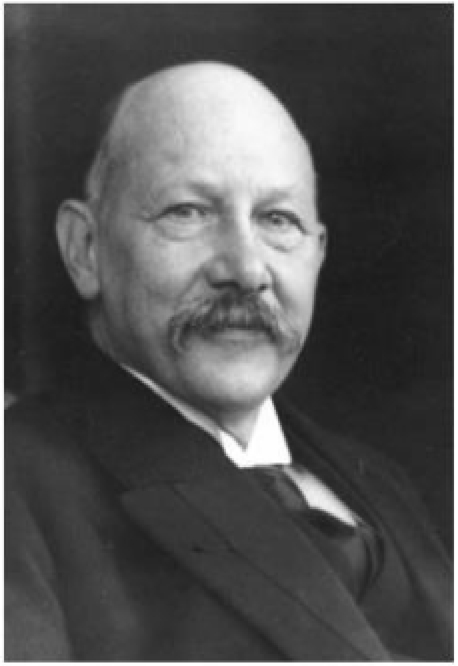
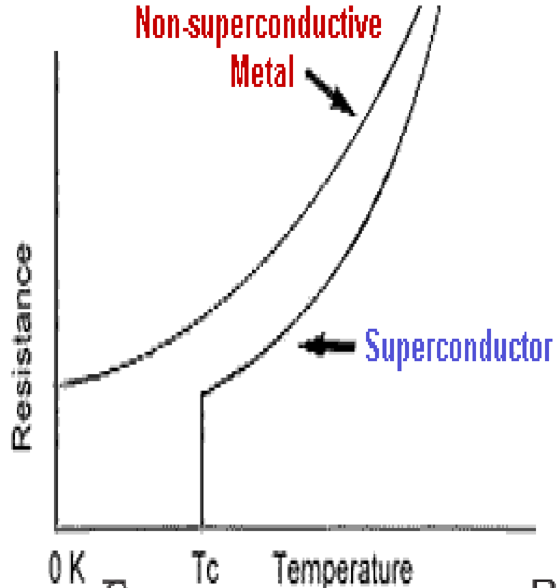
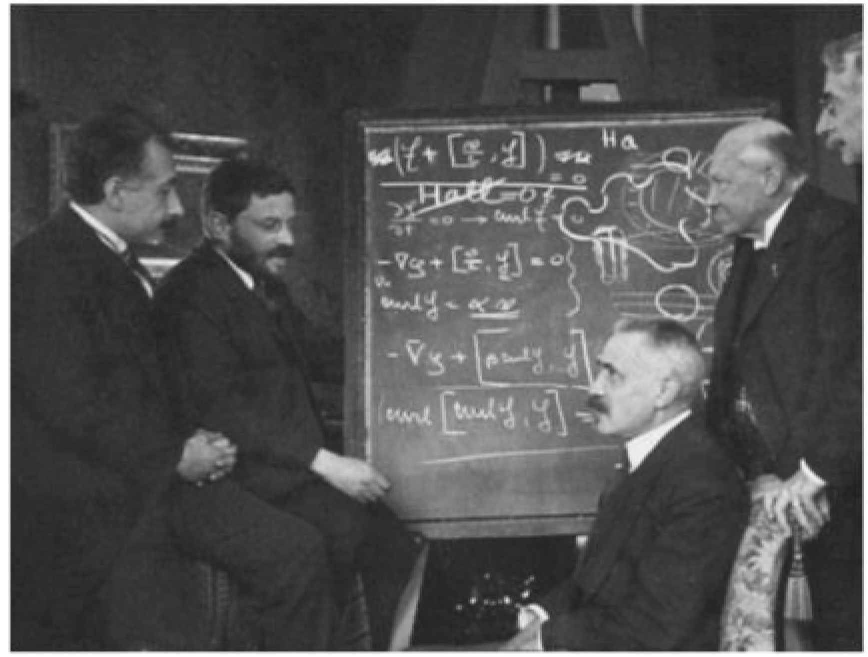
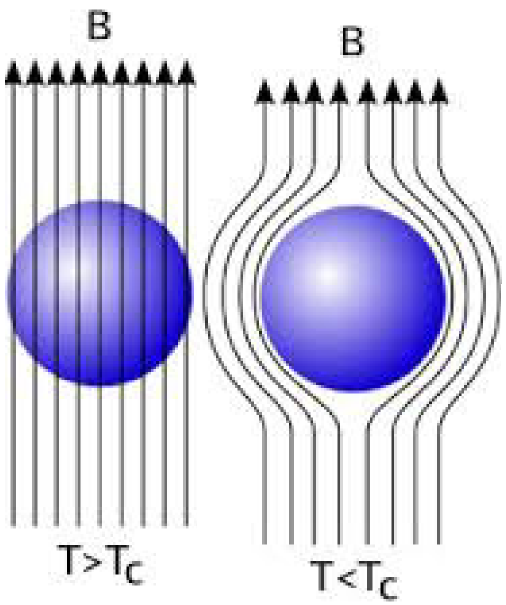
Superconductors

