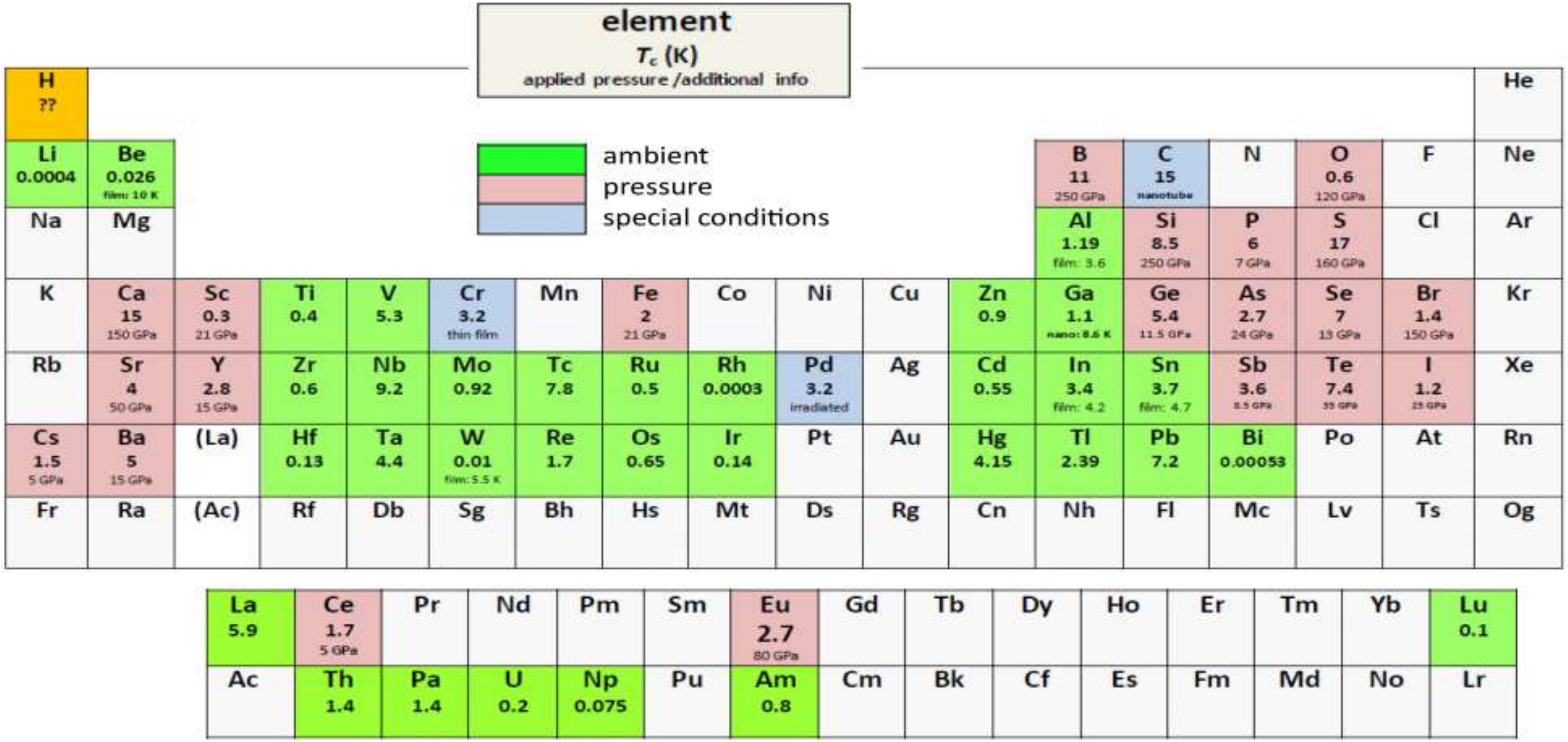
SUPERCONDUCTIVITY

INTRODUCTION TO SUPERCONDUCTORS

- It is a phenomenon observed in some metals
- The phenomenon of superconductivity was discovered by Kammerling Onnes, in 1911, when he was measuring the resistivity of mercury at low temperature.
- He observed that the electrical resistivity of pure mercury drops suddenly to zero at about 4.2K
- He concluded that mercury has passed into a new state which is called the superconducting state.
- The materials that exhibit this behaviour are called superconductors.
- **Thus superconductivity can be defined as the disappearance of the electrical resistivity at temperatures approaching 0K**


