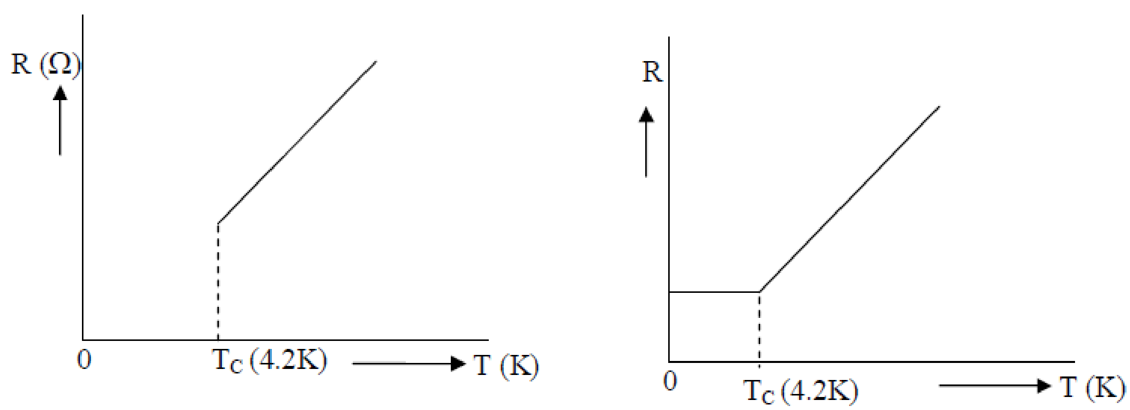
Module No: 6.4

SUPERCONDUCTIVITY

1: Introduction

It had been known for many years that the resistance of metals fell when cooled below room temperature, but it was not known what limiting value the resistance would approach if the temperature were reduced to very close to 0 K. At some very low-temperature point, scientists felt that there would be a resistance of value allowing the current to flow with little or no resistance. In 1908, Kamerlingh Onnes liquefied helium gas at a temperature of 4.2 k and began to investigate the electrical properties of Mercury (a metal) in extremely cold temperatures. He observed that at 4.2 K the resistance suddenly vanished. The current was flowing through the mercury wire and nothing was stopping it, the resistance was zero. Fig-1(a) is a graph of resistance versus temperature in mercury wire as measured. This is compared to the normal metal in Fig 8.1(b). According to Onnes, "Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the **superconductive state**". The experiment left no doubt about the disappearance of the resistance of a mercury wire. Later it was observed that many other metals and some alloys also behave similarly.

The unusual and interesting property of certain metals and alloys exhibiting almost zero resistivity (i.e. infinite conductivity when they are cooled to sufficiently low temperatures is called Superconductivity.



(a) (b)

Figure 1: Variation of resistance with temperature in (a) superconducting state and (b) in normal state

2. : Transition temperature

The temperature at which the transition from the normal state to superconducting state takes place on cooling, in the absence of a magnetic field, is known as the **transition temperature or the critical temperature (T_C).**

Several scientists discovered Nearly 21 elements and a large number of alloys that become superconducting, below a certain temperature are discovered. Each element would possess a transition temperature below which they become superconducting. Not all pure metals are superconductors, for example, alkali metals and noble metals have not shown superconductivity even when they are cooled to the lowest possible temperatures. A large number of alloys also exhibit superconductivity. Even an alloy, which is composed of two metals that are not themselves superconductors can exhibit superconductivity.

Element	**T_C (K)**	**Element**	**T_C (K)**	**Element**	**T_C (K)**
^{78}Hf	0.37	^{90}Th	1.37	^{23}V	4.89
^{44}Ru	0.47	^{81}Tl	2.39	^{57}La	4.82-5.8
^{40}Zr	0.55	^{49}In	3.40	^{82}Pb	7.22
^{40}Cd	0.56	^{50}Sn	3.74	^{41}Nb	8-9
^{31}Ga	1.10	^{80}Hg	4.12	^{43}Te	11.2
^{13}Al	1.20	^{73}Ta	4.38		

Table: Transition temperatures for different elements

3. EXPERIMENTAL OBSERVATIONS

(A) Zero resistance

The disappearance of dc resistance at temperatures below the transition temperature is the most important property of superconductors. This is in contrast with the behaviour of normal metallic resistivity that decreases with fall in temperature and approaches a residual value at T= 0 K. Careful measurements have shown that the dc resistivity of a superconductor is less than one part in 10^{-17} of the normal resistivity. There is thus every reason to assume the resistivity to be zero.

