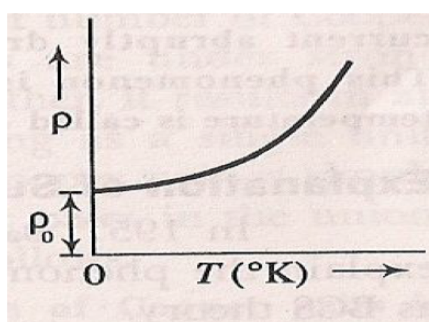
Superconductivity

Super conductivity is the phenomenon observed in some metals and materials. Kammerlingh Onnes in 1911 observed that the electrical resistivity of pure mercury drops abruptly to zero at about 4.2K .This state is called super conducting state. The material is called superconductor .The temperature at which they attain superconductivity is called critical temperature T_c.

Temperature dependence of resistivity of a metal:

All metals are good conductors of electricity. The electrical conductivity of metal varies with the temperature. The electrical resistance of a metal, to the flow of current, is due to scattering of conduction electrons by lattice vibrations. When the temperature increases the amplitude of lattice vibrations also increases, thereby increasing the resistance. The dependence of resistance of metal (non-superconducting state) on temperature is shown in figure. The resistance decreases with temperature and reaches a minimum valueknown as residual resistance, at T = 0K. The residual resistance at T = 0K is due to impurities in the metal.



DEPENDENCE OF ρ ON T

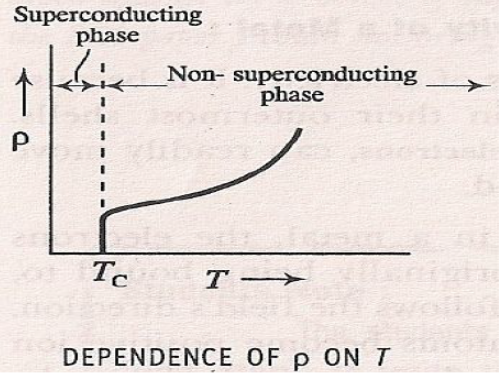
The variation is expressed by Matthiessen's rule

$$\rho = \rho_o + \rho(T)$$

Where 'ρ' is the resistivity of the given material, 'ρ_o'is the residual resistivity and '$\rho(T)$' is the temperature dependent part of resistivity called ideal resistivity.

Temperature dependence of resistivity of a superconductor:

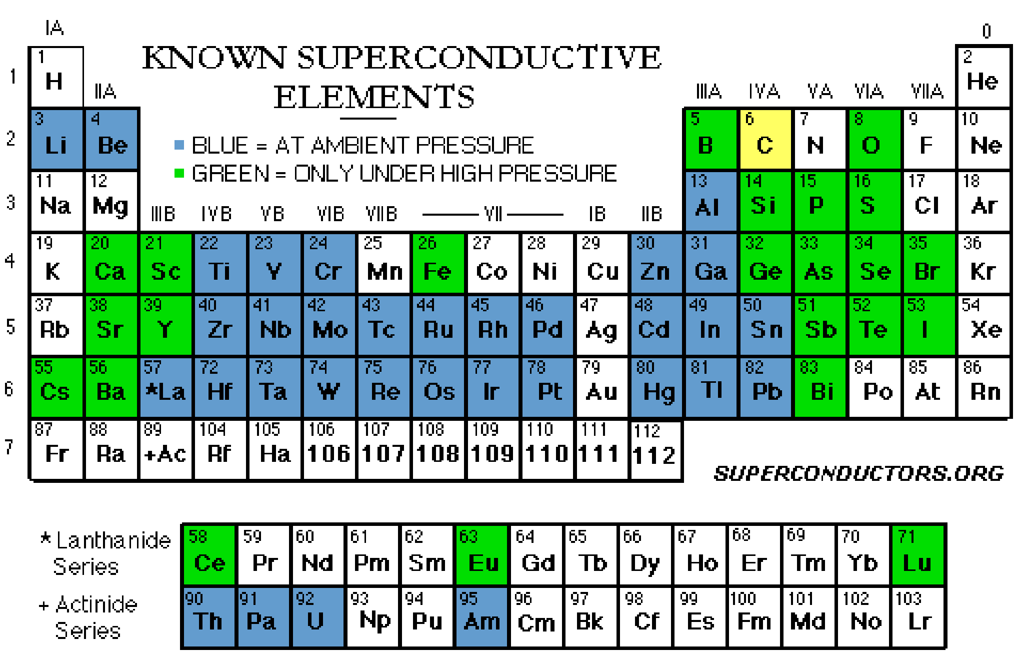
The resistance of a superconductor in the non-superconducting state decreases with temperature and the electrical resistivity of some of the metals and alloys vanish entirely below a certain temperature. *"The resistance offered by certain materials to the flow of electric current abruptly drop to zero below a threshold temperature. This phenomenon is called* ***superconductivity*** *and threshold temperature is called "critical temperature." "The temperature at which a material undergoes transition from normal state to superconducting state losing its resistivity is called the* ***critical temperature or transition temperature Tc****".*Above the transition temperature, the substance is in the normal state and below it will be in superconducting state. The critical temperature is different for different superconducting materials. It is not very sensitive to the presence of small amount of impurities.