element
T_c (K)
applied pressure /additional info
ambient
pressure
special conditions
H ??
He
Li 0.0004
Be 0.026 film: 10 K
B 11 250 GPa
C 15 nanotube
N
O 0.6 120 GPa
F
Ne
Na
Mg
Al 1.19 film: 3.6
Si 8.5 250 GPa
P 6 7 GPa
S 17 160 GPa
Cl
Ar
K
Ca 15 150 GPa
Sc 0.3 21 GPa
Ti 0.4
V 5.3
Cr 3.2 thin film
Mn
Fe 2 21 GPa
Co
Ni
Cu
Zn 0.9
Ga 1.1 nano: 8.6 K
Ge 5.4 11.5 GPa
As 2.7 24 GPa
Se 7 13 GPa
Br 1.4 150 GPa
Kr
Rb
Sr 4 50 GPa
Y 2.8 15 GPa
Zr 0.6
Nb 9.2
Mo 0.92
Tc 7.8
Ru 0.5
Rh 0.0003
Pd 3.2 irradiated
Ag
Cd 0.55
In 3.4 film: 4.2
Sn 3.7 film: 4.7
Sb 3.6 8.5 GPa
Te 7.4 35 GPa
I 1.2 25 GPa
Xe
Cs 1.5 5 GPa
Ba 5 15 GPa
(La)
Hf 0.13
Ta 4.4
W 0.01 film: 5.5 K
Re 1.7
Os 0.65
Ir 0.14
Pt
Au
Hg 4.15
Tl 2.39
Pb 7.2
Bi 0.00053
Po
At
Rn
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Ra
(Ac)
Rf
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La 5.9
Ce 1.7 5 GPa
Pr
Nd
Pm
Sm
Eu 2.7 80 GPa
Gd
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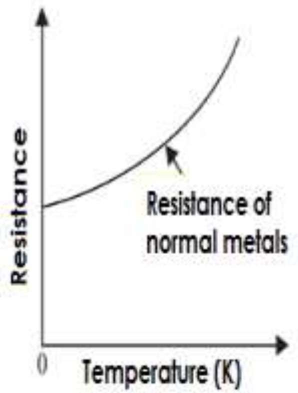
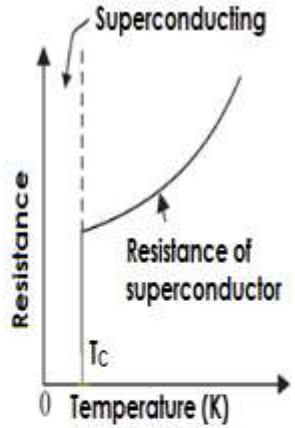
Dy
Ho
Er
Tm
Yb
Lu 0.1
Ac
Th 1.4
Pa 1.4
U 0.2
Np 0.075
Pu
Am 0.8
Cm
Bk
Cf
Es
Fm
Md
No
Lr

<u>Temperature dependence of resistivity of a superconductor</u>

- The dependence of resistivity ρ of a superconductor with temperature as shown in the figure.
- ρ in the non superconducting state decreases with decrease in temperature as in case of a normal metal upto a particular temperature T_c. At T_c, ρ suddenly drops to zero. Thus **the temperature at which the materials attain superconductivity is called critical temperature, T_c. This signifies the transition from normal state to the superconducting state.**
- The critical temperature is different for different superconductors.
- The recognition that a metal with zero resistance can carry very high currents without the loss of energy makes the practical importance of this phenomenon.





Meissner's effect

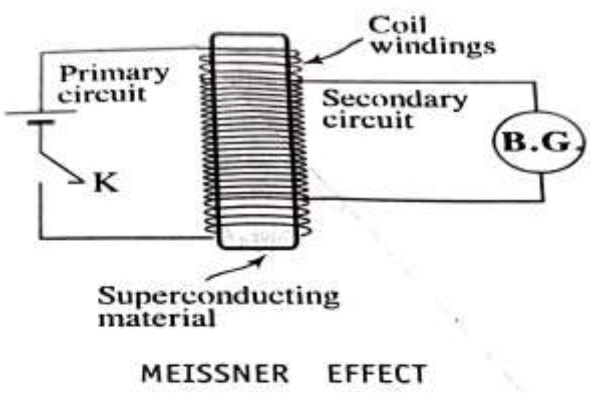
A superconducting material kept in a magnetic fiels expels the magnetic flux out of its body when it is cooled below the critical temperature and thus becomes a perfect diamagnet. This effect is called Meissner effect.

