SUPERCONDUCTIVITY

INTRODUCTION

The electrical resistivity of many metals and alloys drops suddenly to zero when the specimen is cooled to a sufficiently low temperature called **critical temperature or transition temperature** T_c This phenomenon is known as superconductivity.

Superconductivity was first observed in 1911 by a Dutch physicist **H.K. Onnes** in the course of his experiment on measuring the electrical conductivity of metals at low temperatures. He observed that when purified mercury was cooled to 4.2 K, its resistivity was small but finite while the resistivity below this temperature was so small that it became zero. Superconductivity occurs in metallic elements of the periodic system and also in alloys and semiconductors. The range of transition temperatures extends from 23.4 K for the alloy to 0.01 K for some semiconductors. The highest critical temperature found for a conventional superconductor is 39 K for magnesium boride (MgB_2). The cuprate superconductor YBa_2CuO_7 has a critical temperature of 92 K and mercury based cuprates have a critical temperature in excess of 130K. **Bardeen, Cooper and Schrieffer** explained the nature and origin of superconductor in 1957 using BCS theory. The transition from normal to superconducting state is not accompanied by any change in the structure of the crystal lattice and has been interpreted as an electronic phase transition. The superconductivity is known to be an ordered state of the conduction electrons of the metal. The order is in the form of pair of electrons. The electrons are ordered at the temperature below the transition temperature and they are disordered above the transition temperature. Onnes observed that the superconducting transition is reversible. When he heated the superconducting sample, it recovered its normal resistivity. When impurities are added to superconducting elements, the superconducting property is not lost completely but transition temperature has to be lowered further for the complete superconducting property.

The electrical resistivity of a superconductor is zero. The magnetic flux lines are excluded from the material. There is a discontinuous change in the specific heat. There are also small changes in the thermal conductivity and the volume of the material. The entropy of superconducting material is smaller than that of the conducting material. The superconducting properties of the material can be changed by varying temperature, magnetic field, magnetic stress, impurity, atomic structure, size, frequency of the excitation of the applied electric field and isotopic mass.

PROPERTIES OF SUPERCONDUCTORS

1. Critical temperature

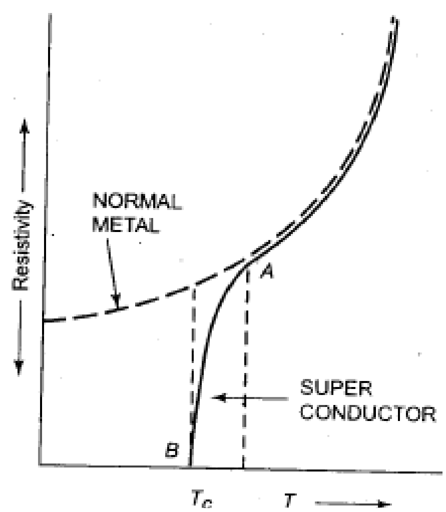


Fig.1- critical temperature

The superconducting transition temperature is defined as a critical temperature T_c at which the resistivity of the material is suddenly dropped to zero. Fig. 1 shows that at critical temperature or transition temperature a material changes from normal to superconducting state. Hence the critical temperature T_c or the transition temperature at which the transition from normal state to superconducting state takes place on cooling in the absence of magnetic field. .The superconductivity is known to be an ordered state of the conduction electrons of the metal. The order is due to the formation of pairs of electrons. The electrons are ordered at temperature below the transition temperature. They are disordered above the transition temperature.

2. Critical field

The superconducting state of metal exists only in a particular range of temperature and magnetic field strength. The condition for the superconducting state to exist in the metal is that some combination of temperature and magnetic field strength should be less than a critical value. Superconductivity will disappear if the temperature of the specimen is raised above critical temperature or if sufficiently strong magnetic field is employed. If a strong magnetic field called critical field is applied to a superconducting specimen it becomes normal and recovers its normal resistivity even at $T < T_c$. The critical value of the applied magnetic field for the destruction of superconductivity is denoted by H_c(T) and is a function of the temperature. For a given substance, the value of H_c decreases as the temperature increases from $T = 0\ K$ to $T = T_c$. The critical magnetic field above which the superconductivity will disappear can be given by the relation,

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

where H_c is the critical field strength at temperature T and H_0 is the maximum critical field at 0 K and T_c is the critical temperature in zero field (example Meissner effect). Thus the above equation defines a curve, which divides the normal region from the superconducting region.

