenly drops to zero, when it is cooled below 4.2 Kelvin and becomes a superconductor.

The temperature at which a normal conductor loses its resistivity and becomes a super conductor is known as transition temperature or critical temperature (T_C) as show in fig.

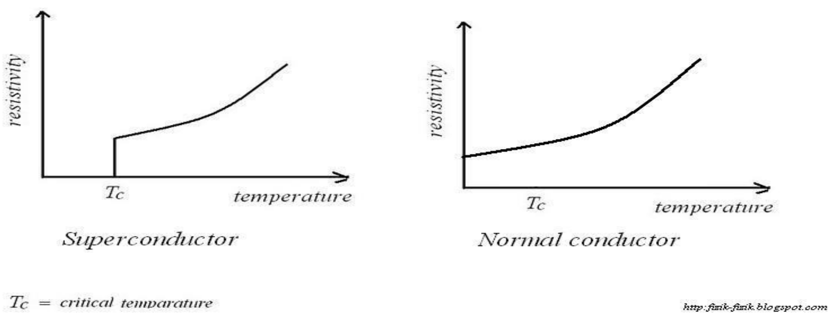


Fig: The variation of electrical resistance with temperature

Figure shows the variation of electrical resistivity with temperature. Below $T_C$the material is said to be in the superconducting state andabove $T_C$the material is said to be in non- superconducting state (i.e., normal state).The value of this critical temperature varies from material to material.

Material	**Type**	**T_c(K)**
Tungsten	Metal	0.01
Zinc	metal	0.88
Aluminum	metal	1.19
Tin	metal	3.72
Mercury	metal	4.15
Lead	metal	7.2
NbTi	Inter metallic compound	9.5
Nb_3Sn	Inter metallic compound	21
Nb_3Ge	Inter metallic compound	23.2
$YBa_2Cu_3O_7$	ceramic	90
TlBaCaCuO	ceramic	125

High temperature superconductors:

Super conductors are divided into two types based on their transition temperatures.

a) Low T_C super conductors

b) High T_C super conductors

If a transition temperature is low (below 30 K), then the superconductors are known as low temperature superconductors.

If a transition temperature is high (above 30 K), then the superconductors are known as high temperature superconductors.

The first high-T_c superconductor was discovered in 1986 by Georg Bednorz and Muller, in ceramics. They found that the mixed metallic oxide of lanthanum-barium-copper ($La_1Ba_2Cu_3O_7$) exhibited superconductivity at about 30 K.

Further it has been developing by many scientists and co-research scholars.

Some examples are:

S.No	Material	T_C K
1	Ba-pbBi-O_3	38
2	$YBa_2Cu_3O_7$	92
3	$Bi_2Sr_2CaCu_2O_8$	85
4	$Bi_2Sr_2Ca_2Cu_3O_6$	110
5	$Tl_2Ba_2CuO_6$	80
6	$Tl_2Ba_2CaCu_2O_8$	108
7	$Tl_2Ba_2Ca_2Cu_3O_{10}$	125
8	$TlBa_2Ca_3Cu_4O_{11}$	122
9	$HgBa_2CuO_4$	94
10	$HgBa_2CaCu_2O_6$	128
11	$HgBa_2Ca_2Cu_3O_8$	134

Properties:

Some of the properties of high T_C superconductors as follows:

1. They have high transition temperature.
2. They are brittle in nature.
3. They are highly anisotropic.
4. They are reactive, brittle and can’t be easily formed or joined.
5. They are oxides of copper in combination with other elements.
6. The hall coefficient is positive indicating that the charge carriers are holes.
7. Their behavior can’t be explained by BCS theory.

Effect of magnetic field - Critical magnetic field:

Kammerlingh Onnes observed in 1913 that superconductivity vanishes if a suffiently strong magnetic field is increased.

When a magnetic field is applied to a super conductor, then particular value of applied field and below its critical temperature, it loses super conductivity and becomes a normal conductor. This minimum magnetic field required to destroy the super conducting state is called the critical magnetic field H_C.

