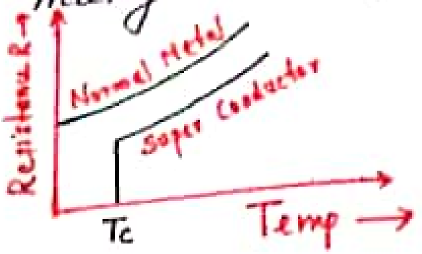
SUPER CONDUCTIVITY

The electrical resistance of metals and alloys decreases as the temperature is lowered. In the case of mercury, it is found that at very low temperatures the resistance becomes immeasurable. At about 4.2 K the resistance falls sharply and below this temperature mercury shows no resistance at all.

The phenomenon in which the electrical resitivity suddenly drops to zero when the material is cooled to a sufficiently low temperature is called superconductivity. The material is known as a super conductor.

The temperature at which the resistance of a material suddenly falls to zero is known as critical temperature T_c. At this temperature the material undergoes a phase transition from a state of normal resistance to a state of superconductivity. This temperature also known as super-conducting transition temperature. Super conductivity has been observed in many metals, alloys and compounds.

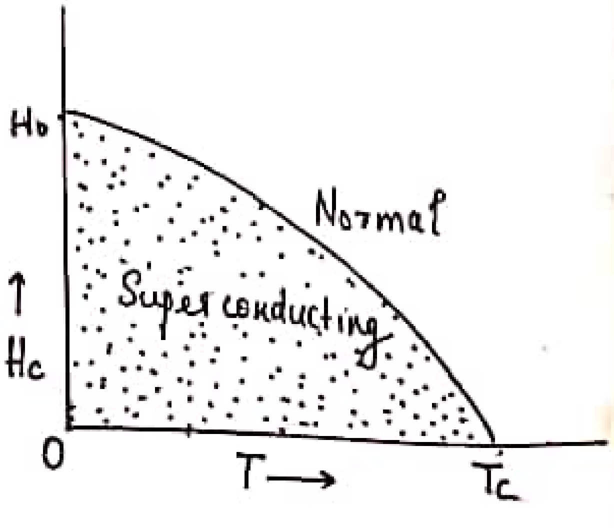


Critical field

It is possible to destroy the superconductivity of a superconducting material by the application of intense magnetic field. If the superconductor is placed in a sufficiently strong magnetic field, the superconductor becomes a normal conductor ie, it regains its resistance.

The value of magnetic field at which super-conductivity is destroyed is called the threshold or critical magnetic field. It is denoted by H_c and found to be a function of temperature.

If we plot a graph of critical magnetic field Vs temperature the curve is approximately parabolic as shown in fig.



It is given by the relation

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

H_0 → critical magnetic field at 0K.

According to this relation at 0 K

$$H_c = H_0$$

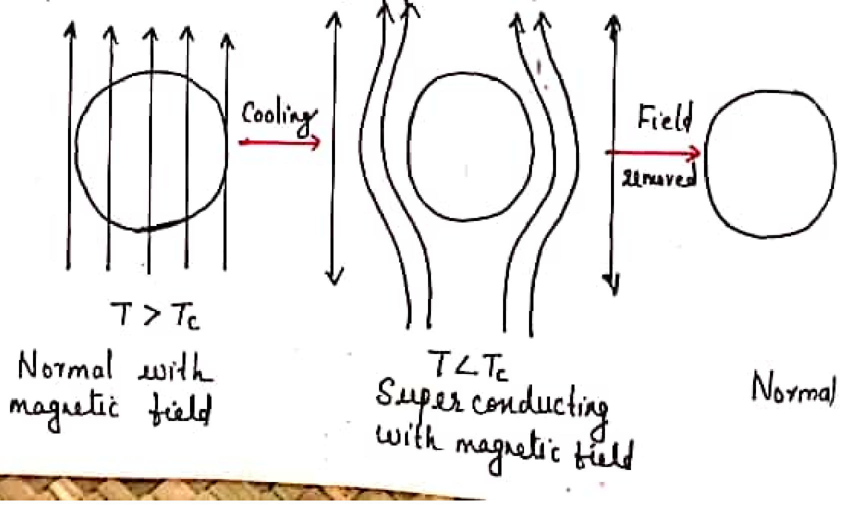
and at $T = T_c$; $H_c = 0$

The curve defines the boundary below which superconductivity is present and outside it, the superconductor ~~becomes~~ behaves as a normal conductor. ie, the super conducting state is stable only in some definite ranges of magnetic fields and temperatures.