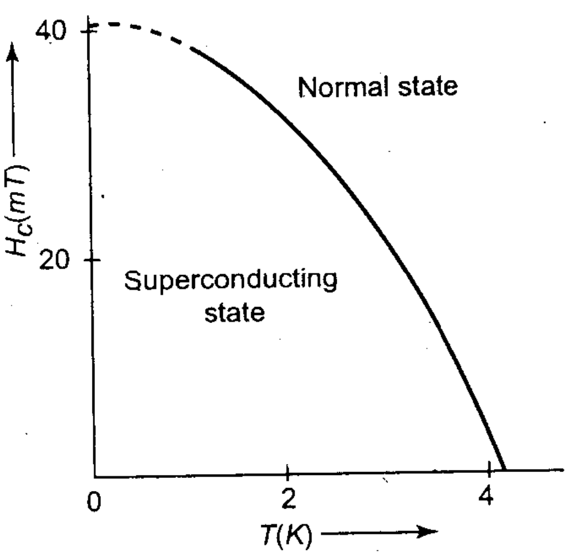
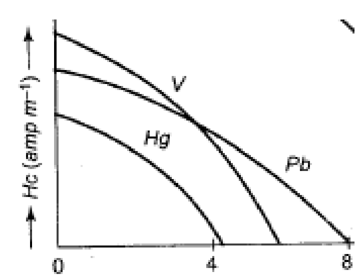


Fig.2- *(a) Critical magnetic field as a function of temperature*



(b) The critical magnetic field as a function of temperature for different superconducting materials

Fig.2 (a) shows the critical field temperature behavior of a typical superconductor. The region inside the curve represents the superconducting phase and the region outside the curve represents the normal phase. The critical field variations with respect to temperature of some pure metals are shown in Fig.2 (b). The curves are plotted for the metal, mercury, vanadium, lead and niobium.

3. Isotopic effect

According to the observations of Maxwell and others, the critical temperature of superconductors varies with isotopic mass. For example, for mercury, Tc varies from 4.185 K to 4.146 K as the isotope mass M varies from 199.5 to 203.4. The argument was that isotopic mass could enter in the process of the formation or superconducting phase of the electron states only through electron-phonon interaction. In the early years of the development of BCS theory the simple law can be written as

$$T_c \propto M^{-\beta}$$

with β = 0.5 which was thought to be valid for most of the materials.
So,

$$T_c M^{1/2} = const.$$

That is, the critical temperature *Tc* is inversely proportional to the square root of the isotopic mass of the material. Comparatively, for lower isotopic mass, the critical temperature is higher and for higher isotopic mass, the critical temperature is lower. The isotopic effect is that, the critical temperature of a material varies with the isotopic mass, since a heavier isotopic mass lowers the lattice vibrations. This indicates that superconductivity is due to an interaction between electrons and lattice vibrations.

4. Meissner effect

The second defining characteristic of a superconducting material is much less obvious than its zero electrical resistance. It was over 20 years after the discovery of superconductivity that Meissner and Ochsenfeld discovered it in 1933. If a specimen is placed in a magnetic field and is then cooled through the transition temperature for superconductivity, the magnetic flux originally present is ejected or pushed out from the specimen. This phenomenon is known as **Meissner effect.**

The exclusion of the magnetic field from a superconductor takes place regardless of whether the sample becomes superconducting before or after the external magnetic field is applied. In the steady state, the external magnetic field is cancelled in the interior of the superconductor by opposing magnetic fields produced by a steady screening current that flows on the surface of the superconductor.

According to Meissner effect, when an external magnetic field is applied to a superconducting material, the magnetic field induction (B) inside the material becomes zero and the superconductor behaves as a diamagnetic material.

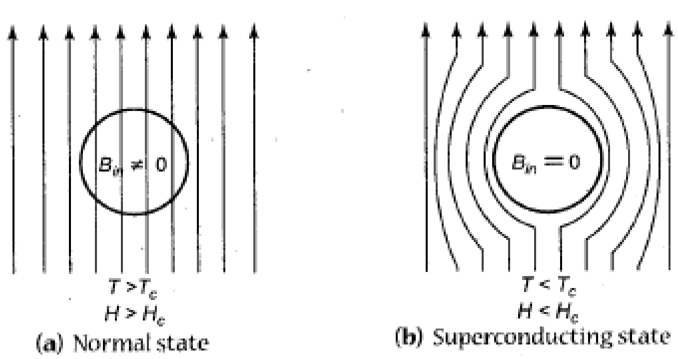


Fig 3: Meissner effect

Fig.3 (a) illustrates the normal state of the specimen at a temperature greater than the transition temperature kept in an external magnetic field greater than critical filed H_c. Fig. 3(b) illustrates that the specimen at a temperature below the transition temperature kept in an external magnetic field less than H_c behaves, as a superconductor resulting in zero magnetic field induction inside the specimen.
The magnetic induction inside the specimen is given by the equation

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

where H is the magnetizing force and M is the intensity of magnetization. When the specimen becomes superconducting $B = 0$ inside the material. Therefore,

$\mu_0 (H + M) = 0$ or $(H + M) = 0$ Or, $M = -H$

Susceptibility $\chi = M / H$, which is negative. The superconductor thus exhibits perfect diamagnetism because of negative value of magnetization and susceptibility.