2. General properties of Superconductors:-

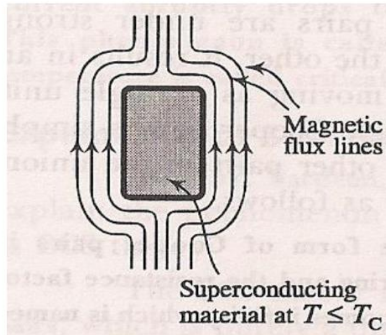
Properties of superconductors:-

1. It is a low temperature phenomenon.
2. The transition temperature is different for different substances.
3. Materials having high normal resistivities exhibit superconductivity.
4. Materials for which $Z\rho = 10^6$ (where Z is a atomic number and ρ is resistivity) show superconductivity.
5. For chemically pure and structurally perfect specimen, the superconductivity is very sharp.
6. Ferro magnetic and Anti ferromagnetic materials are not superconductors.
7. Below the transition temperature the magnetic flux lines are rejected out of the superconductors.
8. Superconducting elements, in general, lie in the inner columns of the periodic table.
9. Those metallic elements having their valence electrons lies between 2 to 8 exhibit superconductivity.
10. Below the transition temperature the specific heat curve is discontinuous.



Meissner effect:

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



EXPULSION OF MAGNETIC FLUX

When the temperature is lowered to T_c, the flux is suddenly and completely expelled, as the specimen becomes superconducting. The Meissner effect is reversible. When the temperature is raised the flux penetrates the material, after it reaches T_c. Then the substance will be in the normal state.

The magnetic induction inside the specimen

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

Where 'H' is the intensity of the magnetizing field and ‘M’ is the magnetization produced within the material.

For $T < T_c$, $B = 0$

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

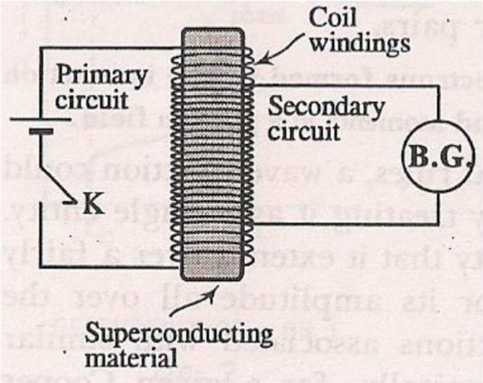
$$M = -H$$

$$M/H = -1 = \chi$$

Susceptibility is -1 i.e. it is perfect diamagnetism.

Hence superconducting material do not allow the magnetic flux to exist inside the material.