Meissner Effect

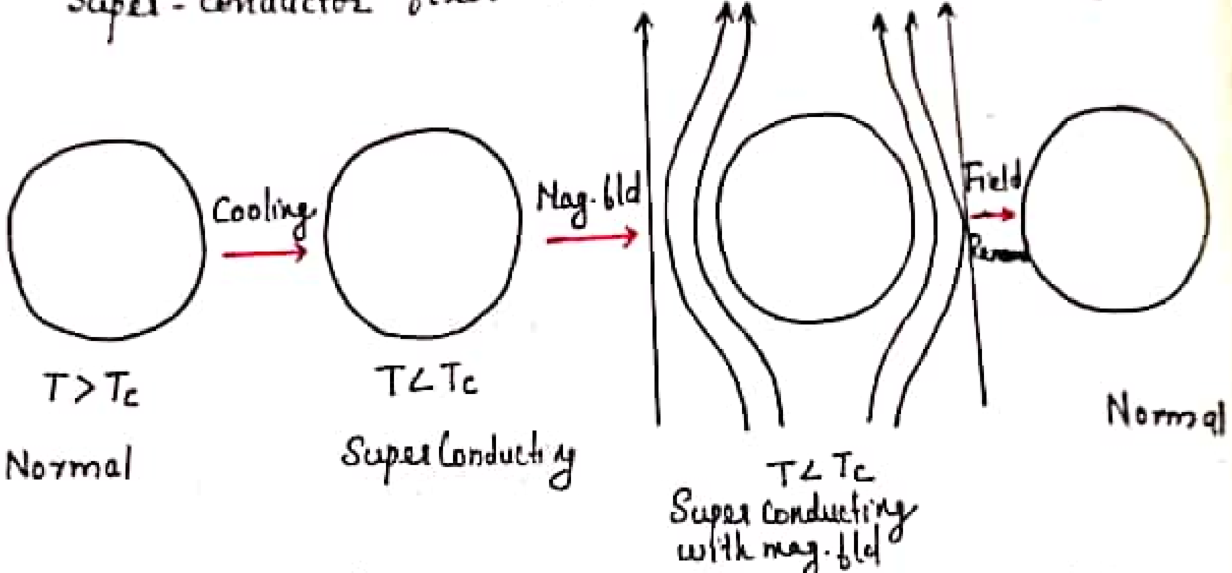
Meissner and Ochsenfeld in 1935 found that if a super conductor ~~is~~ (at a temperature $T > T_c$) is cooled in a magnetic field H below the transition temperature T_c, then at the transition temperature the lines of magnetic flux are pushed out of the specimen.

Super conductor first placed in mag. fld then cooled



The same flux exclusion is observed if the superconductor is first cooled below T_c and then placed in the magnetic field. The flux does not penetrate the material. This means that super conductor behaves as perfect diamagnetic.

Super-conductor first cooled and then placed in a mag. fld



In both cases, Meissner effect is reversible phenomenon ie, as soon as the magnetic field is removed the super conductor resumes its normal state.

Meissner effect shows that in an external applied magnetic field $\vec{H}$ the superconductor behaves as if inside the material the value of $\vec{B} = 0$

$$\vec{B} = \mu_0 (\vec{H} + \vec{M})$$

M → intensity of induced magnetism

$$0 = \mu_0(\vec{H} + \vec{M}) \quad \left[\text{At } T_c,\ \vec{B} = 0\right]$$

$$H = -\vec{M}$$

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

Magnetisation
produced per
unit applied field

ie, the material has a negative susceptibility and behaves as perfect diamagnetic.