However, the field is excluded only if it is below a certain critical field strength, which depends on the material, the temperature and the geometry of the specimen. Above this critical field strength the superconductivity disappears. Fritz and Heinz London brothers proposed a model that described the exclusion of the field in 1935.

5. Entropy

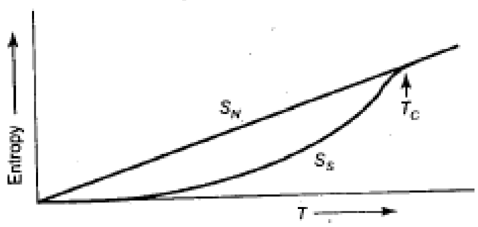


Fig.4 - Entropy of aluminium in the normal and superconducting state as a function of temperature.

Entropy is defined as a measure of disorder of a system. In normal metals with decrease of temperature, the entropy decreases linearly as shown in Fig. 4. In superconducting state metals like aluminium the entropy decreases linearly up to the critical temperature T_c and cooling below the critical temperature the entropy decreases markedly. This means that the superconducting state is more ordered than normal state. The decrease in entropy in superconducting state means that the electrons thermally excited are more ordered in the superconducting state. It has been estimated that in type I superconductors, there is a spatial order which extends over a distance of 10^{-6} meter and this range is called the coherence length.

6. Specific heat

In the normal state, the electronic specific heat $C_v = \gamma$ T. In the superconductor, the electronic specific heat has roughly an exponential dependence of the form

$$C_{es}(T < Tc) = A \exp\left(-b\frac{Tc}{T}\right) = A \exp\frac{-\Delta(T)}{k_B T}$$

Here Δ(T) being the energy gap. The behaviour of specific heat of superconductor is suggestive of excitation of electrons cross the energy gap. Such exponential temperature dependence indicates the system to have a gap Δ(T) in the superconducting electron levels, separating excited states from the ground state by the energy Δ. It has been shown that the gap decreases from a value of 3.5 $k_B Tc$ at 0 K to zero at Tc. Heat capacity measurements provided the first indications of a gap in superconductors and one of the key features of BCS theory is its prediction of a gap in superconductors. Fig. 5 gives the curves of specific heat of conductor and superconductor as a function of temperature. From the figure it can be concluded that near the critical temperature specific heat of conductor is less than the specific heat of superconductor, but at lower temperatures the specific heat of conductor is greater than the specific heat of superconductor. We also find that at the transition temperature there is a discontinuity in the specific heat curve.

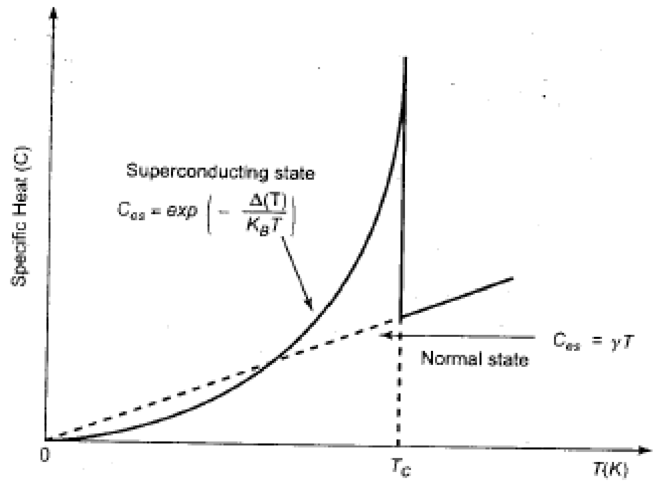


Fig.5 -Specific heat of conductor and superconductor as a function of temperature