(B) Effect of Impurities on the Transition temperature

The transition temperature at which the metal becomes a superconductor, in general, is not very sensitive to small amounts of an impurity, though magnetic impurities tend to lower the transition temperature. Materials in Single-crystal form exhibit sharp transitions as compared to the polycrystalline state. The addition of non-magnetic impurity atoms (minute concentrations) to a superconductor does not affect the superconductivity, but the sharpness of the transition from the normal state to superconducting state is affected.

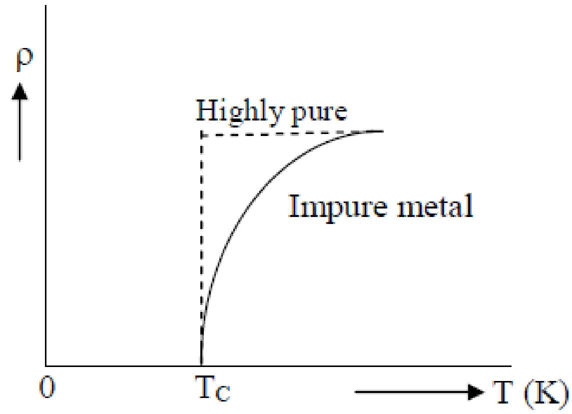


Figure-2: The effect of impurities on the sharpness of transition from normal to superconducting state

(C) Effect of magnetic field on superconductivity

The magnetic properties exhibited by superconductors were as dramatic as their electrical properties. Onnes observed that "there is the appearance of resistance in superconductors which are brought into a magnetic field at a threshold value of the magnetic field". This disappearance of superconductivity above a certain magnetic field was the first hint that superconductivity and magnetism are closely connected. The minimum magnetic field necessary to destroy superconductivity is called the critical magnetic field. It is also observed that the critical magnetic field is a function of temperature. This is shown in Fig-3.

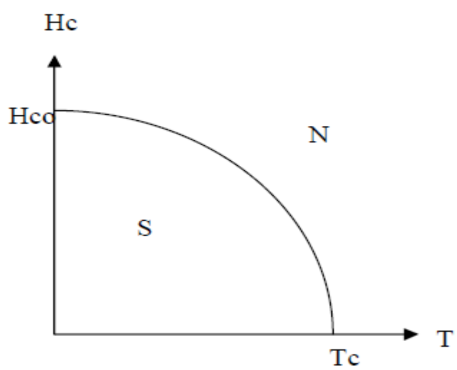


Figure 3 Effect of temperature on critical magnetic field

This variation is approximately given by

$$H_c = H_{co} [1-(T/Tc)^2 \qquad ....(1)$$

Where Hco is the critical field at absolute Zero. This is called Tuyn's law. This equation represents the phase boundary between the superconducting (S) and normal state (N). The value of H_{co} will be different for different materials.

(D) Effect of Current

The original observation on the destruction of superconductivity by the passage of current down a superconducting wire was made by K.Onnes. He found that superconductivity is destroyed when the current exceeds beyond a certain critical value. But since current can also create a magnetic field, according to Silsbee, the two phenomena are related. Silsbee suggested that the important factor in destroying superconductivity was the magnetic field associated with the current, rather than the current itself. The critical magnetic field required to destroy superconductivity need not necessarily be that applied externally. Thus the effect is field controlled. As the current is increased to a critical value I_c, the associated magnetic field becomes H_c and the superconductivity disappears. The critical current I_c flowing through a superconducting ring of radius r is given by

$$I_c = 2\pi r H_c \text{----------------} (2)$$

This limits the maximum possible current that flows through a superconductor. Hence this is the main hurdle in producing high field superconducting magnets.