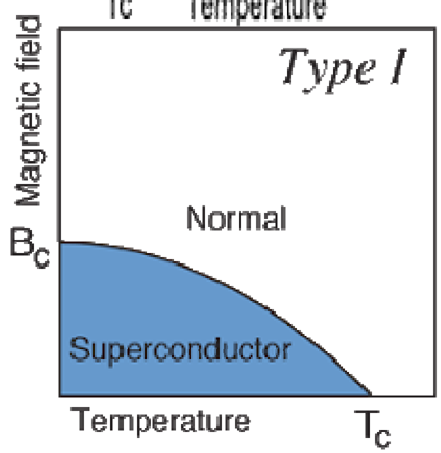


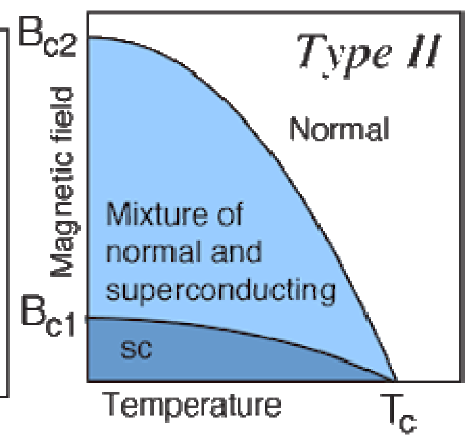


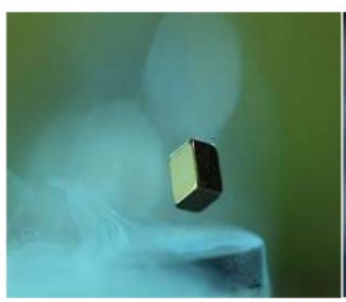


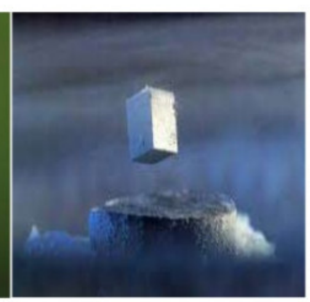
Einstein, Ehrenfest, Langevin, Kamerlingh Onnes, and Weiss at a workshop in Leiden October 1920. The blackboard discussion, on the Hall effect in superconductors