According to Ohm's Law

$$\vec{E} = \rho\vec{J}$$

E → applied electric field
ρ → the resistivity of the material
J → the current density

For a perfect conductor, if the resistivity ρ becomes zero while the current density $\vec{J}$ has a finite value then $\vec{E} = 0$. Further according to Maxwell's equation

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

if $\vec{E} = 0$, $\nabla \times \vec{E} = 0$ $\quad \frac{\partial B}{\partial t} = 0$

or $\quad B =$ a constant

In other words, the magnetic flux density through the material for which $\vec{E}=0$ is a constant. ie, it cannot change on cooling through the transition temperature. Thus, when a perfect conductor is cooled in a magnetic field until its resistance becomes zero, the magnetic field in the material gets frozen and cannot change subsequently irrespective of the applied field. This result is contradicted by Meissner effect, according to which the phenomenon of flux exclusion ($\vec{B}=0$) at the transition temperature T_c ie, diamagnetism is an essential property of super-conducting state.

Hence for superconducting state perfect diamagnetism and zero resistivity are two independent properties Thus

$\vec{E}=0$ (zero resistivity)

$\vec{B}=0$ (Meissner effect / flux exclusion)

go side by side in a superconductor.

ie, the behaviour of a super conductor is different from that of a perfect conductor. The superconducting state may be considered as a characteristic thermodynamic phase of a substance. in which the substance cannot sustain steady electric and magnetic field.

Isotope effect

The critical temperature for a super conductor varies with isotopic mass. The transition temp. is given by $T_c M^{+1/2}$ = a constant where $M \xrightarrow{\text{is the}}$ isotopic mass. Thus heavier isotopes have a lower critical temperature.

A heavier isotopic mass lowers the lattice vibration. ~~It is known that~~ The Debye temperature 'θ_D' of the phonon spectrum is given by

$\theta_D = h\nu_D / k_B$

$$\theta_D M^{1/2} = \text{a constant}$$

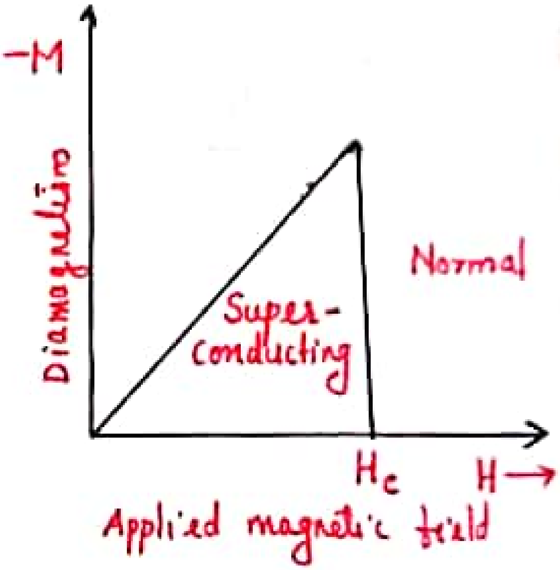
$$T_c \propto \theta_D \propto M^{-1/2}$$

The above relation shows that superconducting transition depends upon the mass of the lattice ions or phonons. In otherwords electron-phonon interaction is an important factor for the superconducting phenomenon.

There are two types of super-conductors depending upon their magnetic behaviour in an external magnetic field.

Type I or soft super conductors

Super conductors are perfectly diamagnetic and exhibit Meissner effect completely.

