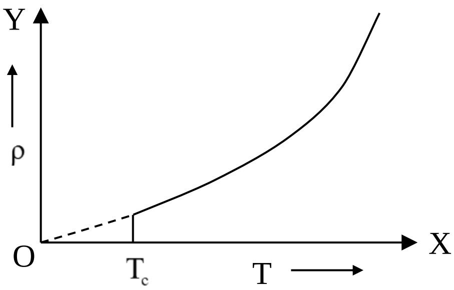
SUPERCONDUCTIVITY

Superconductivity is the **property by which the resistivity of many materials suddenly falls to zero** *(vanishes/disappears) or they show infinite conductivity* **when they are cooled to sufficiently low temperature**s. Materials which exhibit superconductivity are called superconductors. *Superconductivity was discovered by a Dutch Physicist Kamerlingh Onnes in 1911. When he was studying the properties of mercury at very low temperatures, he found that resistivity of pure mercury (Hg) suddenly dropped to zero at 4.2K.*

Transition Temperature (Critical temperature - T_C **):-**

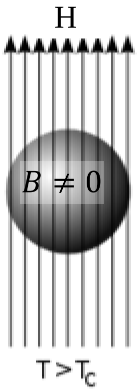
It is the **temperature at which a superconductor** (superconducting material) **changes from its normal state to superconducting state** or it is the temperature at which resistivity of a superconductor suddenly falls to zero and changes to superconducting state.



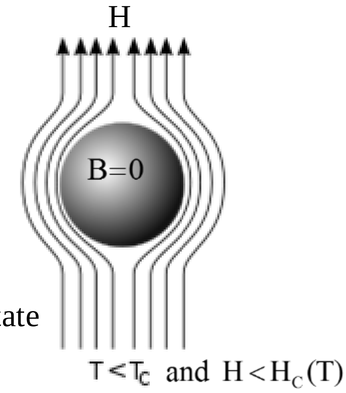
Note: Transition temperature can be changed by adding impurities to the material, by applying external magnetic field, by applying pressure, etc.

<u>Meissner Effect</u>:

The **expulsion** (removal or ejection) **of magnetic field from the interior of a superconductor** (Or vanishing of magnetic field inside a superconductor) **during its transition from normal state to superconducting state** is called Meissner effect.



Normal state



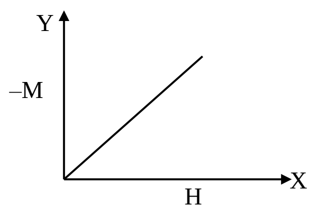
Superconducting state

Consider a superconductor placed in an external magnetising field H. In its normal state magnetic field lines are passing (penetrating) through it. The magnetic flux density (magnetic field) inside the specimen is given by $B = B_o + B_m = \mu_0(H + M)$, where μ_0 is the permeability of free space and M is the intensity of magnetisation produced in the specimen.

When the specimen is cooled below the transition temperature, it becomes superconducting and according to Meissner effect all flux lines will be expelled out. Then $B = 0$ or $\mu_0(H + M) = 0$, $H + M = 0$

or $H = -M$ and magnetic susceptibility $\chi = \frac{M}{H} = -1$. This is the minimum value of susceptibility possible for a diamagnet. Hence superconductor becomes a perfect (ideal) diamagnet below the transition temperature i.e., in the superconducting state.

(*When a superconductor is cooled in a magnetic field below the transition temperature, persistent current is produced on the surface of the material. This circulating current produces a magnetic field in a direction opposite to the applied magnetic field and just cancels the applied field. Thus the material behaves as a perfect diamagnet.*)



For an ideal superconductor in super conducting state

Effect of magnetic field on superconductivity:

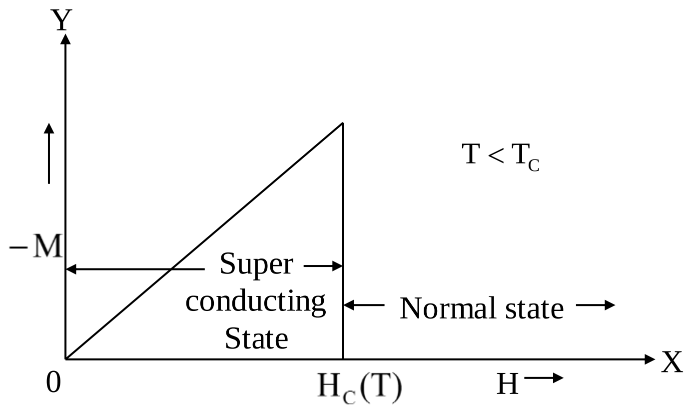
Application of sufficiently strong magnetic fields will destroy the superconducting state of a superconductor. The **minimum strength of the magnetic field required to destroy the superconducting state of a material at a particular temperature ($T < T_C$) is called critical field [$H_C(T)$].**

Types of superconductors:

Superconductors are divided into two depending on their response to magnetizing field.

1) Type-I or soft superconductors

Superconductors which **exhibit a very sharp transition from superconducting state to normal state at the critical field**. In type-I superconductors the intensity of magnetisation increases linearly with the magnetizing field and suddenly falls to zero when the magetising field (H) becomes equal to the critical field [$H_C(T)$] of that temperature.



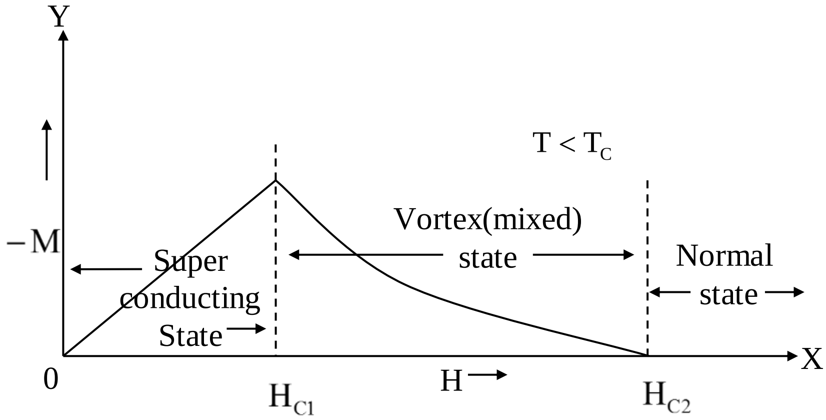
The main properties of Type -I superconductors are

1) Transition from superconducting state to normal state is abrupt.
2) $H_C(T)$ is very small of the order of 0.1 T.
3) Superconductivity can be easily destroyed.
4) The transition at the critical field is reversible.

Eg: lead, tin, mercury, aluminium, magnesium, etc. (most of the pure metals are type-I superconductors).

2) Type -II or hard superconductors

Superconductors **which exhibit a gradual transition from superconducting state to normal state in response to the external magnetizing field**. In type-II superconductors the intensity of magnetistion increases linearly with the magnetizing field up to the lower critical field (H_{C1}) and gradually falls to zero when the magetising field (H) increases from lower critical field H_{C1} to upper critical field H_{C2}.