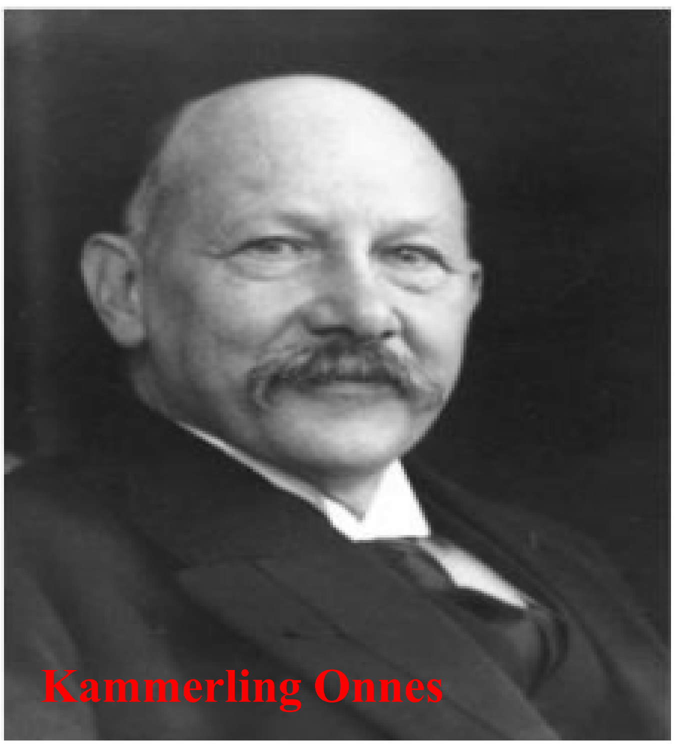


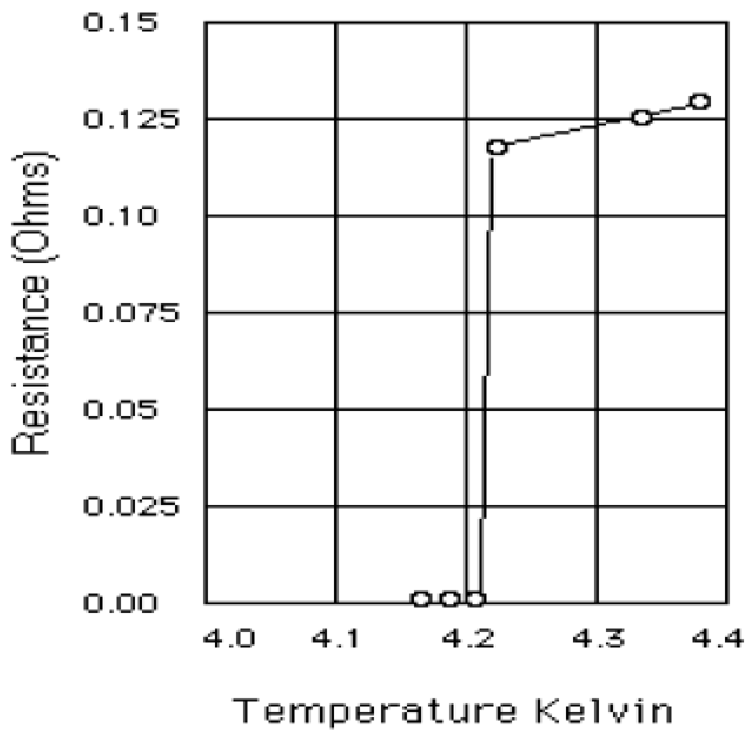
Introduction

Superconductivity is a phenomenon in which certain metals, alloys and ceramic conduct electricity without resistance when it is cooled below a certain temperature called the **critical temperature (Tc)**.

Superconsuctivity was discovered by Dutch physicist, **Heuke Kammerling Onnes, in 1911** and it is still an exciting field of discovery and technological applications.

This new state was first discovered in **mercury when cooled below 4.2 K**. Since then, a large number and wide variety of **metals, alloys, binary and ternary chemical compounds** have been found to show superconductivity at various temperatures.