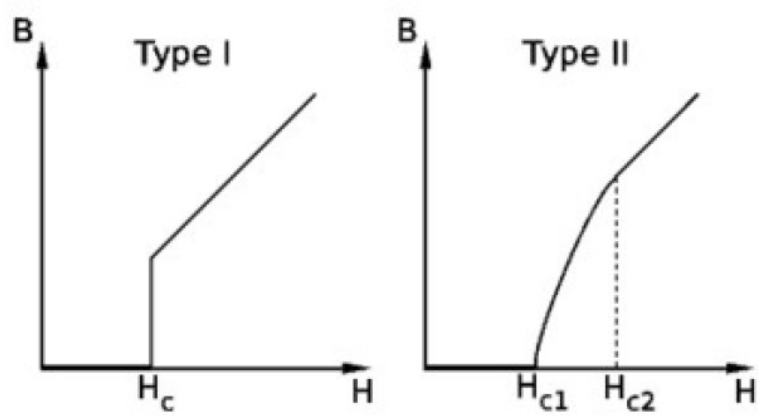
7. Thermal conductivity: The thermal conductivity of a material is usually low in a superconducting transition and at very low temperatures approaches to zero. This suggests that the superconducting electrons possibly play no part in the heat conduction.

Types of superconductors

Based on diamagnetic response, superconductors can be classified as type I superconductor also known as soft superconductors and type II superconductors also known as hard superconductors.

(i) Type I superconductors (or soft superconductors)

Type I superconductors exhibit a complete Meissner effect. The typical magnetic behavior of type-I superconductor is illustrated in Fig.6. It can be observed from the figure that the specimen is a superconductor by exhibiting diamagnetic property below the critical magnetic field H_c. At critical magnetic field the specimen excludes all the magnetic lines of force. The specimen becomes a conductor above the critical magnetic field H_c and the magnetic field penetrates the material completely. These materials give away their superconductivity at lower field strength and so, type I superconductors are also called soft superconductors. The highest known critical field H_c for these materials is of the order of 1000 gauss (0.1 Tesla) making these materials unsuitable for use in high field superconducting magnets. Pure specimens of various metals like lead, tin and mercury exhibit this type of behavior.



Variation of internal magnetic field (B) with applied external magnetic field (H) for Type I and Type II superconductors

Fig. 6 shows that the transition at H_c is reversible, which means that if the magnetic field is reduced below H_c the material again acquires superconducting property and the field is expelled.

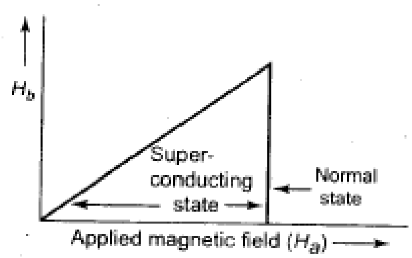


Fig. 6- Type I superconductor

(ii) Type II superconductor (or Hard superconductor)

The typical magnetic behavior of type II superconductor is illustrated in Fig.7. Alloys and transition metals with high values of the electrical resistivity in the normal states fall under type II of superconductors. In type II superconductors if the applied field is below H_c the specimen is superconducting and diamagnetic and hence the flux is completely excluded in this range of magnetic field. At H_{C1} the flux begins to penetrate the specimen and the penetration of the flux increases until the upper critical field H_{C2} is reached. At H_{C2} the magnetization vanishes and the specimen returns to normal conducting state.

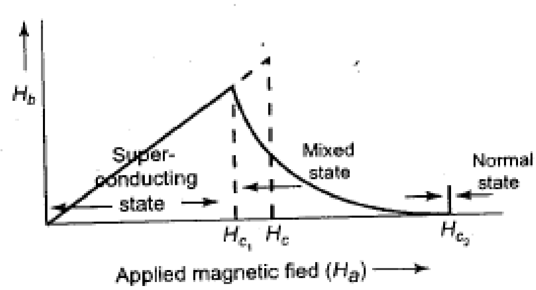


Fig.7- Type II superconductor

In type II superconductors the magnetization vanishes gradually as the field is increased rather than suddenly as for the type I superconductors. The value of the critical field for type II materials may be 100 times or more higher than the value of the critical field obtained for type I superconductors. The type II superconductors are also known as hard superconductors because relatively large fields are needed to bring them back to the normal state. Also large magnetic hysteresis can be induced in these materials by appropriate mechanical treatment. Hence these materials can be used to manufacture superconducting wires, which can be used to produce high magnetic fields of the order of 10 tesla.

Intermediate or vortex state

A distinguishing characteristic of type I superconductors is Meissner effect. In type II superconductors, the magnetic flux penetrates through even after the Meissner region. This is illustrated in the Fig. 7 in which it is clear that superconductivity is only partially destroyed in type II superconductors for

$H_{c_1} \ll H_c \ll H_{c2}$.