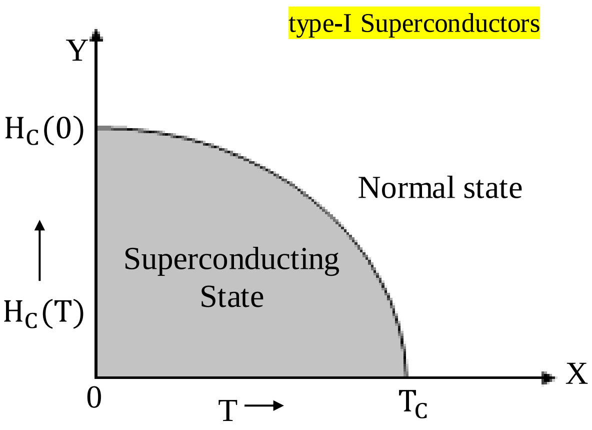


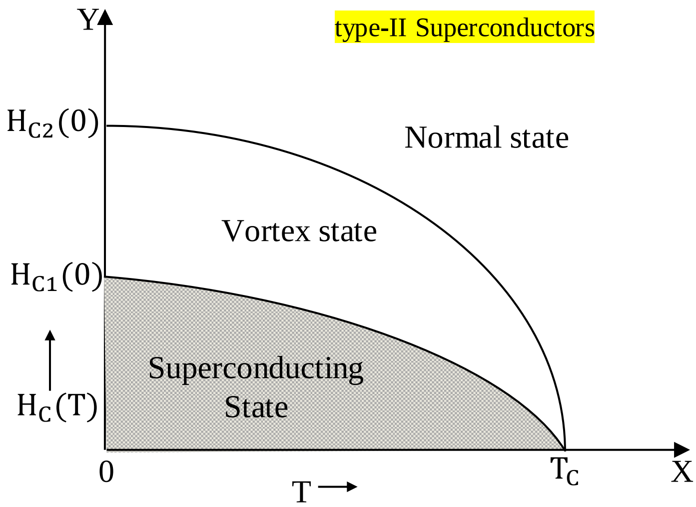
The main properties of Type -II superconductors are

1) Transition from superconducting state to normal state is gradual.
2) H_{C2} is very high of the order of 10T to 20T.
3) Very strong magnetic field is required to destroy superconductivity.
4) The transition between normal state and superconducting state is irreversible due to hysteresis loss.

Eg: Niobium, germanium, niobium-tin, niobium-zirconium, etc. (these are usually made of metal alloys or oxide ceramics. Niobium, vanadium, technetium, etc are elemental type-II superconductors).

Variation of critical field H_C (T) with temperature: The variation of critical field H_C (T) with temperature for type-I Superconductors is represented by a simple parabolic curve.





When the applied magnetising field (H) is below $H_C(T)$, the material will be in the superconducting state.

The variation of critical field with temperature is represented by the equation $H_C(T) = H_C(0)\left[1-\left(\frac{T}{T_C}\right)^2\right]$, where $H_C(T)$ is the critical field at temperature T and $H_C(0)$ is the critical field at 0K (maximum).

$H_C(T) = 0$ when $T = T_C$.

BCS Theory

The quantum theory developed by Bardeen, Cooper and Schrieffer to explain the superconductivity of type-I superconductors is called BCS theory. According to this theory superconductivity is due to the pairing of electrons (**cooper pairs**) through **phonons** close to the Fermi level. Cooper pairs and superconducting energy gap are the important features of BCS theory.

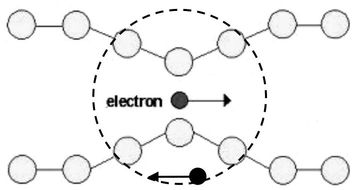
Phonon:

Phonon is the vibrational wave created in a crystal due to the interaction of a conduction electron and neighboring positive ions (**electron – lattice interaction**)

When an electron is advancing through the space between two layers (sets or arrays) of positive ions in the crystal, the electron attracts the nearby positive charges and the lattice gets distorted. This distortion produces a region of increased positive charge density and this region is propagating inside the lattice like a vibrational wave. This is called a phonon. These phonons are effective at very low temperatures.

Cooper pair:

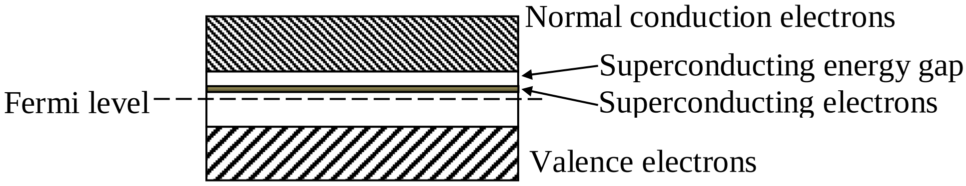
Cooper pair is the electron pair formed in a superconductor at the Superconducting state due to electron-phonon-electron interaction.