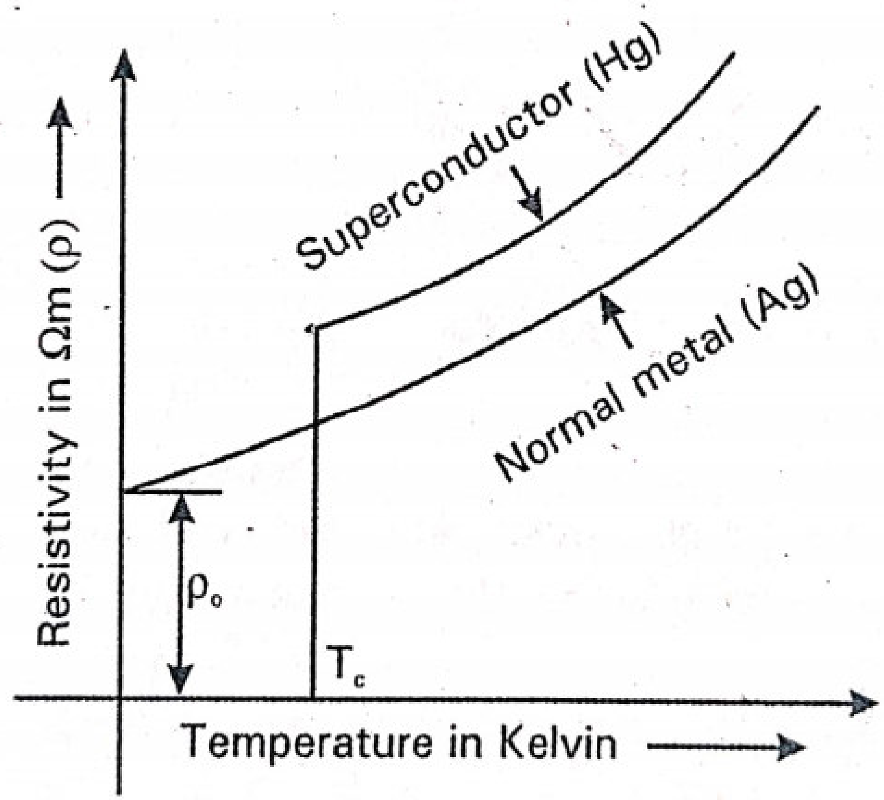




H. K. Onnes, Commun. Phys. Lab.12,120, (1911) A **superconductor** is a material that loses all **its resistance (offer zero resistance)** to the flow of electric current when it is cooled below a certain temperature called **critical temperature or transition temperature (Tc).**

Examples: Mercury **(Hg),** Znic **(Zn),** Vanadium **(V),** Tin **(Sn)** and Niobium **(Nb)**

At and below Tc, the material is said to be in the **superconducting state** and above this temperature, the materials is said to be in the **normal sate**.
Figure shows the variation of electrical resistivity of **normal metal silver (Ag)** and a **superconducting metal mercury (Hg)** versus **temperature**.
It can be seen that the electric resistivity of normal metal decrease steadily as the temperature is decreased and reaches a low value at 0 K called the residual resitivity ρ(0). But in contrast , the electrical resitivity of mercury suddenly dropes to zero at critical temperature Tc and is 4.2 K for Hg.