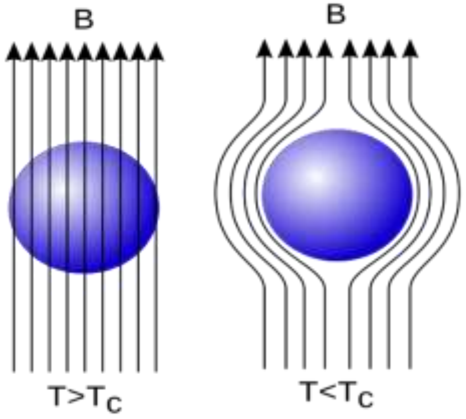
Demonstration of Meissner effect:

Consider a superconducting material above its critical temperature. A primary coil and a secondary coil , are wound on the material as shown in the figure. The primary coil is connected to a battery and a key K. The secondary coil is connected to a battery and a galvanometer. When the key K is pressed, the primary circuit is closed and a current flows through the primary coil which sets up a magnetic field in it.

The magnetic fiels instantly links with the secondary coil. This accounts for a change of flux across the secondary coil, and hence a momentary current is driven through the galvanometer which shows the deflection. Since the primary current is steady , the magnetic field flux will also become steady, and the flux linkage with the secondary becomes unchanging.

As there is no further change in the flux linkage in the secondary coil, the current will no more be driven in the secondary circuit. Now, the temperature of the superconductor is decreased gradually. As soon as the temperature crosses down the critical temperature, the galvanometer shows the deflection , indicating that the flux linkage with the secondary coil has changed. The change in the flux linkage is attributed to the expulsion of flux from the body of the superconducting material.





The magnetic induction inside the specimen is given by

$$B = \mu 0(H + M)$$

Here H is the applied magnetic field and M is the magnetization produced within the specimen.

$$\text{at } T<T_C \text{ , } B=0$$

$$\text{i.e.,} \qquad B=0=\mu_0 (H+M)$$

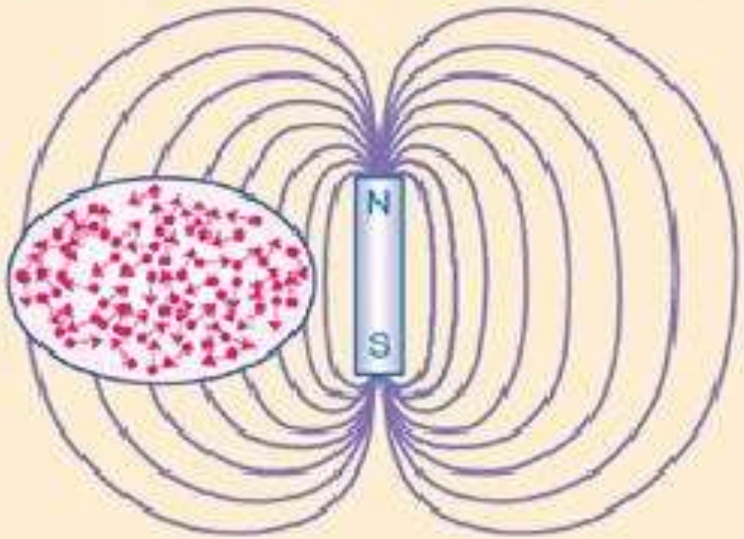
$$M=-H$$

thus the susceptibility of the material is $\chi = \frac{M}{H} = -1$

This indicates , superconducting state is characterized by perfect diamagnetism.

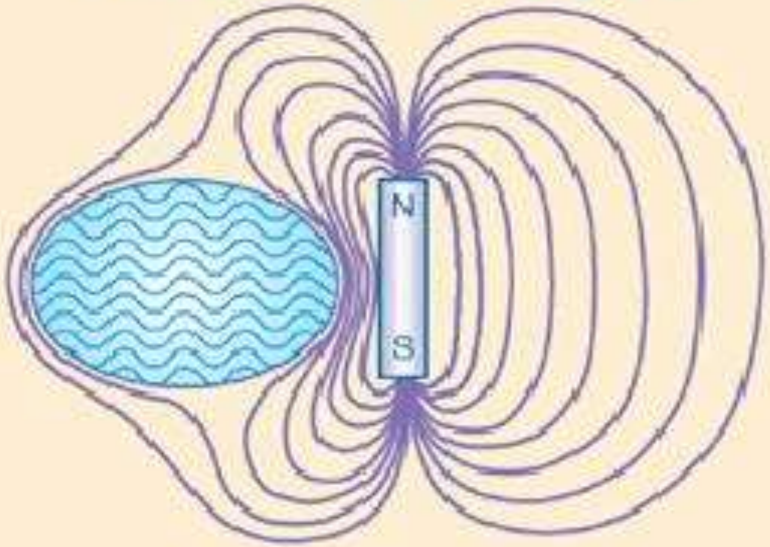
Thus, the two mutually independent properties, namely zero resistivity and perfect diamagnetism are the essential properties that characterize the superconducting state. Meissner effect is the standard test which proves whether a particular material has become a superconductor or not.