Consider a primary coil and a secondary coil, wound on a superconducting material. The primary coil is connected to a battery and a key. The secondary coil is connected to ballistic galvanometer (BG). When the key is closed the current flows through the primary coil and the magnetic field is produced. This flux is linked with the secondary coil and the current flows through the secondary coil which makes a deflection in the galvanometer. If the primary current is steady the magnetic flux and the flux linked with the coil will become steady. As the temperature of the specimen is decreased below the critical temperature, BG suddenly shows a deflection indicating that the flux linked with the secondary coil is changed. This is due to the expulsion of the magnetic flux from the specimen.



Critical current

An electric current is passing through the superconducting material it self may gives rise to necessary magnetic field. For example, when the current is passing a superconducting ring, it gives rise to its own magnetic field. As the current increases to critical value I_c, the associated magnetic field becomes H_C. And the superconductivity disappears.

$$I_C = 2\pi r H_C$$

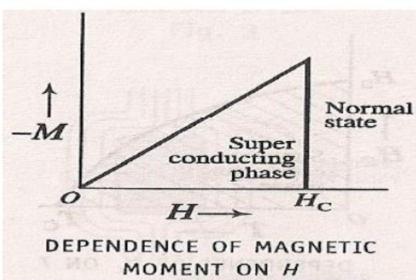
The current in a superconductive material above which the material is normal and below which the material is superconducting, at a specified temperature and in the absence of external magnetic fields is known as critical current.

Type of superconductors

1.Type I superconductors:

These materials exhibit complete Meissner effect and have well defined critical field H_c. These are perfect diamagnetic in the superconducting state and possesses negative magnetic moment.

The material remains in the superconducting when the field is less than the critical field. It expels the magnetic lines of force from the body of the mater immediately after H_c the material transits to normal state and the flux penetrates the material i.e. Meissner effect is absent. H_c is of the order of 0.1 T or less. Since H_c very low, even weak magnetic field can destroy the phenomenon. As weak magnetic field can penetrate the material more easily and they are also called *soft superconductor.*

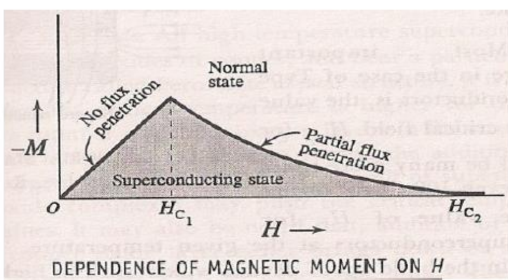


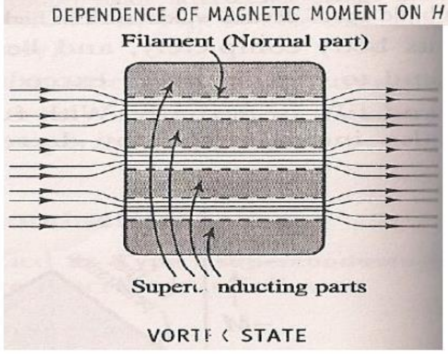
Element	T_c (K)
Aluminium	1.196
Cadmium	0.52
Gallium	1.09
Indium	3.40
Tin	3.72
Mercury	4.12
Lead	7.175

2.Type II Superconductors:

These materials are having two critical fields H_{c1} and H_{c2}. For the field less thenH_{c1}(lower critical field), it expels the magnetic field completely and there is no flux penetration. It becomes a perfect diamagnetic and the material is in the super conducting state. After Hc_1 the flux penetrates and partially fills the body of the material through channels called filaments. As the field is increased these filaments broaden and by Hc_2 (the material possesses both normal and superconducting state, hence the state is called *'Mixed State'*. This is also referred to as *'vortex state'* where the material is in a magnetically mixed state but electrically it is a superconductor. After Hc_2 the material transits to normal state and the resistance is finite.Type II superconductors can carry larger currents when the magnetic field is between Hc_1 and Hc_2.

Hc_2 the upper critical field is many a folds greater than Hc_1 the lower critical field. Only strong magnetic field of the order of 10T can penetrate the material hence these are called hard super conductor.Type-II superconductors are used in the manufacturing of the superconducting magnets of high magnetic fields above 10 Tesla.