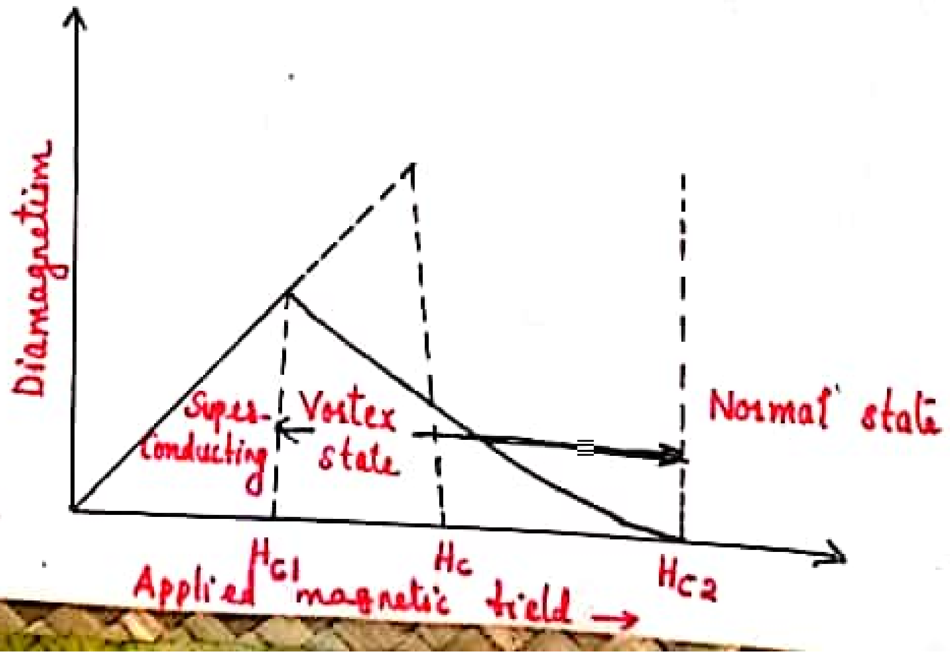


A graph between the applied magnetic field $\vec{H}$ and corresponding values of diamagnetism (−M) for a superconducting material is shown in the fig. It is seen from the graph that below a critical value of the applied magnetic field denoted by H_c, the specimen is superconducting exhibiting complete Meissner effect, ie perfect diamagnetism. The material loses super conductivity abruptly at the critical value H_c and diamagnetism suddenly drops down to zero ie, magnetic flux penetrates fully. Above the critical value H_c the material behaves as a normal conductor.

Such materials known as type-I superconductors are classified as SOFT superconductors, because of their tendancy to give away to low magnetic fields. The value of H_c is too small for SOFT superconductors and hence these do not have any useful technical applications. This behaviour is generally shown by pure specimens of some materials. Lead, Tin and Mercury belong to this group of superconductors.

Type II / hard superconductors

Alloys and transition metals with high values for electrical resistivity in the normal state belong to type II superconductors. Materials of this class exhibit a magnetisation curve as shown in the diagram. They have two critical fields – lower and upper critical fields.



Below the lower critical field Hc_1, the specimen is diamagnetic. Hence the magnetic flux is completely excluded from the interior of the superconductor in this range of magnetic fields. At Hc_1, the flux begins to penetrate the specimen. The penetration of the magnetic flux or magnetic field increases till the upper critical field Hc_2 is reached. At Hc_2 the magnetisation disappears and the specimen returns to the normal conducting state. However it may be said that this class of materials are completely superconducting for all magnetic fields below the upper critical field Hc_2. In type II superconductors, as the magnetic field is increased, the magnetisation vanishes gradually and not abruptly as in the case of type I superconductors. The value of the critical field for this type of superconductor is much higher than that for type I superconductors. Unlike type I superconductors, type II materials are technically very useful.

If the magnetisation curves shown in the graphs are reversible, the superconductor is said to be an ideal superconductor. Type I superconductors are always ideal while type II may or may not be ideal. Superconductors which exhibit irreversible magnetisation behaviour (magnetic hysteresis - residual magnetism on the withdrawal of magnetising field) are said to be non-ideal. Type II superconductors with large amount of magnetic hysteresis induced by mechanical treatment are called hard superconductors.

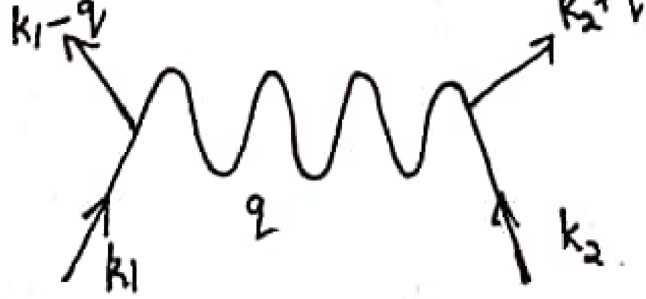
B.C.S. Theory

The microscopic theory of superconductivity put forward by Bardeen Cooper and Schrieffer (B.C.S.) in 1957 provides the better quantum explanation of the phenomenon. It accounts very well for all the properties exhibited by superconductors. This theory involves the electron interaction through phonons as mediators. In ordinary metal, the electrical resistivity is the result of the collision of the conduction ēs with the vibrating ions in the crystal lattice. B.C.S. theory describes superconductivity as a quantum phenomenon in which the conduction ēs move in pairs and thus show no electrical resistance.