This region between H_{c1} and H_{c2} is called intermediate or mixed or vortex state. It is really a mixture of normal and superconducting state. In this region the magnetic flux lines gradually penetrate the specimen as the magnetic filed is increased beyond H_c. In general the vortex or intermediate state is unstable in type I superconductors but stable in type II superconductors.

Distinction between Type I Superconductors and Type II Superconductors

Type I Superconductors	**Type II Superconductors**
They exhibit complete Meissner effect.	They do not exhibit, complete Meissner effect, because they lose magnetization gradually.
There is only one critical magnetic field.	There are two critical magnetic fields namely lower critical field H_{c1} and upper critical field H_{c2}
No mixed state exists.	Mixed or vortex state is present.
Highest known critical field is 0.1 *T*	The critical field is much greater than in - type I superconductor, which is l0 T.
Examples: Lead, tin, mercury.	Examples: Niobium and vanadium.
They are also known as soft superconductors.	They are also known as hard superconductors.

The two-fluid model

In 1934, in order to explain thermodynamic properties of superconductors in fuller detail, **Gorter and Casimir** introduced the *two-fluid model of superconductivity.* According to this model, there are two types of conduction electrons in a superconductor namely the superconducting electrons and normal conducting electrons. The normal electrons behave in the usual fashion as charged particles flowing in a viscous medium. But the superelectrons have several novel properties which endow the superconductor with its distinctive features. These electrons experience no scattering, have zero entropy (perfect order), and a long *coherence length (about* 10^3 nm). At 0 K a superconductor contains only superconducting electrons, but as temperature increases the ratio of the normal electrons to superconducting electrons increases, until at the transition temperature all the electrons are normal. At any temperature the sum of superconducting electrons and normal conducting electrons is equal to the conducting electrons in the material in the normal state.

$i = i_n + i_s$

The number of superelectrons depends on the temperature. To obtain agreement with experiment, Gorter and Casimir found that the concentration of these electrons is given by the formula

$$n_s = n\left[1 - \left(\frac{T}{Tc}\right)^4\right]$$

Thus, at $T = 0$ K, all the electrons are superelectrons, but as T increases, the superelectrons decrease in number, and eventually they all become normal electrons at $T = Tc$. The two-fluid model explains the zero-resistance property of the superconductor. For $T < Tc$, some superelectrons are present, and since these have infinite conductivity-recall that they experience no scattering-they essentially short-circuit the normal electrons, resulting in infinite conductivity for the sample as a whole.

This model may be readily related to the concept of the energy gap. All the electrons below the gap are essentially frozen in their state of motion by virtue of the gap; hence these are the superelectrons. Those above the gap are normal electrons. The gap decreases as the temperature increases, and vanishes entirely at $T = Tc$, as shown in Fig. Thus, as $T \rightarrow Tc$ and the gap vanishes, all the electrons become normal.

London equations

The most interesting superconducting phenomena, and the most useful in practice, are the electrodynamic properties. The theory underlying these phenomena was put forward by the London brothers in 1935.The theory is semi-phenomenological in nature, in that it uses an additional equation which could not at that time be derived from first principles, but it is nevertheless extremely useful because it explains known observations with minimum mathematical effort. The London theory is based on the *two-fluid model.* The Maxwell's electromagnetic equations are inadequate to explain the *electrodynamics* of superconductors, namely, the zero resistance state and perfect diamagnetism. F. London and H. London derived two field equations to explain the superconducting state of matter by modifying Ohm's Law.

First London equation

Since superconducting electrons are not subjected to any lattice scattering, they are continuously accelerated by the electrons field E with a force eE on the superconducting electrons. We can write the equation of motion

$$eE = m\frac{dv_s}{dt}$$

Where e is the charge of the electron, m is the mass of electron and $\frac{dv_s}{dt}$ is its acceleration. If n is the number of superconducting electrons per unit volume and $v,$ is the average velocity, then the current density $J,$ is given by the equation.

$$J_s = n_s e v_s$$

Differentiating the above equation, we get

$$\frac{dJ_s}{dt} = n_s e\frac{dv_s}{dt} = n_s e\frac{eE}{m} = n_s e^2\frac{E}{m}$$

$$\frac{dJ_s}{dt} = \frac{n_s e^2 E}{m} \qquad \text{-----(1)}$$

This is the **first London equation**. In the equation (7.14) if $E = 0$, then $J,$ is finite and steady. Hence the first London equation describes that it is possible to have steady current even in the absence of electric field which is the phenomenon of superconducting state. But the expression for normal current density is $J_n = \sigma E$, for which we can say that in the absence of electric field, there n can be no current flow which is the behaviour of the material in the normal conducting state.