Element	T_c (K)
Tantalum	4.5
Thallium	2.4
Niobium	9.3

5. Differences between type I and Type II superconductor

Type I superconductor	Type II superconductor
1. It follows complete Meissner effect.	1. It does not follow the complete Meissner effect
2. It has single critical field value H_C	2. It has two critical field values H_{C_1} and H_{C_2}
3. There no mixed state.	3. There is a mixed state
4. They are soft superconductors	4. They are hard superconductors
5. Materials with pure form are type I superconductors	5. Materials with impurities or alloys are type II superconductors
6. Examples; Zn, Al, Hg and Sn	6. Examples: Zr, Nb

***BCS Theory* (Explanation of superconductivity):**

Bardeen, Cooper and Schrieffer (BCS) in 1957 explained the phenomenon of superconductivity based on the formation of cooper pairs. It is called BCS theory. It is a quantum mechanical concept.

During the flow of current in a superconductor, when an electron approaches a positive ion lattice of the metal there is a Coulomb force ofattraction between the electron and the lattice ion and thus ion core is set in motion causing lattice distortion. Smaller the mass of the positive core, larger will be the distortion. The lattice vibrations are quantized in a terms of*Phonons*. Now another electron passing by this distorted lattice will interact with it and thus the energy of this electron is also reduced. This interaction is looked upon as if the two electrons interact via the phonon field, (because the lattice vibrations are quantized and quanta of these vibrations are *phonons*) resulting in lowering of energy for the electrons. Due to this interaction an apparent force of attraction develops between the electrons and they tend to move in pairs.*This interaction is strongest when the two electrons have equal and opposite spinsand momenta.*This leads to the formation of cooper pairs. *"**Cooper pairs** are a bound pair of electrons formed by the interaction between the electrons with opposite spin and momenta in a phonon field".*

At normal temperatures the attractive force is too small and pairing of electrons does not take place.At lower temperature, that is below the critical temperature the apparent force of attraction exceeds the Coulomb force of repulsion between two electrons leading to the formation of cooper pairs. According to quantum mechanics a cooper pair is treated as single entity. A wave function is associated with each such cooper pair and wave functions associated with similar cooper pairs start overlapping which extends over a million pairs and hence virtually over the entire volume of the superconductor. Finally large number of cooper pairs forms a union one aiding the motion of the other. So the entire union of cooper pairs will therefore move as one unit. The resistance experienced by any one cooper pair is overcome by the co-operative action of the other pairs in the union. Ultimately when electrons flow in a material in the form of cooper pairs do not encounter scattering. The resistance vanishes and conductivity is very large and thus the phenomenon superconductivity.

Effect of magnetic field:

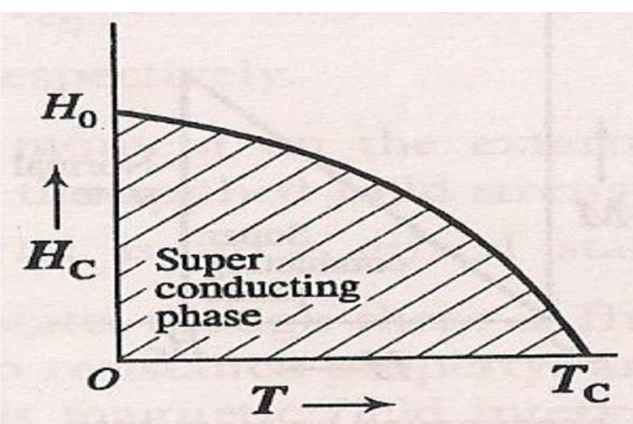
Superconductivity can be destroyed by applying magnetic field. The strength of the magnetic field required to destroy the superconductivity below the T_c is called critical field. It is denoted by $H_c(T)$.

If 'T' is the temperature of the superconducting material, 'T_c' is the critical temperature, 'H_c' is the critical field and 'H_o' is the critical field at 0^oK.

They are related by

$$H_c = H_o[1-(T/T_c)^2]$$

By applying magnetic field greater than H_o, the material can never become superconductor whatever may be the low temperature. The critical field need not be external but large current flowing in superconducting ring produce critical field and destroys superconductivity.