The critical magnetic field of a superconductor is a function of temperature. The variation of Hc with temperature is given by

$$H_C = H_0\left[1 - \left(\frac{T}{T_C}\right)^2\right]$$

Where H_C=critical magnetic field,

H_0= critical magnetic field at T=ok, and

T_C= critical temperature.

Figure shows the variation of critical magnetic field H_C as a function of temperature. The material is said to be in the superconducting state within the curve and is non super conducting (i.e., normal state) in the region the outside the curve.

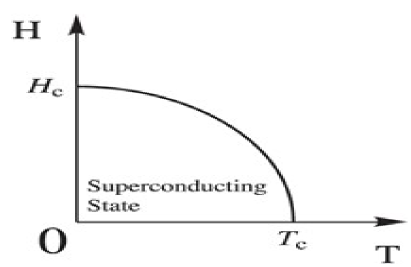


Figure: Effects of temperature and magnetic field on the superconducting state.

Meissner effect:

When the supper conducting material is placed in magnetic field, under the condition when $T \leq T_C$ and with $H \leq H_C$ the flux lines are expelled from the material. Thus the material exhibits perfect diamagnetism. This phenomenon is called as Meissner effect.

Explanation:

Consider a normal conducting material at room temperature. When a magnetic field H is applied to it, then it allows the magnetic lines of force to pass through it. Thus we have a magnetic tic field B in a conductor as shown in fig (1).

Now, when the material is cooled below its critical temperature ($T \leq T_C$) and with $H \leq H_C$, thenthe magnetic lines of forces are expelled or ejected out from the material as shown in fig(2).

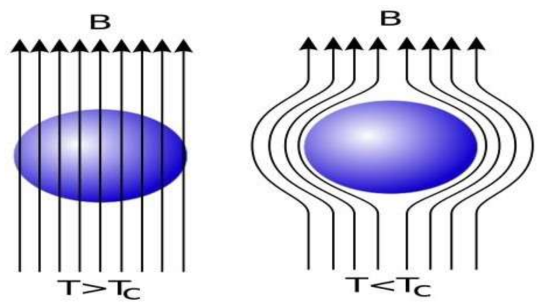


Fig (1): Normal state ($B \neq 0$ at $T > T_c$).**Fig (2): Superconducting state**. ($B=0$ at $T < T_c$)

Proof:

We know that, thetotal magnetic flux density in a normal conductor is given by

$$B= \mu_0 (M+H) \quad \ldots\ldots (1)$$

Where μ_0 is the permeability of free space$=4\pi x10^{-7}$ H/ m

M is the intensity of magnetization and, H is he4 applied magnetic field strength.

But, for superconductor B=0

Therefore, equation (1) can be written as

$$0= \mu_0 (M+H)$$

$$[\because \mu_0 \neq 0]$$

$$M+H=0$$

$$\text{or} \quad M=-H$$

$$\text{or} \quad \frac{M}{H} = -1$$

Hence,$\chi_m = \frac{M}{H} = -1$ is called the magnetic susceptibility. Thus this means that, for a superconductor the susceptibility is negative .i.e., a super conductor exhibits perfect diamagnetism.

Types of superconductors:

Depending upon their behavior in an external magnetic field, superconductors are divided into two types:

1) Type I superconductors and 2) Type II superconductors

Let us discuss them one by one:

Type I superconductors:

Those superconductors which loose their superconductivity very easily or abruptly when placed in the external magnetic field are known as Type I superconductors.

Explanation:

When the super conductor is kept in the magnetic field and if the field is increased the super conductor becomes a normal conductor abruptly at critical magnetic field as shown in fig. These types of materials are termed as Type – I super conductors. After Hc, the Type I superconductor will become conductor.