Second London equation

The Meissner effect may be incorporated by modifying Maxwell's equation.

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

The first London equation is

$$\frac{dJ_s}{dt} = \frac{n_s e^2 E}{m}$$

Taking curl on both sides of the above equation

$$\nabla \times \frac{dJ_s}{dt} = \frac{n_s e^2}{m}\nabla \times E = -\frac{n_s e^2}{m}\frac{\partial B}{\partial t}$$

Integrating the above equation

$$\nabla \times J_s = \frac{-n_s e^2}{m} B + B_0$$

where the field Bo is the constant of integration. Since Meissner effect prohibits magnetic fields in the superconductor, the constant must be zero.

$$\nabla \times J_s = \frac{-n_s e^2}{m} B \text{ ---(2)}$$

The above equation is the **second London equation** of superconductivity in which the current J, is maintained by the local field *B*.

Penetration depth

From one of the Maxwell's equations we write

$$curl\vec{B} = \mu_0 J_s$$

Taking curl on both sides we have, $curlcurl\vec{B} = \mu_0 curlJ_s$ ---(3)

Using the general vector identity, we can write

$curlcurl\vec{B} =$ grad. div B - ∇^2B

From another Maxwell's equation div $B = 0$, Equation (3) becomes

$$-\nabla^2\vec{B} = \mu_0 curlJ_s$$

Substituting Equation (2) in the above equation we get

$$-\nabla^2\vec{B} = \mu_0\frac{-n_s e^2}{m}B \quad \text{or} \quad \nabla^2\vec{B} = \frac{\vec{B}}{\lambda^2} \text{ -----(4)}$$

where

$$\lambda^2 = \frac{m}{\mu_0 n_s e^2} \quad \text{or} \quad \lambda = \sqrt{\frac{m}{\mu_0 n_s e^2}} \text{ ----(5)}$$

The parameter has the dimension of length and is known as London penetration depth. For a one dimensional case, equation (4) can be written as,

$$\frac{d^2\vec{B}}{dx^2} = \frac{\vec{B}}{\lambda^2} \text{ along x-axis ----(6)}$$

The solution of Equation (6) is

$$B = C\exp\left(\frac{x}{\lambda}\right) + D\exp\left(\frac{-x}{\lambda}\right)$$

where C and D are constants and x represents the distance inside the metal from the surface. The first factor C exp(x / λ) predicts that *B* increases with *x,* which is contrary to the fact. Therefore, only the second factor D exp(-x / λ) should be the appropriate solution.

At x = 0, Let *D* = *Bo* where *Bo* is the flux density of the applied field at the surface.

Therefore, $B = B_0 \exp\left(\frac{-x}{\lambda}\right)$ ----(7)

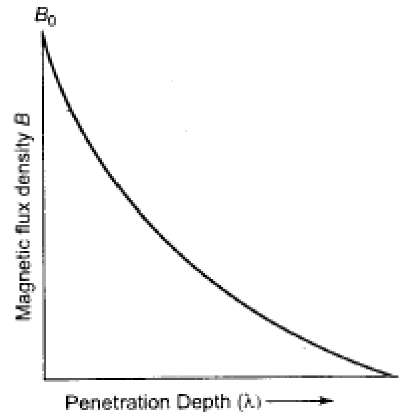


Fig 8. Exponential decrease of the magnetic field inside a superconductor

The graphical representation of the above equation is shown in Fig. The graph indicates that the magnetic field does not drop to zero abruptly at the surface of a superconductor, but decays exponentially inside the superconductor in a characteristic distance λ called **penetration depth**.

This prediction was later verified experimentally and was a great success of the London theory. If one substitutes appropriate values for the parameters, one finds that λ ~ 50 nm, which is close to the experimentally observed values, as shown in Table.

Penetration Depths (Measured Values)

Element	$\lambda(0)$, Å
Al	500
Cd	1300
Hg	380–450
In	640
Nb	470
Pb	390
Sn	510

Another impressive confirmation of the London theory is its prediction of the variation of λ with temperature. If we substitute for *n,* we get

$$\lambda = \lambda(0)\left[1 - \left(\frac{T}{Tc}\right)^4\right]^{-1/2}$$

where $\lambda(0) = \sqrt{\frac{m}{\mu_0 n_s e^2}}$ is the penetration depth at *T* = 0. Thus, λ increases as *T* increases from 0 K, and becomes infinite at *T* = *Tc,* as shown.