DEPENDENCE OF H_c ON T

Critical Temperatures for various Superconductors

Material	T_c(K)
Zn	0.88
Al	1.19
Sn	3.72
Hg	4.15
Pb	7.18
Nb	9.46
Nb_3Sn	18.05
Nb_3Ge	23.2
YBa_2Cu_3O7	92
Bi–Sr–Ca–Cu–O	105
Tl–Ba–Ca–Cu–O	125
$HgBa_2Ca_2Cu_3O_8$	134

Isotopic effect

In superconducting materials the transition temperature varies with the average isotopic mass of their constituents. The variation is found to be in general form

$$T_C \propto M^{-\alpha}$$

Or $T_C M^{+\alpha} = \text{constant}$

Where α is the isotopic effect coefficient and is defined as

$$\alpha = \frac{\partial \ln T_C}{\partial \ln M}$$

The value of α is approximately 0.5. For example, the average mass varies from 199.5 to 203.4 atomic mass units and accordingly the transition temperature varies from 4.185K to 4.146K.

High temperature superconductors / New superconductors

Superconductors with a transition temperature above 100°K are known as high temperature superconductors.In 1987 it was shown that Materials such as $YBa_2Cu_3O_{7-x}$,(x≤0.1) have critical temperature which is well above that of liquid nitrogen (77K). Hence they do not require liquid helium at all for cooling. These compounds are known as 1-2-3 compound as the constituent present are in the ratio 1, 2 & 3.

These are not metals or inter metallic compound, they are oxides classified as ceramics. All high temperature superconductors are different types of oxides of copper, and bear a particular type of crystal structure called Perovskites crystal structure. The number of copper layers increases the Tc value increases. The current in the high T_C materials is direction dependent. It is strong in parallel to copper-oxygen planes and weak in perpendicular to copper-oxygen planes.

High Tc materials are Type-II superconductors and they are brittle and not easily formed into wires, unable to carry large currents and unstable over long periods. The formation of electron pairs is not due to interaction of electron lattice as in the BCS theory. Still it is not clear what does cause the formation of pairs. Research is being conducting in this direction. The above said difficulties are not there with recent high temperature super conductors where the rare earth elements are replaced by Bismuth or Thallium(around 100K).Today one cannot rule out the possibility of room temperature superconductivity.

The high temperature superconductors are useful in high field applications. It can carry high currents of 10^5 to 10^6 amps in moderate magnetic fields. They are used in military applications, Josephson junction in SQUIDS, under sea communication, submarines.

Applications of Superconductors:

Superconductors are mainly used in

(1) Superconducting Magnets

(2) Magnetic levitation and permanent magnets

(3) Wires and cables for motors and power distribution systems

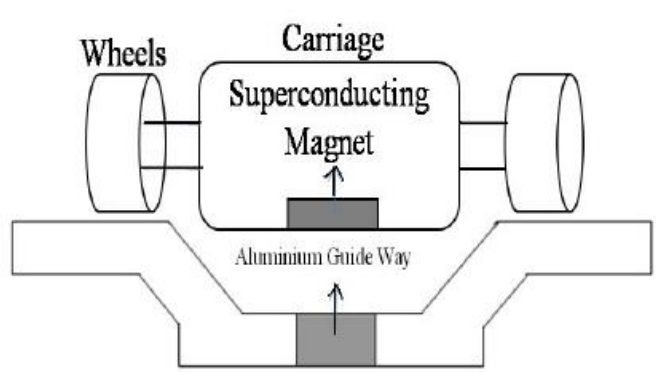
(4) Microwave filters for cellular telephone networks

(5) SQUIDS as sensors of foetal heart beats and brain signals, and

(6) Single flux quantum logic in quantum computing system

Magnetically Leviated Vehicles (Maglev vehicles): Magnetically leviated vehicles are called Maglev vehicles. The magnetic leviation is based on the principle of Meissner effect. The repulsion between the two strong fields produced by the superconducting magnet and electric currentlevitates the vehicleand is set afloat. The afloating of the vehicles by this principle is called *Magnetic Levitation.*