The qualitative description of the theory is given in the following steps.

Electron - lattice - electron interaction

When an $\bar{e}$ approaches a +ve ion core it undergoes attractive coulomb interaction. Due to this attraction the ion core is set in motion and consequently distorts the lattice. The oscillatory distortion of the lattice is quantised in terms of phonons. If a second $\bar{e}$ now interacts with the distorted lattice, the energy of the second $\bar{e}$ is lowered. In otherwords the two $\bar{e}$s interact via the lattice distortion or the phonon field resulting in the lowering of energy of the $\bar{e}$s. This type of interaction is called electron - lattice - electron interaction. The interaction between the lattice and the $\bar{e}$s is in the form of constant emission and re-absorption (creation & annihilation) of phonons by the $\bar{e}$s. These phonons are therefore termed as virtual phonons.



Electron - phonon - electron interaction.

In quantum mechanical terms, the first electron of wave vector $\vec{k}_1$ creates a virtual phonon q and looses momentum while the second electron of wave vector $\vec{k}_2$ acquirs this momentum during its collision with the virtual phonons so that the overall momentum remains conserved.

BCS 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.

Cooper pairs

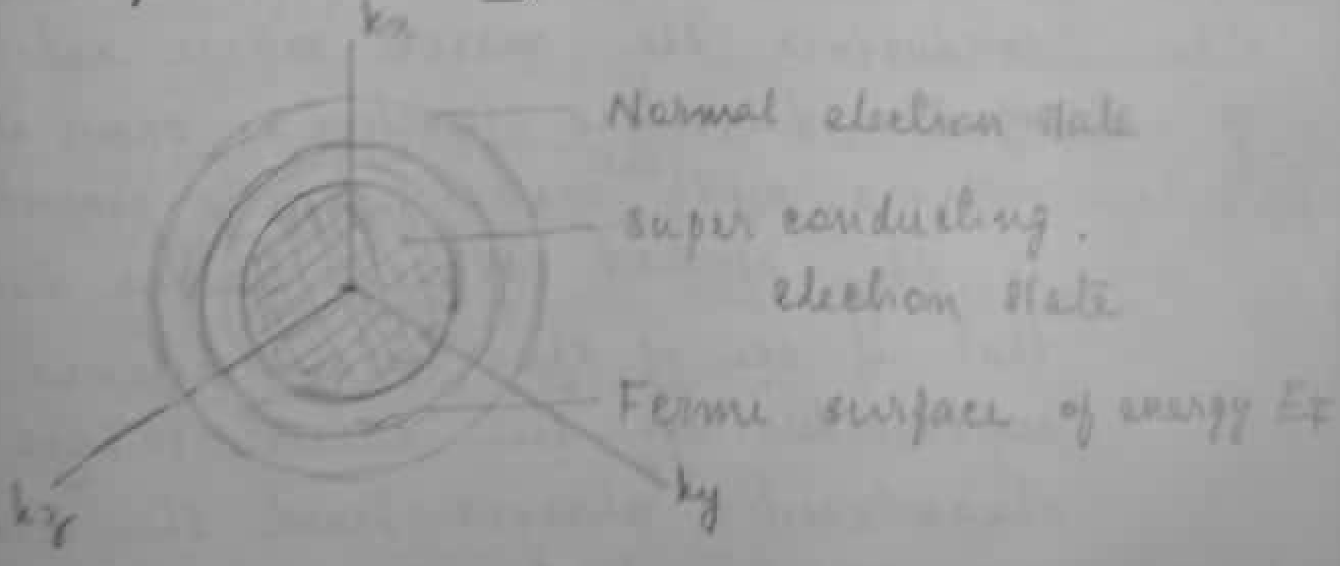
According to BCS theory superconductivity occurs when an attractive interaction between two $\bar{e}$s by means of a phonon exchange dominate the usual repulsive coulomb interaction. Two such $\bar{e}$s which interact attractively in the phonon field are called a cooper pair which has an energy of the order of 10^{-3} eV in a superconductor. When such pairs are created the conductor becomes a superconductor. Cooper has shown that two ēs would then be in a bound state. In a bound state the ēs are paired to form a single system and their motions are correlated. Such pairing is complete at $T=0K$. But as the temperature increases the no. of pair decreases and is completely broken at $T=T_c$, the transition temperature. The pairing can be broken only if an amount of energy equal to the binding energy is supplied to the system.