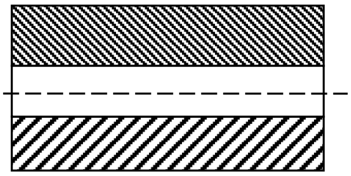


When a free electron in a superconductor at low temperature ($T < T_C$) approaches a phonon, it is attracted by the high positive charge density region of the phonon. Thus, two free conduction electrons in a super conductor can attract each other (or held together) through electron – phonon – electron interaction and this pair of electrons is called cooper pair.

The electrons in the cooper pair have opposite spins and equal and opposite linear momenta. Thus, a cooper pair behaves as a single particle having zero spin and zero momentum or it can be considered as a boson. Collection of such cooper pairs forms a cloud of bosons. They do not obey Pauli's exclusion principle. i.e., any number of cooper pairs can occupy the same quantum state with the same energy. At low temperatures, there is a strong correlation among them and they can move together with same velocity in an ordered form without making any collision with the lattice. Thus, superconducting state is an ordered state of conduction electrons. At 0K, almost all electrons are coupled as cooper pairs.

<u>Superconducting Energy gap</u>: *The net energy of electrons in a cooper pair is less than the total energy of these electrons in their normal conduction state. This reveals that there exists an energy gap between the normal conduction electrons and superconducting electrons*. This **energy gap existing between normal conduction electrons and superconducting electrons in a superconductor is called superconducting energy gap** ($E_{g(S)}$). Superconducting electron states are below this gap close to the Fermi level. This energy gap at absolute zero is given by $E_{g(S)} = 3.5kT_C$ where k is the Boltzmann's constant and T_C is the critical temperature. This energy gap is $\cong 10^{-4}$ eV .





Normal state

superconducting energy gap can also be defined as the minimum energy required to separate the electrons apart in a cooper pair.

When temperature increases, superconducting energy gap decreases. When temperature reaches critical temperature ($T = T_C$) energy gap becomes zero, it disappears and cooper pairs are broken up and thus electrons are separated.

<u>High temperature superconductors (HTSC):</u>

HTSCs are ceramic superconductors having transition temperature greater than 40K. All known HTSCs are type II superconductors. Copper oxide based superconductors or cuprate superconductors containing atoms of 4 or more elements are some groups of HTSC. Eg: $YBa_2Cu_3O_7$. HTSC cannot be explained by BCS theory. But the Resonating Valence Bond Theory explained certain aspects of this type of superconductivity.

<u>Application of superconductors</u>:

Science and Technology:

Superconductors are used to produce a very strong and powerful magnetic field of the order of 20T at low cost. This high magnetic field is used in so many devices.

a) To bend and guide the charged particles in particle accelerators like cyclotron.
b) Used for controlling and focusing high temperature plasma for the controlled nuclear fusion.
c) Used in magnetic levitation – maglev.
d) Superconducting magnets are used to produce very efficient ore separating machines.
e) Used for flux concentration, energy storage and magnetic shielding

Medical field:

a) MRI (Magnetic Resonance Imaging): MRI scanning is used to take detailed images of various internal organs and structures (tissues) of our body. It helps to diagnose a variety of conditions from torn ligaments to tumors. MRI scanning is free from the harmful effects of other radiations like X-rays.
b) Used to remove tumour cells from the healthy cells using high gradient magnetic separation method.
c) MEG (Magneto Encephalography) : used to detect the magnetic field created by the brain's neuronal activity and thus used for the diagnosis of epilepsy.
d) Magneto Gastrography (MGG) is used to record weak magnetic fields in the stomach.