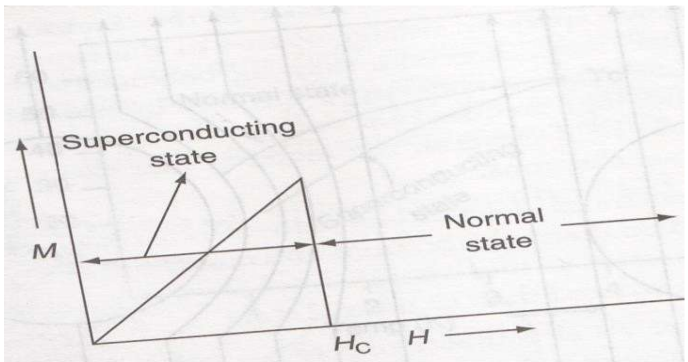


Fig: The variation of magnetization (M) with external magnetic field H in a type I Superconductor.

Properties:

- These superconductors are also known as **soft superconductors** because of this reason that is they loose their superconductivity easily and relatively small magnetic field requirement to bring them back to their normal state. These superconductors exhibit perfect and complete Meissner effect.
- Only one critical field exists for these superconductors.
- The critical magnetic field value is very low and highest value is 0.1Tesla.
- No mixed states exist in these superconductors.
- Materials with pure form are Type I superconductors.
- Examples: :

Material	Hc(Tesla)
Zinc	0.0054
Aluminum	0.0105
Mercury	0.014
Stransiam	0.03
Lead	0.08

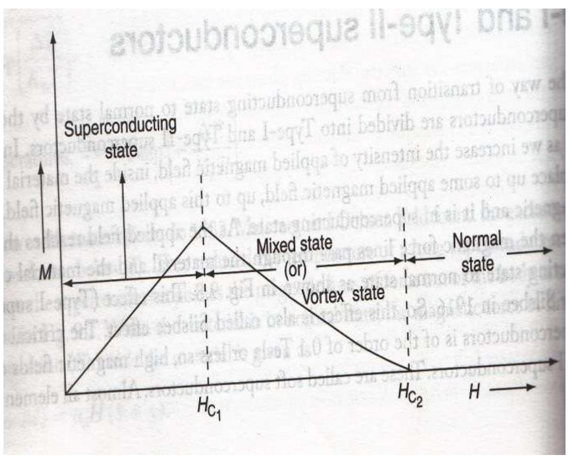
Type II superconductors:

Those superconductors which lose their superconductivity gradually but not easily or abruptly when placed in the external magnetic field are known as Type II superconductors.

Explanation:

When the super conductor is kept in the magnetic field and if the field is increased, below the lower critical field Hc_1, the material exhibits perfect diamagnetism i.e., it behaves as a super conductor and above Hc_1, the magnetization decreases and hence the magnetic flux starts penetrating through the material. The specimen is said to be in a mixed state (or) vortex state between Hc_1 and Hc_2, above Hc_2 (upper critical field) it becomes a normal conductor as shown in fig.

Type – II Super conductors are also called as hard super conductors because of relatively small magnetic field requirement to bring them back to their normal state.



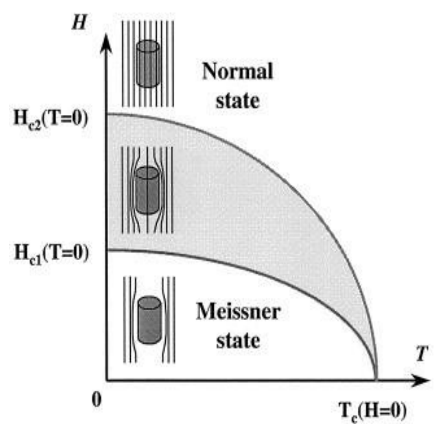


Fig: The variation of magnetization (M) with external magnetic field H in a type II Superconductor.

Properties:

- These superconductors are also known as **hard superconductors** because of this reason that is they lose their superconductivity gradually but not easily and relatively large magnetic field requirement to bring them back to their normal state.
- These superconductors exhibit Meissner effect but not completely.
- Two critical fields Hc_1 (lower critical magnetic field) and Hc_2 (upper critical magnetic field) exist for these superconductors.
- The critical magnetic field value is very high.
- Mixed states exist in these superconductors.
- Materials with impurities or alloys are of Type II superconductors.