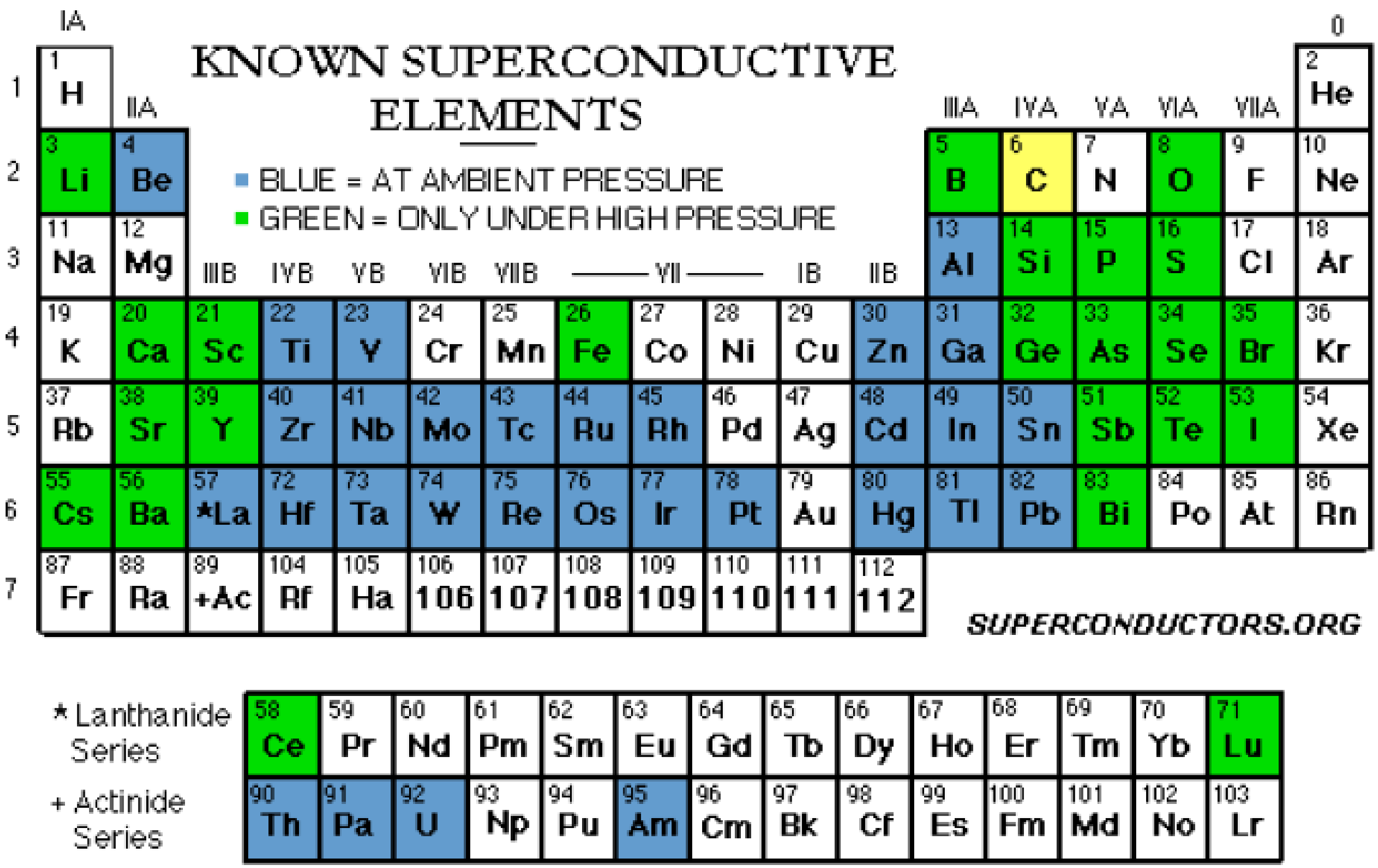


Below the critical temperature , not only does the superconductor suddenly achieves zero resistance, it also exhibits a verity of several astonishing magnetic and electrical properties.

The Tc values for some selected metals, intermetallic and ceramic superconductors are given in Table.

Metals	Tc in K	Intermatallic	Tc in K	Ceramic	Tc in K
Tin (Sn)	3.7	NbTi	9.5	Y1Ba2Cu2O7-x	93
Mercury (Hg)	4.2	Nb3Sn	21	Tl-Ba-Ca-Cu	125
Vanadium (V)	5.3	Nb3Ge	23.2	HgBaCuO	133

Known superconductive elements



The phenomena of superconductivity can be explained satisfactorily on the basis of wave mechanics.