ORDINARY CONDUCTOR



In an ordinary electrical conductor, incoherent, disordered electrons allow penetration by an external magnetic field.

SUPERCONDUCTOR



In a superconductor, coherent collective functioning of the electrons spontaneously excludes an external magnetic field, and maintains its impenetrable status.

Critical field

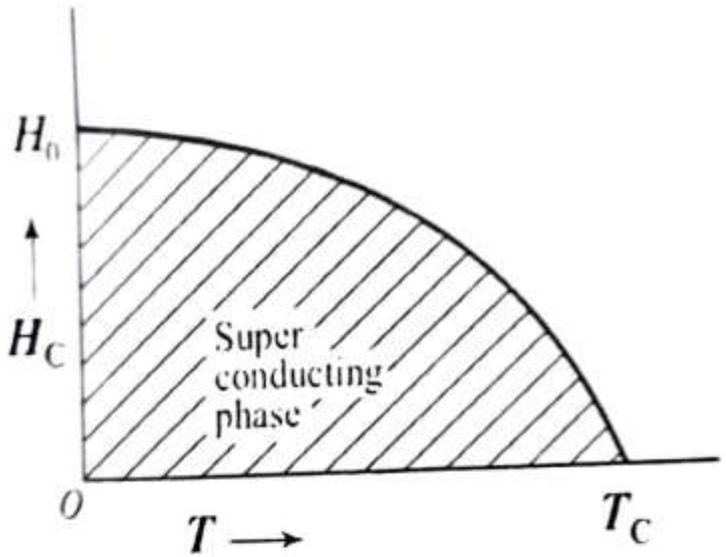
- A superconducting material looses its resistivity at temperature T_C and becomes a superconductor.
- But at this stage, if it is subjected to a magnetic field, it becomes a normal conductor again.
- Then it needs to cool the material to still lower temperatures for it to recover its superconducting property.
- However, it is possible to turn a superconductor into a normal conductor by subjecting it to a sufficiently strong magnetic field at all temperatures $T<T_C$.
- Thus **critical field can be defined as the strength of minimum magnetic field required to just turn a material from superconducting state to a normal state.**

Temperature dependence of critical field

- For a superconducting material in the superconducting state, the critical field will be higher when the temperature is lower. If T is the temperature of the superconducting material ($T<T_C$) , H_C is the critical field and H_0 is the field required to turn the superconductor to a normal conductor at 0 K, then the relation for the critical field is given by

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

- The dependence of H_C on T is shown in fig. the curve is almost parabolic(though not exactly).
- Under the influence of a magnetic field whose strength is greater than H_0, the material can never become superconducting however low the temperature may be.