- Examples:

Material	Hc (Tesla)
NbN	8×10^6
Babi3	59×10^3
Nb_3Sn	24.5
Nb_3Ge	38
$Y_1Ba_2Cu_3O_7$	300

Occurrence of superconductivity:

Bardeen, cooper and Schrieffer (BCS) theory:

This is the first microscopic theory, based on quantum mechanics.In 1957 John Bardeen, Leon Cooper, and John Robert Schrieffer wrote a paper called 'Theories of Superconductivity'.

Principle:

According to this theory, superconductivity occurs due to the movement of electron pairs called cooper pairs through the lattice points. These cooper pairs are formed due to electron-lattice –electron interaction.

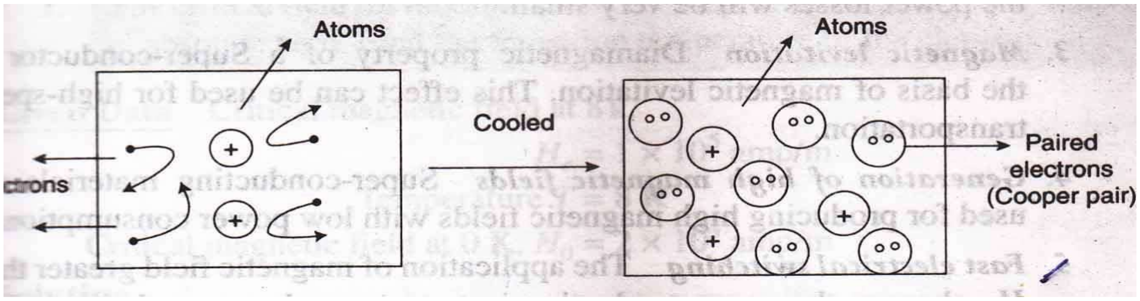
In this interaction, electrons experience a special kind of attractive interaction, overcoming the coulomb forces of repulsion between them. As result cooper pairs (electron pairs) are formed. At low temperature, these pairs move without scattering through the lattice points and as result resistance or resistivity decreases (i.e., conductivity increases).

Explanation:

Under normal condition, the ions in the lattice vibrate about their equilibrium positions due to thermal energy. These vibrations are lattice vibrations.

When electrons pass through the lattice ions in the normal state, they collide and scatter with the lattice and with each other. As a result, resistance arises in the material.

When the temperature decreases below its critical temperature, due to decrease in energy the scattering of electrons by vibrating lattice ions also decreases. As a result, electron pairs (cooper pairs) are formed. These cooper pairs move without scattering through the lattice ions and as result resistance or resistivity decreases (i.e., conductivity increases) and material becomes superconductor. **These cooper pairs are formed due to electron-lattice – electron.**



$\rho \neq 0$ when $T > Tc$ $\rho = 0$ when $T < Tc$

Fig: (a) scattering of electrons in normal state (T > Tc), b) movement of cooper pairs without scattering in superconducting sate (T < Tc).

<u>Formation of cooper pairs:</u>

<u>Electron-Lattice (phonon) - Electron interaction:</u>

According to BCS theory, suppose an electron (1st electron) moves through the lattice, it will be attracted by the positive ion core. It suffers attractive coulomb interaction. . Due to this attraction, positive ion core is disturbed and it is called as lattice distortion. This is shown in the figure below. The lattice vibrations are quantized in terms of phonons.

At that instant, if another electron (2nd electron) moves through the distorted lattice, it will be attracted by the greater concentration of positive ion core. It also suffers attractive coulomb interaction.

Therefore, the two electrons interact via lattice distortion or the phonon field, lowering the energy of electrons. This lowering of energy implies that the force between the two electrons is attractive. This type of interaction is called electron-lattice-electron interaction. This interaction can also be interpreted as electron –electron interaction through phonons.