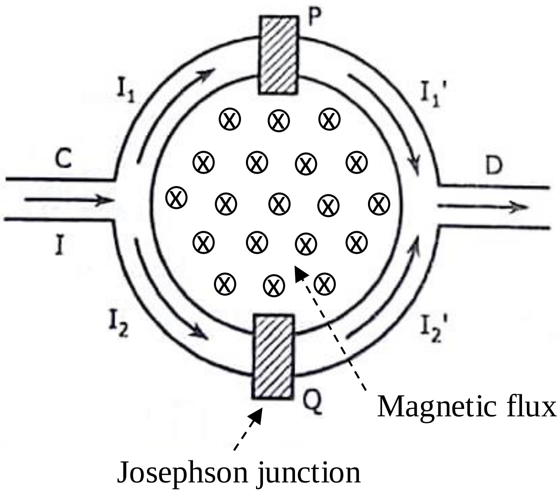
Quantum mechanical superconducting devices like Josephson Junction and SQUID (Superconducting Quantum Interference Device) are having many applications in scientific, industrial, medical and communication fields.

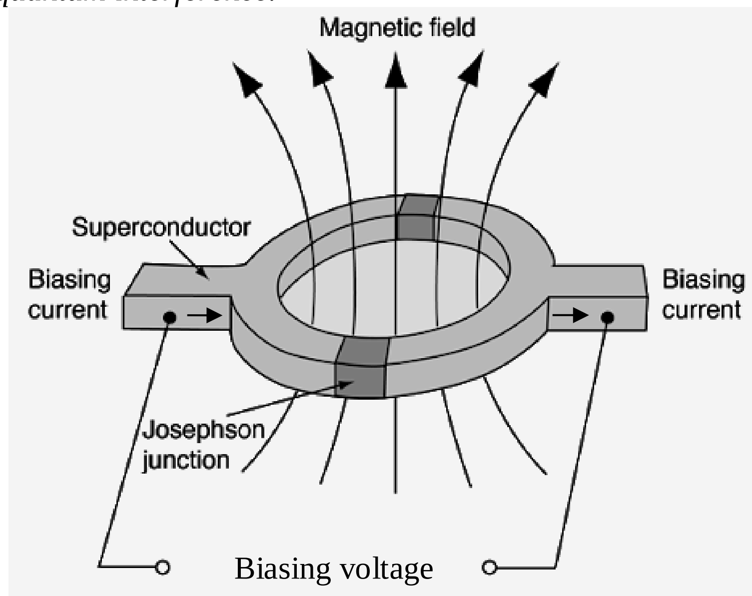
Other applications:

a) Used in the manufacture of electrical motors, generators, transformers, and other machines using superconducting windings.
b) Used for constructing low loss transmission lines.
c) High capacity and high speed computer chips are developed with superconductors.
d) Used as efficient storage devices in computers
e) Cryotron (a fast electrical switching system) utilizes superconductivity for its operation.
f) Used for non-destructive testing of materials and structures.
f) Used in oil prospecting, mineral exploration, earthquake prediction, geothermal energy surveying, etc.
g) HTSC cables are used for undersea communication.
h) SQUID and Josephson Junction are the devices based on superconductivity.

SQUID:

SQUID (Superconducting Quantum Interference Device) is a very sensitive device for measuring extremely small magnetic fields and its changes, based on quantum interference. It consists of two Josephson junctions arranged in parallel as part of a superconducting ring so that electrons tunneling through the junctions undergo quantum interference.





Working:

The biasing voltage applied across the arms C and D produces a biasing current I. After entering through the arm C, it is divided into two as I_1 and I_2. On tunneling through the junctions P and Q, they become I_1' and I_2' respectively. They undergo quantum interference and come out through the arm D. When a magnetic field (magnetic flux) is applied perpendicular to the loop, it changes the interference condition and that can be easily detected.

Josephson Effect:

The setup consisting of an insulating material of very small thickness (1 to 10 nm) sandwiched between two pieces of superconducting materials is called Josephson junction or weak link.
The phenomenon of tunneling of superelectrons (cooper pairs) through a Josephson junction is called Josephson effect.

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