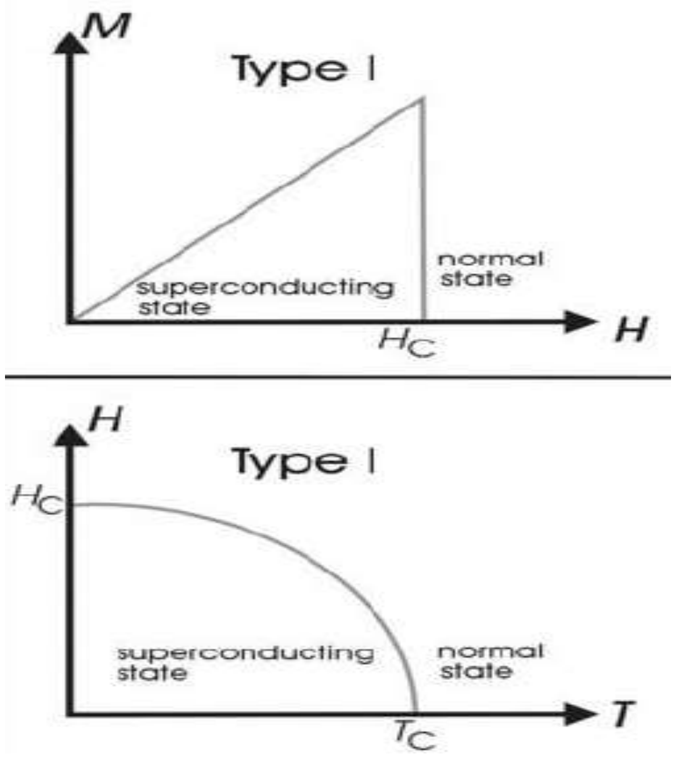


DEPENDENCE OF H_c ON T

Types of superconductors

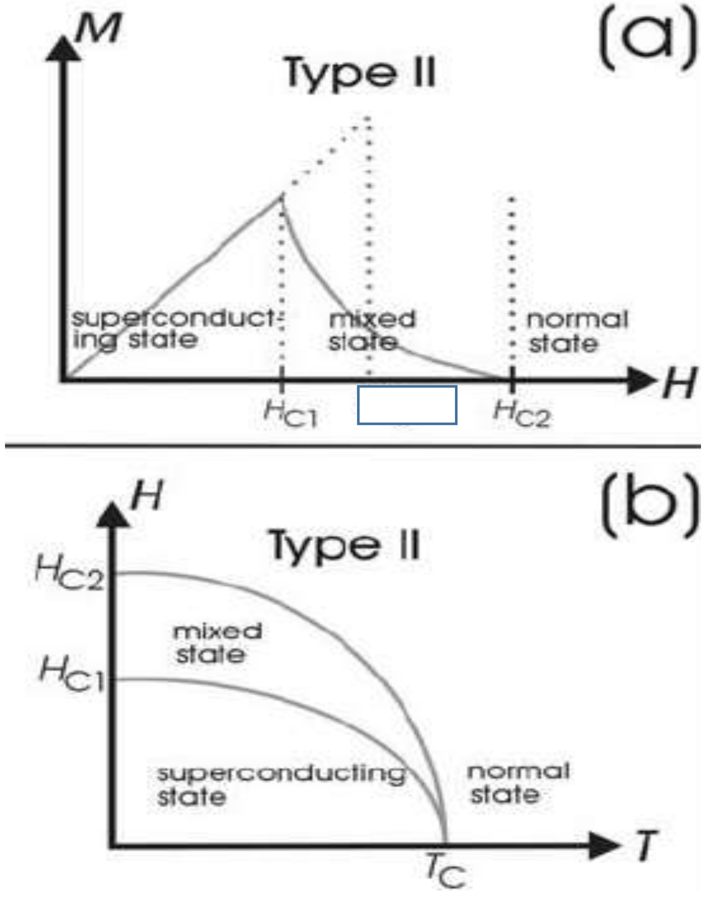
Type I superconductors (soft superconductors)

- Type I superconductors exhibit complete Meissner effect.
- In the presence of the external magnetic field $H<H_C$, the material in superconducting state is a perfect diamagnet.
- The dependence of magnetic moment on H for Type I superconductors is shown in the figure.
- As soon as the applied field H exceeds H_C , the entire material becomes normal by loosing its diamagnetic property completely, and the magnetic flux penetrates throughout the body.
- The resistance changes from zero to a value as applicable to a normal conductor.
- The critical field value for Type I superconductors are found to be very low.
- The low H_C value excludes them from being used for high end applications.
- Example for Type I supercopnductors are Hg, Pb, Zn etc



Type II superconductors (hard superconductors)

- A Type II superconductor is characterized by two crtical magnetic fields H_{C1} and H_{C2}.
- For any applied field strength less than the critical value H_{C1}, it expels the magnetic field from its body completely, and behaves as a perfect diamagnet from end to end.
- When H exceeds H_{C1}, the flux penetrates the body and fills in partially.
- With further increase in H, the flux filling also increases thereby decreasing the diamagnetic part of the material and covers the entire body when H becomes equal to or greater than a second critical value H_{C2}.The material then turns into a normal conductor.
- H_{C1} and H_{C2} are called lower and upper critical field value respectively.
- The dependence of magnetic moment on the external magnetic field is as shown in the figure.
- When the applied field strength is between H_{C1} and H_{C2}, the material is in a mixed state. This state is called Vortex state.
- In this state, though there is flux penetration the material retains its zero resistance property, and it is still a superconductor in this magnetic field interval.
- Most important advantage in the case of Type II superconductors is, the value of upper critical field H_{C2} for them will be many more times higher than the value of H_C for Type I superconductors at the given temperature. Thus they find use in the build of the devices which work in high magnetic fields.
- Example for Type II supercopnductors are NbTi, Nb_3Sn etc



BCS theory of superconductivity

- Many theories for the explanation of phenomenon of superconductivity were proposed out of which BCS theory (1951) which is named after initials of 3 Physicists Bardeen, Cooper and Shriffer is most successful and most widely accepted theory. They received the Noble prize for Physics in 1972.