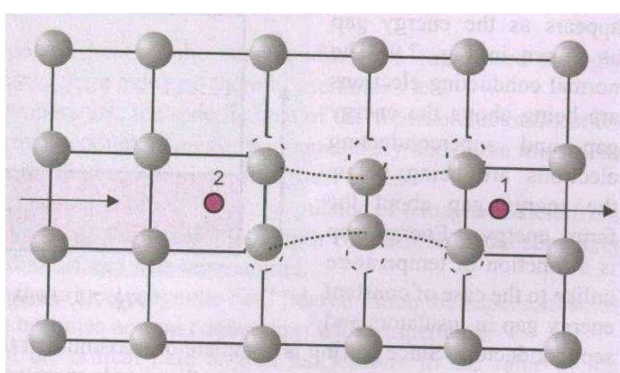
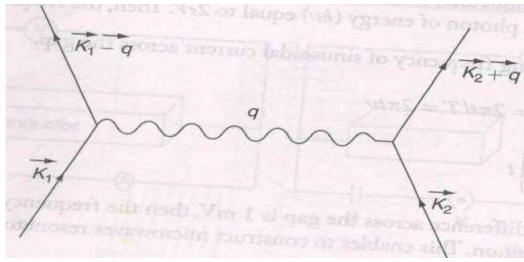


Fig: Electron-Lattice (phonon) - Electron interaction

Copper Pairs:

Cooper showed that the pair of electrons formed by the interaction between the electrons with opposite spins and momenta are known as cooper pairs. This interaction can be represented in terms of the wave vector of electrons as shown in fig.



Consider the 1st electron with wave vector **k** distorts the lattice, there by emitting a phonon of wave vector **q**. This results in the wave vector for k-q for the 1st electron.

Now, if the 2nd electron with wave vector k^I, seeks the lattice, it takes up the energy from the lattice and wave vector changes to k^I +q as shown in fig.

Two electrons with wave vectors k-q and k^I +q form a pair of electrons known as cooper pairs.

Therefore, the pair of electrons formed due to electron-lattice-electron (force of attraction) by overcoming the electron-electron (force of repulsion), with equal and opposite momentum and spins with wave vectors k-q and k^I +q, and are called cooper pairs.

Josephson Effect:

When two super conductors are separated by a very thin insulator (oxide layer of about $20A^O$), forms a Joseph junction and then cooper pairs can tunnel or penetrates through the thin insulator and constitute a small super current .This effect is called Josephson Effect.

Explanation:

Consider two superconducters which are joined together with help of a thin insulating layer and forms a junction called josephson junction.These super conductors consist of paired electrons known as cooper pairs in the superconducting state.These cooper pairs will try to penetrate or tunnel through the thin insulator and constitute a small super current as shown in fig.

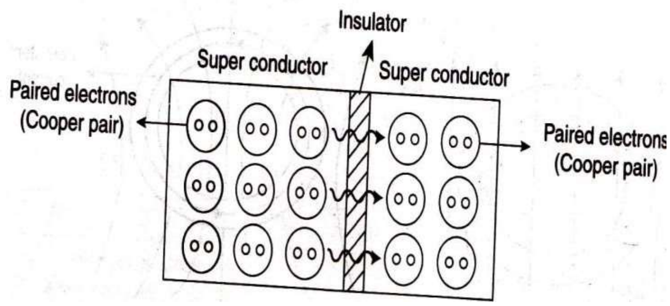


Fig: D.C. Josephson effect

Josephson Effect can be dived into two types .They are:

a) D.C. Josephson Effect
b) A.C. Josephson Effect.

D.C. Josephson Effect:

Josephson observed that the cooper pairs can tunnel from one film of superconductor into another through the thin insulator and a small direct super current flows across the junction without applied voltage across the junction. This effect is known as D.C. Josephson Effect.Josephson showed that the dc current through the in junction is given by

$$I=I_O \sin\Phi_o \text{..............................(1)}$$

Where $\Phi_o = \Phi_2 - \Phi_1$ is the phase difference the wave functions describing cooper pair4s on both sides of the barrier, and I_O is the critical current which the junction can support and is dependent on the thickness and width of the insulating layer