4. Meissner effect

Meissner in the year 1933 found that if a superconductor is cooled in a magnetic field down to the transition temperature, then at the transition temperature, the lines of induction B are pushed out of the body of the superconductor. This phenomenon is called the **Meissner Effect**. This experimental observation was the first to demonstrate that superconductors are something more than materials which are having zero resistance; they have an additional property that a merely resistance less metal would not possess. Metal in the superconducting state never allows a magnetic flux density to existing in its interior. That is to say, inside a superconducting material we always have **B=0** and whereas inside a merely resistance less metal there may or may not be a flux density depending on the circumstances. Hence the essential properties of the superconductor are zero resistance and B=0 inside the specimen.

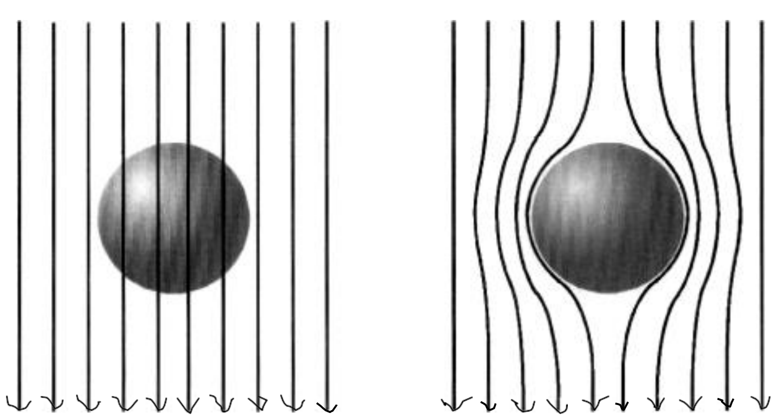


Figure- 4: Meissner Effect

This implies that a superconductor responds to the external field with a magnetic induction which exactly cancels it.

That is $B = \mu_o (H_e + M) = 0$ --------------------- (3)

Where μ_o is the permeability of the free space and M is magnetization. Thus a superconductor has a magnetic susceptibility $\chi = M/H_e = -1$, i.e., it behaves as a perfect diamagnetic. No substance is more diamagnetic! Typically, negative diamagnetic susceptibilities of normal metals are of the order of 10^{-5} to 10^{-6}. A diamagnet when placed in a uniform magnetic field, excludes about ten-millionth of it, while a superconductor excludes it.

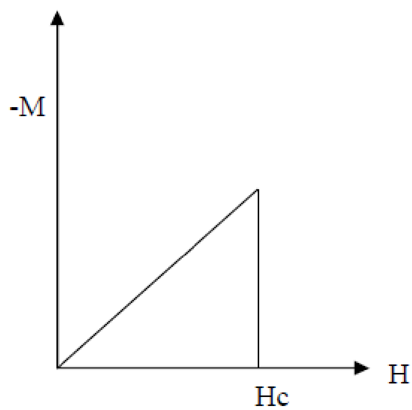


Figure-5: Magnetization vs external applied field in a superconductor

The flux at the transition temperature is ejected due to the induction of current in the specimen which produces a flux equal and opposite to the original flux due to the magnetic field. Since in superconducting state resistivity is zero, the current due to induction in specimen persists as long as the field is on. Due to this persistent current, specimen acquires a negative moment, producing a field in a direction opposite to the direction of the applied field. Due to the negative magnetic moment, the specimen behaves as a diamagnetic one.

5. Persistent currents

A current can be induced in a superconductor in the form of a ring, by cooling it in the presence of the magnetic field from a temperature above the critical temperature (T_c), to below Tc, and then removing the field. As the dc resistance of a superconductor is practically zero, the current set up is expected to persist forever even after the removal of the field. This current is called the persistent current which was observed by S.C.Collins. The persistent currents in a superconductor can be observed only if a properly shaped specimen is taken.

6. Type I and Type II superconductors

Based upon their diamagnetic response superconductors may be classified into two classes which depend on how the transition from the superconducting to the normal state proceeds when an applied magnetic field exceed the critical field, H_c.

(A) : Type I superconductors:

Superconductors exhibiting a complete Meissner effect i.e., perfect diamagnetism is called Type I superconductors. They are also called as soft superconductors. When the magnetic field strength is gradually increased from its initial value H<Hc, at Hc the diamagnetism abruptly disappear and the transition from the superconducting state to a normal state is sharp as shown in fig 6(a). They are usually pure specimens of some elements like Al, Zn, Hg and Sn, and the values of Hc for them are always too low (about 0.1 Tesla) to have any useful technical applications in coils for superconducting magnets.