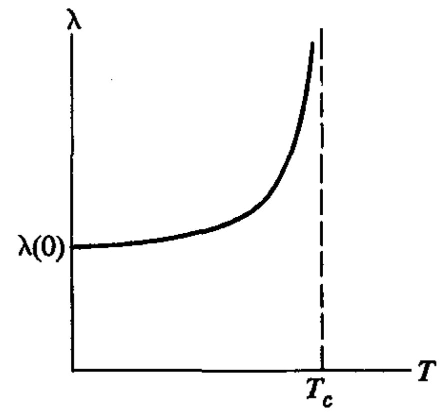


Fig 9: Increase of the penetration depth λ with temperature, according to the London theory.

A third conclusion from the London theory is the existence of an electric current flowing near the surface. If one substitutes for B and solves for the current, we get

$$J_z(x) = -\sqrt{\frac{n_s e^2}{\mu_0 m}} B_y(x) = -J_s(0)\exp\left(\frac{-x}{\lambda}\right)$$

which is a current flowing in the negative z-direction. Since this current decays exponentially as one moves into the superconductor, it is essentially a *surface current.* Therefore the Meissner effect is accompanied by a surface current, and it is this current which acts to shield the inner superconductor from the external magnetic field, resulting in a perfectly diamagnetic medium. (In other words, the magnetic field due to the surface current completely cancels the external field inside the medium.)
So we get a very interesting picture: The current in a current-carrying superconductor (the *supercurrent)* is restricted to the region very close to the surface. If, for example, the specimen is in the shape of a cylinder, the current flows only along the surface of the cylinder, leaving the whole inner region free of any current. This is very different from a normal conductor, in which the current is uniform throughout the sample.

BCS theory of superconductivity

The long awaited quantum theory of superconductivity was published in 1957 by three US physicists, John Bardeen, Leon Cooper and John Schrieffer, and they were awarded the Nobel Prize for Physics in 1972 'for their jointly developed theory of superconductivity, usually called the BCS theory'. According to their theory, in the superconducting state there is an attractive interaction between electrons that is mediated by the vibrations of the ion lattice. A consequence of this interaction is that pairs of electrons are coupled together, and all of the pairs of electrons condense into a macroscopic quantum state, called the **condensate**, that extends through the superconductor. Not all of the free electrons in a superconductor are in the condensate; those that are in this state are called **superconducting electrons**, and the others are referred to as **normal electrons**. At temperatures very much lower than the critical temperature, there are very few normal electrons, but the proportion of normal electrons increases as the temperature increases, until at the critical temperature all of the electrons are normal. Because the superconducting electrons are linked in a macroscopic state, they behave coherently, and a consequence of this is that there is a characteristic distance over which their number density can change, known as the **coherence length** ξ.

It takes a significant amount of energy to scatter an electron from the condensate – more than the thermal energy available to an electron below the critical temperature – so the superconducting electrons can flow without being scattered, that is, without any resistance. The BCS theory successfully explained many of the known properties of superconductors, but it predicted an upper bound of roughly 30 K for the critical temperature.

High-temperature superconductors

Ever since Kamerlingh Onnes discovered that mercury becomes superconducting at temperatures less than 4.2 K, **scientists have been searching for superconducting materials with higher transition temperatures**. The term **high-temperature superconductor** was initially used to designate the new family of ceramic materials discovered by **Bednorz** and **Müller in 1986**. The so-called high-temperature superconductors are generally considered to be those that exhibit superconductivity **at or above the temperature of liquid nitrogen (77 K**). These materials have received a great deal of attention because they can be maintained in the superconducting state with liquid nitrogen (the boiling point of nitrogen is 77 K). This is important commercially because liquid nitrogen can be produced cheaply on-site with no raw materials.

These high-temperature superconductors are **ceramics**. They contain lanthanum, yttrium or other rare earth elements. Most prominent high-T_c superconductors are the so-called cuprates i.e., compounds containing copper,oxygen and other elements.Other atomic species can sometimes be introduced by chemical substitution while retaining the high-Tc properties. Varying the oxygen content or the heat treatment of the materials dramatically changes their transition temperatures, critical magnetic fields, and other properties. Yttrium-Barium-Copper-Oxide (**$YBa_2Cu_3O_7$**), one of the first cuprate superconductors, has a critical temperature of **90 K**, and **mercury-based cuprates** have been found with critical temperatures in excess of **130K**. Recently, many high temperature superconductors have been discovered, although the record is still held by a **cuprate perovskite material (*T*c=138 K**).