Coherence length

The cooper pair of ēs have a property of smoothly sailing over the lattice points without any energy ~~exch~~ exchange ie, cooper pairs are not scattered by the lattice points. Hence no transfer of energy takes place from the ē pair to the lattice ions. If an electric field is established inside the substance the ēs gain additional kinetic energy and give rise to a current. But they do not transfer this energy to the lattice, so that they do not get slow down. As a consequence the substance does not posses any electrical resistivity. So BCS theory explains the zero resistivity of a superconductor. The Cooper pair of ēs can maintain the coupled motion up to a certain distance among the lattice points in a superconductor called coherence length. This is found to be of the order of 10^{-6}m.

Existence of energy gap

The cooper pairs are bound together by a very small energy Δ and form a new ground state, which is superconducting and is separated by an energy gap 2Δ from excited state above it. The energy difference between the free or normal state of the electron and the paired or the superconducting state appears as the energy gap at the Fermi surface. The normal electron states are above the energy gap and superconducting ē states are below the energy gap at the Fermi surface. Energy gap is a function of temperature unlike the case of constant energy gap in semiconductors and insulators. Since pairing is complete at 0K, the difference in energy of free and paired electron states is maximum or in other words energy gap is maximum at absolute zero. At $T = T_c$, pairing is dissolved and energy gap reduces to zero resulting in the transition from superconducting state to normal state.



High temperature Superconductors

The extremely lower critical temperatures of ordinary superconductors puts a limit to their use in technological applications. High temperature or high T_c superconductors refers to those materials mainly oxides, which have high transition temperatures. The era of high T_c superconductors started with the discovery of certain class of oxide ceramic superconductors by Bednorz and Muller in 1986 which showed critical temperature greater than 30 K. The first group of such superconductors discovered was $La_{2-x} M_x CuO_4$ (M = Ba, Sr, Ca) with T_c ranging from 25 K to 40 K. Another important class of high T_c superconduc developed then was having the general formula $LnBa_2Cu_3O_{7-x}$ (Ln = Y, Nd, Eu, Gd) with transition

Lanthanium series $x \simeq 0.2$

temperature around 90 K. Another class of materials showing high temperature superconductivity is the Bi and Tl (Thallium) cuprates. (copper oxide) Eg:- $Bi_2Sr_2Ca_2Cu_3O_{10}$, $Tl_2Ba_2Ca_2Cu_3O_{10}$) having critical temperature in the range 70 - 125 K.

High T_c superconductivity in materials, chiefly ceramic oxides with high temperature accompanied by high critical currents and magnetic fields. Copper Oxide based superconductors are known as cuprate superconductors. All known high T_c superconductors are Type-II superconductors. The critical magnetic field tends to be higher for materials with a high T_c and in magnet applications this may be more valuable than the high T_c itself. Some cuprates have an upper critical field around 100 Tesla. Cuprate superconductors differ in many ways from conventional superconductors.

Questions from Superconductivity

1) What is superconductivity?
2) Define 'critical temperature' and 'critical magnetic field'
3) What is Meissner effect? Show that a superconductor is a perfect diamagnet
4) Explain the effect of magnetic field on a superconductor and compare soft and hard superconductors.
5) Write a short note on BCS theory
6) What is meant by high T_c superconductors Give its advantage
7) Write down the important applicatio of superconductivity.