BCS theory showed that the basic interaction responsible for superconductivity appears to be that of a pair of electrons by means of an interchange of virtual phonons. This is explained as follows:-

Electron phonon electron interaction

- Consider a lattice consisting of positive ions. When an electron approaches a positive ion core it suffers attractive coulomb interaction. Due to this attraction ion core is set in motion and thus distorts that lattice. Let a second electron come in the way of distorted lattice and interaction between the two occurs which lowers the energy of the second electron. The two electrons therefore interact indirectly, via lattice distortion or the phonon field, thus lowering the energy of electrons. This type of interaction can also be interpreted as electron –electron interaction through phonons.

Cooper Pairs.

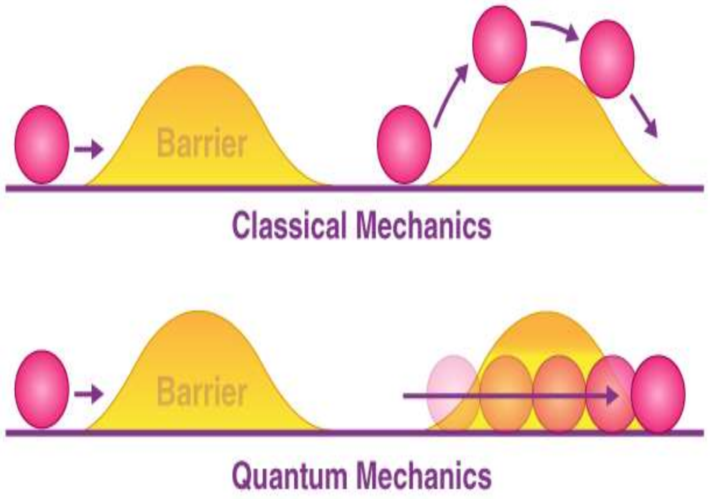
- A cooper pair is formed when two electrons interact with each other through phonon attractively and by overcoming the coulomb's repulsive forces. The binding energy of cooper pair is of the order of 10^{-3}eV which is very small. As the superconductivity phenomenon is due to these cooper pairs , superconductivity is a low temperature phenomenon. The electrons in cooper pair have opposite spin and hence total spin of the cooper pair is zero. As the total spin is zero, they behave as bosons and not fermions. Due to the orderly motion of these cooper pairs in group, and less collision with the lattice, large current is produced. At temperatures greater than T_C , cooper pairs are broken resulting in the transition of superconducting state to normal state.

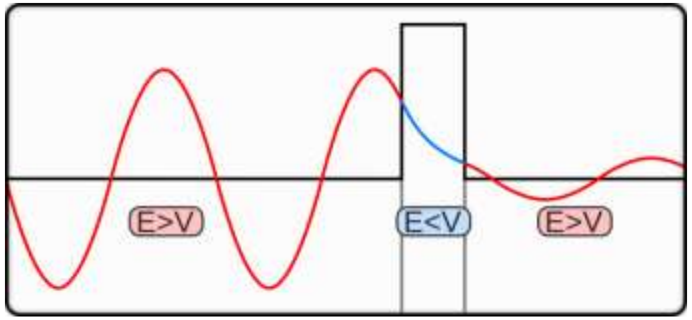
High TemperatureSuperconductors

- Super conductors that exhibit high T_c are called as High temperature superconductors
- Generally, those superconductors that can work at liquid Nitrogen temperature (above 77K) are classified under High T_c superconductor.
- They are oxides of copper bearing pervoskite crystal structure
  Ex : Barium copper oxide, Yettrium barium copper oxide etc
- Recently developed high Temperature superconductors are from ceramics compounds.
- All the high temperature superconductors are classified under Type 2, since they have higher critical magnetic fields.

Quantum Tunnelling

- It is a quantum mechanical phenomenon in which an object such as an electron or atom passes through a potential energy barrier. This concept is notpossible, according to classical mechanics.
- Tunneling is a outcome of wave nature of matter and is found in low mass particles like electrons, protons etc
- Probability of transmission of a wavepacket through a barrier decreases exponentially with the barrier height. When the quantum wave reach the barrier, its amplitude will decrease exponentially.





<u>Josephson Effect</u>

- B D Josephson , in 1962 observed that when a very thin layer is sandwiched between two superconductors then a supercurrent flows across the junction without developing any voltage. This phenomenon is called Josephson effect.
- Here insulating layer forms a weak link between superconductors. This weak link is called Josephson junction.
- A current is made to flow in a bar of superconductor. A voltmeter is connected across the ends of bar. The voltmeter reading is 0 in this.
- Suppose the bar is cut into 2 pieces and the 2 pieces are separated by 1cm , now no current flows through them and voltmeter shows the reading equal to open circuit voltage of the cell.
- Now if the distance between the two pieces is reduced to 1nm, voltmeter again shows 0 reading indicating that a current flows across the gap. This is called Josephson effect.
- The current flowing through this junction is called supercurrent.