(B) : Type II superconductors:

In this class of superconductors for applied fields below H_{c1}, the specimen is diamagnetic and hence the flux is completely excluded in this range of field. H_{c1} is called the lower critical field.

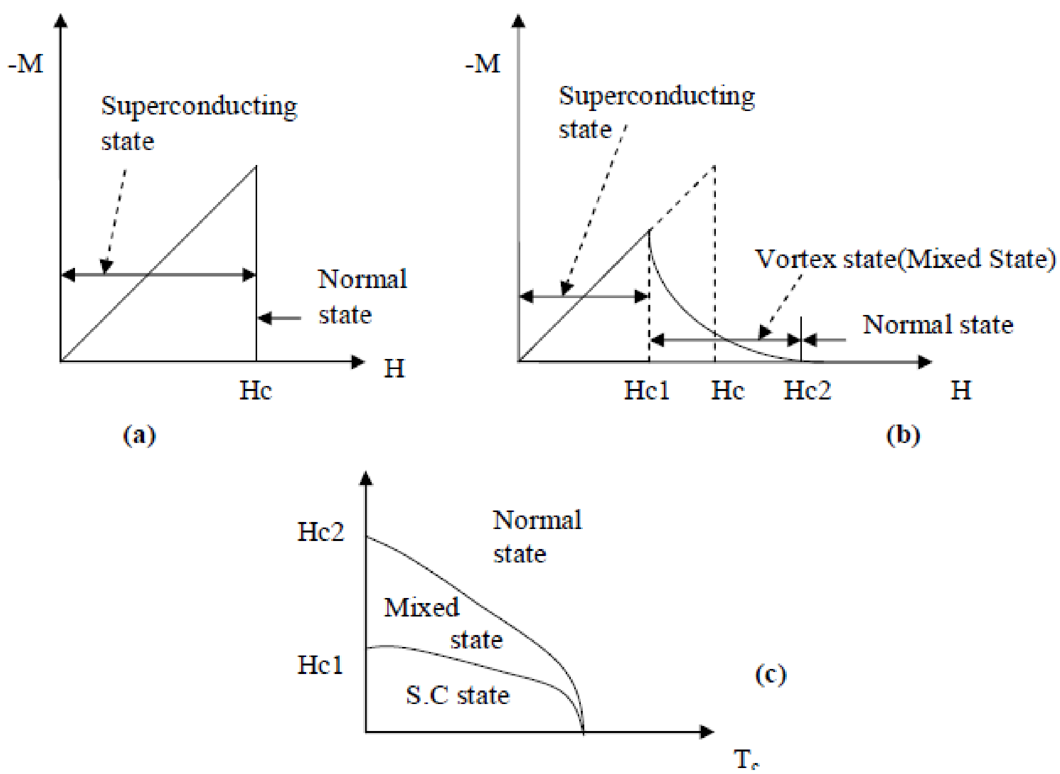


Figure-6: Magnetisation curves for (a) Type I (b) Type II and (c) Mixed state superconductors

At H_{c1} the flux begins to penetrate the specimen and the penetration increases till a critical field H_{c2} is reached. At H_{c2} the magnetization vanishes and the specimen becomes a normal conductor. H_{c2} is called the Upper critical field. Moreover, the magnetization of this group of superconductors vanishes gradually as the field is increased, rather than suddenly as in the case of Type I superconductors. In the region of partial penetration from H_{c1} to H_{c2}, the specimen assumes a complicated mixed structure of the normal and superconducting states. The specimen is said to be in vortex state or mixed state. Some of the alloys or transition metals with high values of electrical resistivity in the normal state behave as Type II superconductors. These are technically very useful materials. Type II superconductors are called hard superconductors. The hard superconductors have been used as solenoids in superconducting magnets that are capable of producing steady fields of over 20 Tesla. These magnets are useful in the Magnetic Resonance Imaging (MRI), an import application in medical diagnosis.

7. Specific heat of superconductors

The specific heat of normal metal comprises of two contributions; electronic and phonon contributions. The expression for the specific heat of a normal metal is of the form

$$C_{normal} = C_n = \gamma\, T + \beta\, T^3 \quad \text{--------------} \ (4)$$

Where the linear term, γ T is due to electronic excitations and the cubic term, β T^3 is due to lattice vibrations at low temperatures.