6.3.3 Comparison between Type I and Type II Superconductors

The comparison of Type I and Type II superconductors is given as :

S.No.	*Type I Superconductor*	*Type II Superconductor*
1.	These superconductors are called as soft superconductors.	These superconductors are called hard superconductors.
2.	The critical field value is very low.	The critical field value is very high.
3.	Only one critical field (H_C) exists for these superconductors.	Two critical fields H_{C_1} (lower critical field) and H_{C_2} (upper critical field) exist for these superconductors.
4.	These superconductors exhibit complete Meissner's effect.	These do not exhibit a perfect and complete Meissner's effect.
5.	These materials have limited technical applications because of very lower field strength.	These materials have wider technological applications because of very higher field strength value.
6.	*Examples* : Pb, Hg, Zn etc.	*Examples* : Nb_3Ge, Nb_3Si etc.

with genuine electronic ctors. The search for a theoretical understanding of high Tc superconductivity is widely regarded as one of the most important unsolved problems in Physics.

9.5 APPLICATION OF SUPERCONDUCTORS

Superconductivity has wide ranging application from large scale devices which employ very fine superconducting windings made of type II materials to small scale electronic devices used in measuring instruments and computers.

Large-scale superconducting devices consists of magnets, motors, generators and cables. Very large scale superconducting magnets are used in magnetohydrodynamic (MHD) power plants, controlled fusion and energy storage. Large scale magnets have applications for sea and land transportation. The most spectacular application of superconducting magnet is in its use in levitated trains for a rapid transit system. 'Maglev' is the name given to such trains. Other important applications of a superconductors are as follows.

1. Low loss transmission lines and transformers can be made with superconductors.
2. Superconductors are used to perform logic and store function in computers.
3. Small size electric generators are developed with superconducting coils.
4. High capacity and high speed computer chips can be developed with superconductors.
5. Cryotron, a fast electrical switching system utilises superconductivity for its operation.
6. SQUID, a superconducting device has many applications in scientific, industrial, medical and communication fields.

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Fig 9.5 Threshold curves of the critical field Hc(T) vs. temperature for several superconductors

3 BCS THEORY OF SUPERCONDUCTIVITY

A microscopic theory of the electronic structure of superconductor was given in 1957 by Bardeen, L.N. Cooper and J.R. Schrieffer and is known as BCS theory. It is based on the mation of cooper pair of electrons.

During the flow of current in a superconductor, when an electron approaches a positive n of the metal lattice, there is a coulomb attraction between the electron and the lattice ion. his produces a distortion in the lattice. ie., the positive ion gets displaced from its mean osition. Smaller the mass of the positive ion core, the greater will be the distortion. This teraction called the electron-phonon interaction leads to scattering of the electron and causes lectrical resistivity. Now a second electron which approaches the distorted positive ion also xperiences coulomb attractive force. This process can be looked upon as interaction of two lectrons via the lattice. Because of this interaction an apparent force of attraction develops etween the electrons and they tend to move in pairs.

At normal temperatures the attractive force is too small and pairing of electrons does not take place. Below the transition temperature, the apparent force of attraction reaches a maximum value for any two electrons of equal and opposite spin. This force of attraction exceeds the coulomb force of repulsion between two electrons and the electrons move as pairs. These pairs of electrons formed by the interaction between the electrons with opposite spin and momenta in a phonon field are called cooper pairs.

Phonons are quanta of lattice vibrations. The pair has a total spin of zero. As a result, the electron pairs in a superconductor are bosons. The dense cloud of cooper pairs form a collective state and they drift co-operatively through the material. Thus the superconducting state is an ordered state of conduction electrons. The motion of all cooper pairs is the same. Either they are at rest; or if the superconductor carries a current, they drift with identical velocity. Since the density of cooper pairs is quite high, even large currents require a small velocity. The small velocity of cooper pairs combined with their precise ordering minimizes collision process. The extremely rare collisions of cooper pairs with the lattice leads to vanishing resistivity. At this stage, the cooper pairs of electrons smoothly sail over the lattice point without any exchange of energy. As a consequence, the substance possesses infinite electrical conductivity.

The BCS theory provides two important results, namely the existence of energy gap and the flux quantization.