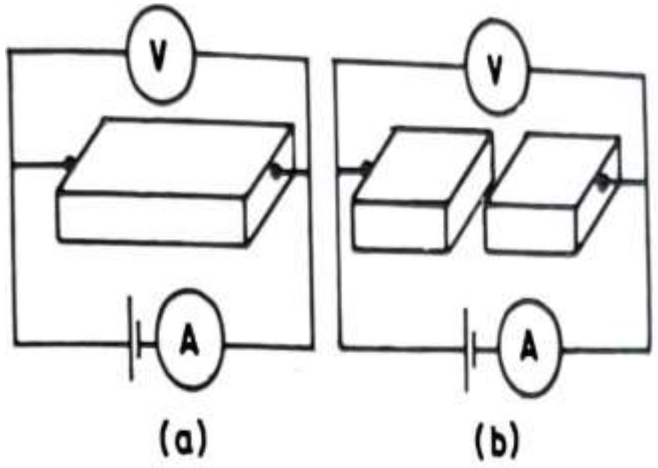


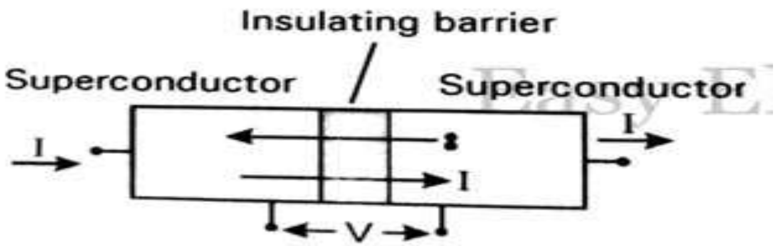
Fig. 8.24 Josephson's effect.

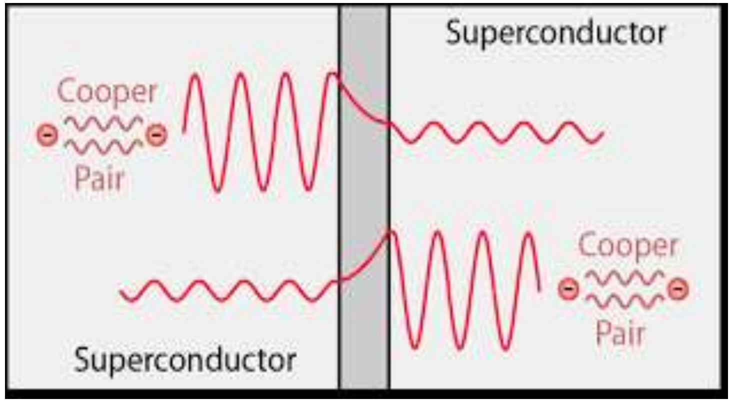
Josephson effect is of two types:

1) DC Josephson effect

- It is the phenomenon of flow of super current through the junction even in the absence of external emf . If the voltage across the junction is measured, it gives zero.
- Consider a Josephson junction containing two superconducting films separated by thin oxide layer. Here cooper pairs in the superconductor starts tunneling through the oxide layer which are represented by wave function. The cooper pairs tunnel from one side of the junction to the other side easily.
- The effect of the insulating layer is that it produces a phase difference between the wave function of cooper pairs on one side of the insulating layer and the wave function of the pairs on the other side.
- Because of this phase difference, super current appears across the junction even though the applied voltage is zero. This is known as DC Josephson effect.
- Josephson showed that the super current through the junction is given by, $I_S = I_C \sin \Phi_0$

where I_C is the critical current(maximum current that the junction can sustain), which depends on the thickness of the junction layer and the temperature , Φ_0 is the phase difference of the wave functions on two sides of the junction.





2) **AC Josephson effect**

- When dc voltage is applied across the Josephson junction, it leads to the development of oscillating current. In other words an alternating emf of high frequency is established across the junction. This effect is called as AC Josephson effect.
- The oscillating current is because of the fact that, the application of dc voltage across the junction causes the additional phase change for the cooper pairs.
- The energy difference of cooper pairs on both sides is of the order of 2eV.
- Using quantum mechanical calculations it can be shown that the tunneling current is represented by the following equation. It represents the alternating current with angular frequency ω.