A.C. Josephson Effect: If we apply the voltage across the junction, then ac current is produced and is given by

$$I=I_O \sin(wt+\Phi) \text{.................................(2)}$$

Where w = angular frequency $= \frac{4\pi eV}{h}$

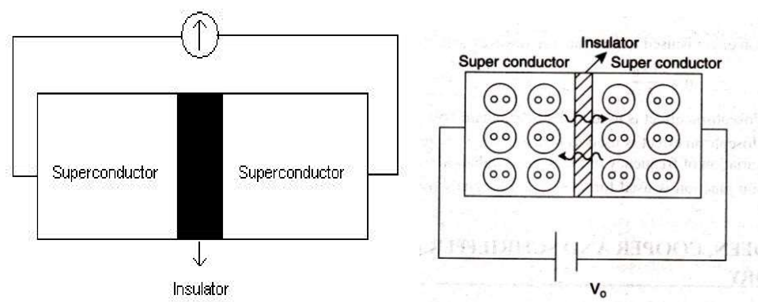


Fig: A.C. Josephson effect

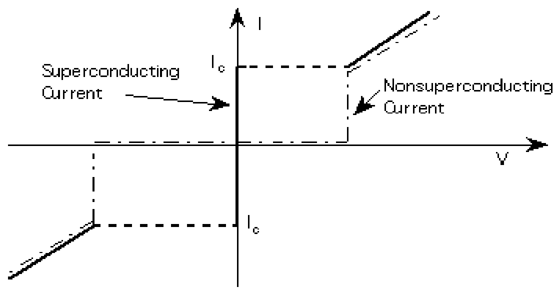


Fig: I-V characteristics of a Josephson junction

Applications:

Superconductors are used in the following applications:

1. MagneticLevitation

Magnetic levitation, **maglev**, or **magnetic suspension** is a method by which an object is suspended with no support other than magnetic fields.

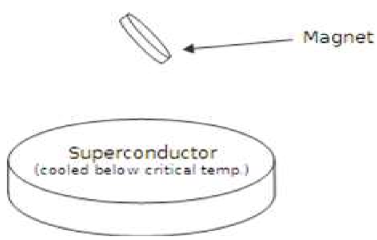
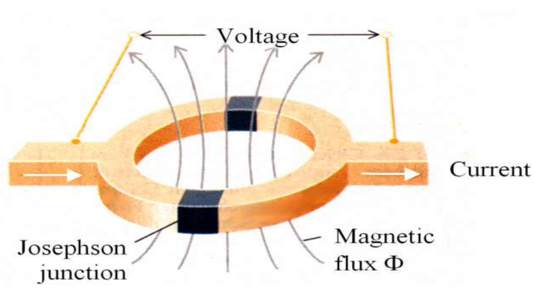


Fig: Maglev train

Magnetic levitation is used for high speed transportation.For example, Maglev (magnetic levitation) trains travel 500 km/h.These work because a superconductor repels a magnetic field so a magnet will float above a superconductor (Messiner effect)– this virtually eliminates the friction between the train and the track.

2. SQUID:

The superconducting quantum interference device (SQUID) consists of two superconductors separated by thin insulating layers to form two parallel Josephson junctions as shown fig.



Uses:

- This device used as sensitive magnetometer to detect small magnetic fields from brain and heart. Threshold magnetic field for SQUID: 10^{-14} T

  Magnetic field of heart: 10^{-10} T
  Magnetic field of brain: 10^{-13}T.
- They are used in mine detection equipment to help in the removal of landmines.

3.**Large hadron collider or particle accelerator:**

This use of superconductors was developed at the Rutherford Appleton Laboratory in Oxford shire, UK in the 1960s. The latest and biggest large hadron collider is currently being built in Switzerland by a coalition of scientific organizations from several countries. Superconductors are used to make extremely powerful electromagnets to accelerate charged particles very fast (to near the speed of light).

4. Magnetic Resonance Imaging (MRI)

MRI is a technique developed in the 1940s that allows doctors to see what is happening inside the body without directly performing surgery.

Fig:MRI scan of a human skull

5.Efficient Electricity Transportation:

Superconducting magnets are also more efficient in generating electricity than conventional copper wire generators - in fact, a superconducting generator about half the size of a copper wire generator is about 99% efficient; typical generators are around 50% efficient.