The high-Tc superconductors **also exhibit zero resistance, the Meissner effect, and the characteristic temperature dependences of the specific heat and the thermal conductivity.** Therefore, it is clear that the conduction electrons in these materials form the Cooper pairs used to explain superconductivity in the BCS theory. It is not known, however, why the transition temperatures of these oxides are so high. Nevertheless it is widely believed that **if room temperature superconductivity is ever achieved it will be in a different family of materials.**

Applications of superconductivity

1) Superconductors are used **to make the most <u>powerful electromagnets</u> known to man including those used in MRI machines and the magnets used in <u>particle accelerators</u>.** These generate large magnetic fields with no energy loss.
2) Superconductors are also **used to make SQUIDs** (superconducting quantum interference devices), the most sensitive magnetometers known to detect incredibly small magnetic fields. **SQUIDs** are used in **oil prospecting, earthquake prediction** and **geothermal energy surveying** and **to study neural activity inside brains**.
3) Promising future applications include **high-performance power storage devices, electric motors** and perhaps, most important of all, **<u>more efficient generation and transmission of electric power</u>.**
4) They are used in **<u>magnetic levitated trains</u> for high-speed travel ("Maglev")** and **<u>nuclear fusion reactors</u>** in which ionized gas is confined by magnetic fields.
5) Possible applications of the high-temperature superconductors include the **construction of computer parts** (logic devices, memory elements, and switches).

The ceramics have problems and these problems may soon be solved with the continued development of high temperature superconductors.

******

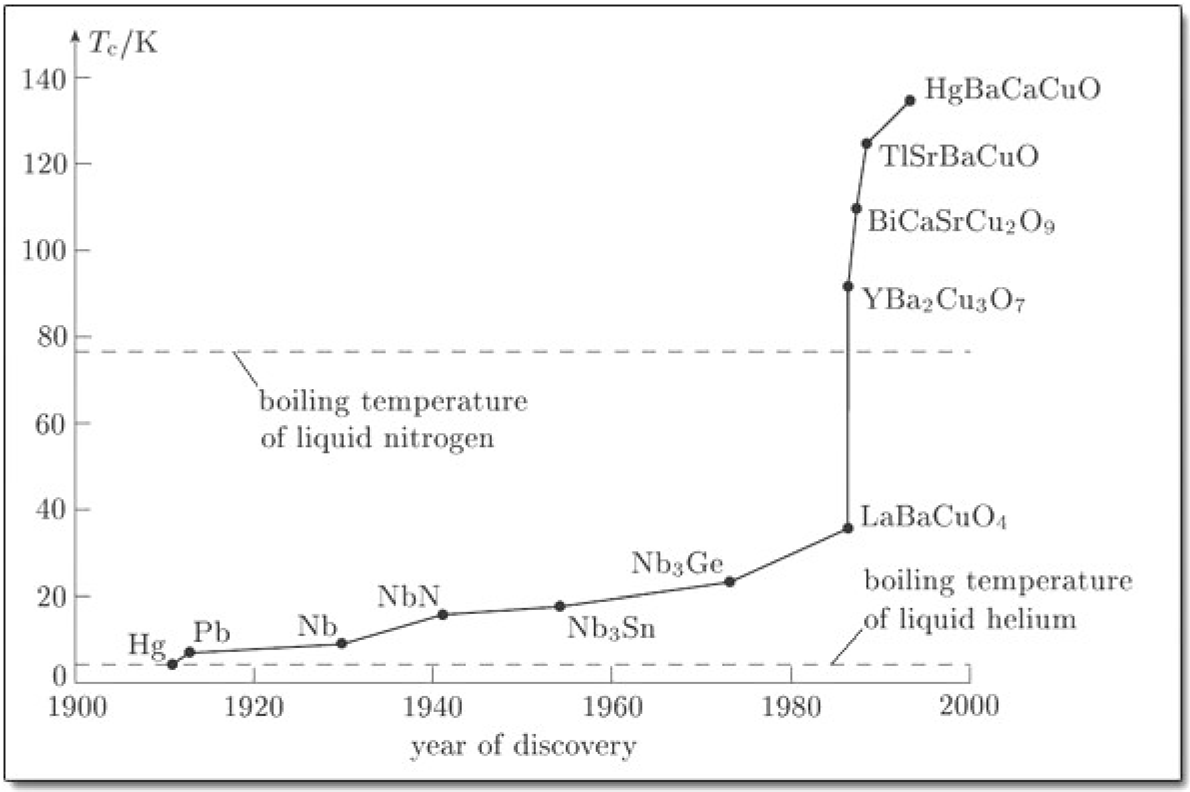


Fig. 10. The critical temperature T_c of various superconductors plotted against their discovery date.