$$I = I_c \; Sin\left(\phi_0 + \frac{2eV\,t}{\hbar}\right)$$

$$I = I_c \; Sin(\phi_0 + \omega t)$$

$$\text{Where } \omega = \frac{2eV}{\hbar}$$

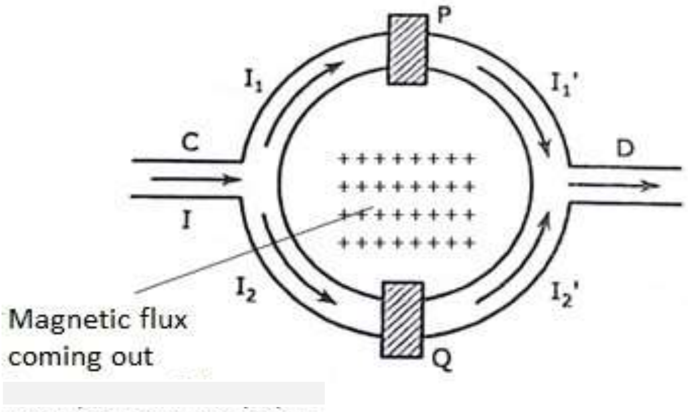
SQUIDS

- It stands for Superconducting Quantum Interference Device.It is an instrument used to measure extremely weak magnetic field of the order of 10-13 T. Heart of the SQUID is a super conducting ring containing one or more Josephson junctions.It works on the principle of Josephson effect.

Two types of SQUIDS are available:-

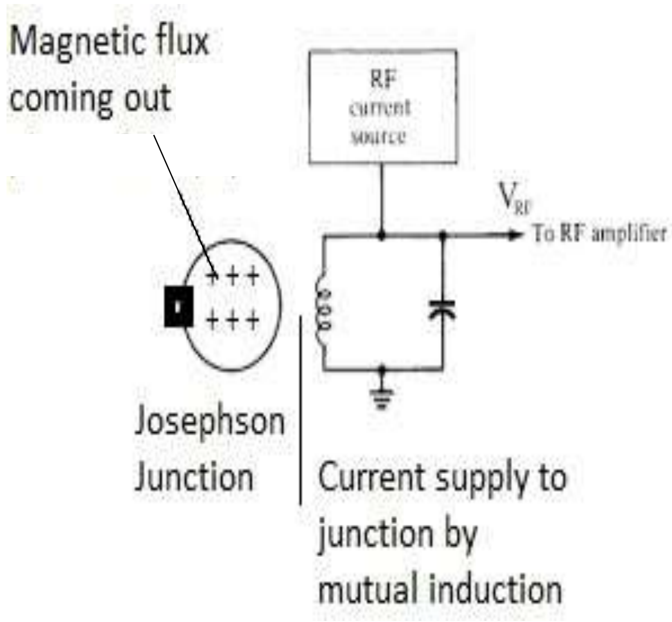
DC SQUID

- It has two Josephson junctions connected in parallel and works on the interference of current from two junctions.
- It works on the principle of DC Josephson effect which is the phenomenon of flow of super current through the junction even in the absence of external emf.
- The cross sectional view of the arrangement is shown.P and Q are two Josephson Junctions arranged in parallel. When current I flows through the point C, it divides into I_1 and I_2. Hence the wave function due to these super currents or the cooper pairs experience a phase shift at P and Q.
- In the absence of applied magnetic field, the phase difference between the wave functions is zero. If the magnetic field is applied perpendicular to the current loop, then phase difference between the wave functions will not be zero. This is identified by the sum of the currents I_1' and I_2'.The magnitude of phase difference is proportional to applied magnetic field. Hence, Even if there is a weak magnetic field in the region it will be detected.



RF SQUID

- It works on the principle of AC Josephson effect - When dc voltage is applied across the Josephson junction, it leads to the development of oscillating current.
- It has single Josephson Junction.
- Magnetic field is applied perpendicular to the plane of the current loop.
- The flux is coupled into a loop containing a single Josephson Junction through an input coil and an RF source.
- Hence when the RF current changes, there is corresponding change in the flux linked with the coil.This variation is very sensitive and is measured.
- It is also used in the detection of low magnetic field.
- It is less sensitive compared to DC Squid.
- Due to its low cost manufacturing, it is commonly used SQUID in many applications.



Year	Scientists	Contribution
1913	H. K. Onnes	Properties of materials at low temperature
1972	J. Bardeen, L. Cooper, and R. Schrieffer	Microscopic (BCS) theory of conventional superconductors
1973	I. Giaever and B. Josephson	Tunnelling effects in superconductor
1986	J. G. Bednorz and K.A. Müller	Discovery of the copper oxide-based high temperature superconductor
1991	P. de Gennes	Studies on complex systems including superconductivity
2003	V.L. Ginzburg and A.A. Abrikosov	For pioneering contributions to the theory of superconductors