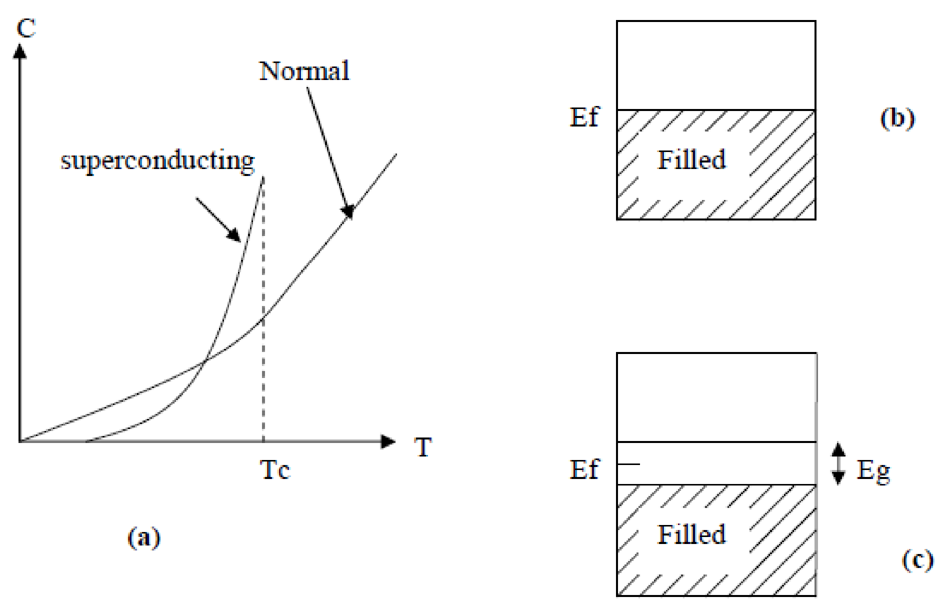


Figure-7: (a) Variation of specific heat with temperature in normal and superconducting states.
(b) Absence of energy gap in normal state
(c) Energy gap Eg in superconducting state

However, below the superconducting critical temperature, this behaviour is substantially altered. As the temperature drops below Tc, the specific heat jumps to a higher value and then slowly decreases, eventually falling well below the value one would expect for a metal. Such an analysis reveals that in the superconducting state, the βT^3 term has the same value in both states and the linear electronic contribution to the specific heat is replaced by a term that vanishes much more rapidly at very low temperatures having a dominant low-temperature behaviour of the form $\exp(-\Delta /KT)$. This is the characteristic thermal behaviour of a system whose excited levels are separated from the ground state by a certain energy. Thus the total specific heat of the superconducting state is $C_s = \beta T^3 + C_{es}$, where C_{es} is the electronic contribution in the superconducting state. C_{es} can be written as, $C_{es} = A \exp(-\Delta /KT)$. Hence

$$Cs = \beta T^3 + A \exp(- \Delta/KT) \text{------------------------} (5)$$

An exponential dependence implies that it requires definite energy Δ to excite an individual electron in a superconductor. The superconductor has an energy gap against the excitation of electrons. The energy gap Δ is of the order of KT.

8 : Thermal conductivity in superconductors

Good conductors of electricity should also be good conductors of heat, which is true with normal conductors. In normal metals, the heat current is predominantly carried by the conduction electrons at low temperatures. But superconductors in contrast with the behaviour of normal conductors exhibit low values of thermal conductivity, notwithstanding their excellent electrical conductivity. The interpretation of this behaviour is based on the argument that the electric current in a superconductor is due to the flow of electron pairs and not of single electrons. Since electron pairs have zero energy, they cannot transport thermal energy though their flow does constitute an electrical current by their net charge. This implies that the electronic contribution to the thermal conductivity of a superconductor comes entirely from normal electrons whose excitation occurs through the energy gap, E_g