The superconducting magnet is kept inside the vehicle and the electric current flows in the Aluminium guide way. Once the magnetic field in the vehicle is switched on is repelled by the magnetic field of the guide way. As it is about to levitate, the guide way propels the vehicle forward by the segments provided in the Aluminium guide way. The vehicle is provided with retractable wheels. Initially the vehicle runs on the guide way, once it is levitated in air the wheels are retracted into the body. The height to which the vehicle is levitated above guide way is about 10 to 15cm. While stopping, the wheels are drawn out and the vehicle slowly settles on the guideway by running a distance. Since such vehicles float under magnetic effect, they do not have friction, less power consumption, and noiseless travel.



Difference between conductor, perfect conductor and superconductor:

Term for comparision	**Conductor**	**Perfect conductor**	**superconductor**
-----------	Conductivity is due to electrons	Conductivity is due to electrons	Conductivity is due to cooper pairs
-----------	A potential difference is required to drive the current	A potential difference is required to drive the current	A potential difference is not required to drive the current
Conductivity (σ)	σ is large	σ tends to infinity	σ is equal to infinity
Mean Collision time (τ)	τ is large	τ tends to infinity	τ is equal to infinity
Temperature dependence of σ	σ decreases with increase of temperature	σ decreases with increase of temperature	$\sigma = \infty$ at all temperatures below T_c.
Effect of magnetic field	Magnetic flux lines exist within the body and do not effect the flow of current.	Magnetic flux lines exist within the body and do not effect the flow of current	Expels all the magnetic flux lines out of its body and effect the flow of current.
-----------	There is loss of energy due to current flow	There is loss of energy due to current flow	There is no loss of energy due to current flow
Attainability of state	Realizable in practice	Theoretical concept	Realizable in practice
Theory to explain conductivity	Free electron theory	Free electron theory	BCS theory

Objective Type Questions

1) Superconductivity is a phenomenon in which the conductor becomes ---- diamagnetic.
2) Superconductivity is a phenomenon in which the conductivity becomes--- infinite
3) Superconductivity in mercury was discovered by ------ Kamerling Onnes
4) The temperature at which Superconductivity occurs is called the ---- critical temperature, then R=0 and B=0.
5) Superconductivity can be explained on the basis of BCS theory
6) The resistivity of the metals at 0 K --- is not zero
7) The resistance of a conductor becoming zero at a particular temperature is called---- Superconductivity
8) Mercury loses its resistance completely at temp----4.2 K.
9) Expelling of magnetic flux from the material of superconductor when it is kept in the magnetic field cooled below critical temperature is called ----- Meissner effect
10) The magnetic field at which a superconductor kept loses its

Superconductivity is called ------ critical field

11) Meissner effect is ---- reversible
12) Type I superconductors are not used in large applications because they posses ---- low H_C
13) The critical field H_C at any temp T below critical temp (T_c). H_0 is the critical field at 0K are related by

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

14) Type II superconductors are---- hard

15) Type II superconductors are used in many applications because the ----critical field is high

16) In superconducting magnet wires of superconducting substance are embedded in a thick copper matrix because while the material is in superconducting state ----- copper part helps in overcoming the mechanical stress developed

17) All high temperature superconductors are the oxides of ----copper

18) The quantum of magnetic flux is given by $\left(\frac{h}{2e}\right)$

19) When a magnetic field is applied it needs to cool the superconductor to a temp. $T < T_c$ to observe superconductivity

20) Magnetic levitation is based on ----- Meissner effect.

21) S Q U I D is used to measure the ----- low magnetic field up to 10^{-14} T

22) S Q U I D is used to measure the -----field of heart and brain.

23) The width of the energy gap of a superconductor is at 0K.

24) When the type-I superconducting material is placed in an external magnetic field, it repels the magnetic field lines.

25) Superconducting material, on being subjected to critical field, changes to normal state.

26) The relation between superconducting transition temperature T_c and atomic weight M of isotope is $T_c \alpha (1/\sqrt{M})$.