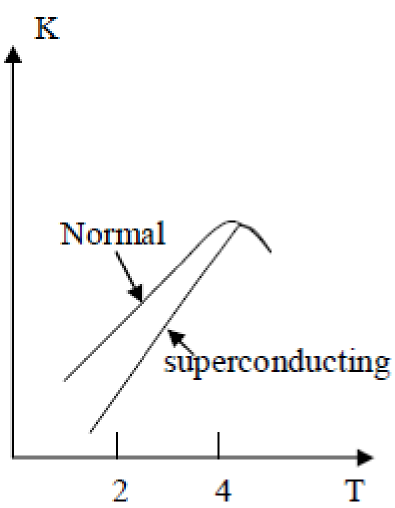


Figure-8: Variation of thermal conductivity with temperature

9: Absorption of electromagnetic radiation

A direct way of testing the presence of an energy gap in superconductors is by light absorption. The energy gap, E_g, determines the threshold photon energy, hν, below which no absorption occurs in a superconductor. For photons with $h\nu<E_g$, a superconductor has zero resistance at absolute zero. But photons of energy higher than E_g cause excitation to the unoccupied normal energy states above the gap and the resistance approaches its normal state value. The resistance in both the superconducting and normal states is essentially the same in this case.

10: High T_c Superconductors

In 1986, a real breakthrough in superconductivity took place. Bednorz and Muller discovered metallic, oxygen-deficient copper oxide compounds of the Ba-La-Cu-O system with a transition temperature of about 35K. Chu and co-workers formed the Y-Ba-Cu-O system with a transition temperature of 90K. These are called High-Temperature superconductors. Further with the development of new oxide superconductors having Tc of 125K or above, there has been tremendous excitement in the scientific world. This has opened up a new age of high-temperature superconducting devices, which have widespread commercial applications.

11 : Some applications of superconductors

The applications of superconductors are many and diverse. Some of them are mentioned below:

a) Electromagnets: Strong magnetic fields can be produced by winding Type II superconducting wire with the form of solenoids or circular coils. They can easily produce fields of 20 Tesla. The superconducting wire has to be maintained below the transition temperature of the wire taken. The advantage is that the power consumption would be 1000 times less than that required for ordinary metal would electromagnets. The energy stored in the magnetic field that can be achieved would be around $4KJ/m^3$ at 10 Tesla.

   The Superconducting wires are also used in transformers that do not require magnetic cores.

b) ***Bearings***: Bearings use the Meissner effect. The mutual repulsion between two superconductors that expel the magnetic flux is used in the principle. The bearings operate without power loss and friction.

c) High Power Transmission: The superconducting cable transmits power without power loss-niobium-zirconium alloy wires, niobium-titanium wires, niobium-titanium – zirconium alloy wires are very useful for this purpose. It is expected that high-temperature superconducting wires will be of immense use for power transmission.

d) Superconductors are useful in Cryotronics. Cryotronics is a branch of electronics that deals with low temperatures electronic systems. Superconductors are useful in receiving or detecting extremely weak radio signals. They possess a high degree of frequency stability and frequency selectivity of microwave signals. The long-range reception is possible now with them with an extension of radio wavebands into microwave region and infrared region.

e) The memory systems, logic units, Cryotronic switches, Oscillators, amplifiers, modulators, etc., are possible with superconductors. The capacity of a Cryotronic memory cell is up to a billion bits and the speeds that can be achieved are of the order of 10^{-6} to 10^{-7}sec.

f) The outer space is a vacuum, extremely cold and radiation full. Rockets are based on Cryogenic liquids. Therefore, satellite-borne apparatus should be of a mini size and be able to use the low-temperature facility for the operation. In such cases, compact superconductivity based systems are extremely useful.

g) **Superconducting magnetometers**: They are capable of measuring magnetic fields whose induction B is smaller than 10^{-11} Tesla. SQUID (Super Conducting Quantum Interference Devices) is useful for measurement of very low magnetic moments. A Josephson junction place in a magnetic field gives a change in the current density across the junction just like the simple slit diffraction pattern in optics. Of two junctions are placed side by side, then supercurrent density exhibits an interference pattern like a double slit arrangement in optics. SQUID magnetometer is useful for the precision determination of h/e. A superconducting ring acts as a storage house for magnetic flux. A very low magnetic field can be detected with SQUIDs. They are extremely useful in detected ores or oil deposits inside the earth. The magnetic maps are taken in several regions of the earth. SQUIDs are also useful in medical diagnostics of heart and brain. Nuclear magnetic resonance imaging is useful in medical diagnostics.