In an ordinary metal, the electrical resistance is the results of collision of the conduction electrons with the vibrating ions in the crystals lattice. In the superconducting state, the electron trend to be scattered in pair rather than individually. This give rise to an exchange force between the electrons. The force is attractive and is very strong if the electrons are opposite spin and momenta.

In superconducting state, the force of attraction between the conduction electrons exceed the forces of electrostatic repulsion. The entire system of conduction electron become bound system. No transfer of energy takes place from the system to the lattice ions.

If an electric field is established the bound system of electrons gain additional kinetic energy and give rise to current. But they do not transfer this energy to the lattice, so that they do not get slowed down. As a consequence of this, the substance does not posses any electrical resistivity.

This **(BCS)** theory was put forward by John **B**ardeen, L.N. **C**ooper and J.R. **S**chriffer in 1957.

The bound pairs of the electron is called **Cooper Pair.**

Properties of Superconductors

Electrical Resistance: At room temperature, superconducting material have greater resistivity than other elements.

Effect of Impurities: When impurities are added to superconducting elements, the superconducting property is not lost but the Tc value is vary. There is no change in crystal structure as revealed by X-ray Diffraction studies.

Effect of Pressure and Stress: Certain materials are found to exhibit the superconductivity phenomena on increasing the pressure over them. For example, cesium is found to exhibit superconductivity phenomena at Tc =1.5 K on applying a pressure of 110 Kbar. In superconductors, the increase in stress results in increase of the Tc value.

Isotope Effect: The critical or transition temperature (Tc) value of a superconductor is found to vary with its isotopic mass (M). This variation in Tc with its isotopic mass is called the isotopic effect. The relation between Tc and the isotopic mass (M) is given by,

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

Magnetic Field Effect: If sufficient strong magnetic field is applied to superconductor at any temperature below its critical temperature Tc, the superconductor is found to undergo a transition from the superconducting state to the normal state.

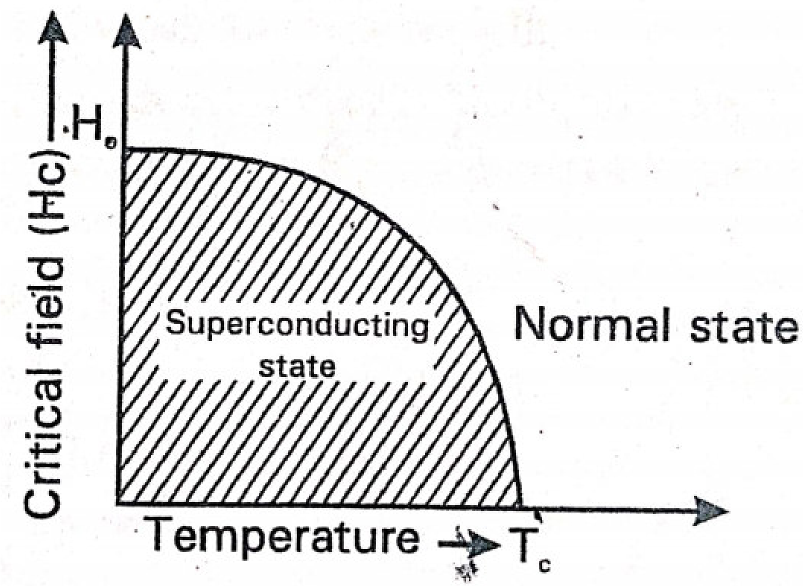
This minimum magnetic filed required to destroy the superconducting state is called the **critical magnetic field (Hc).**

The critical magnetic field of a superconductor is a function of temperature. The variation of Hc with temperature is given by,

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

Where H_0 is the critical field at T= 0. The critical field decreases with increasing temperature and becoming zero at T=Tc.

Figure shows the variation of critical field Hc as a function of temperature. The material is said to be in the superconducting state within the curve and is non super conducting (normal state) in the region outside the curve.



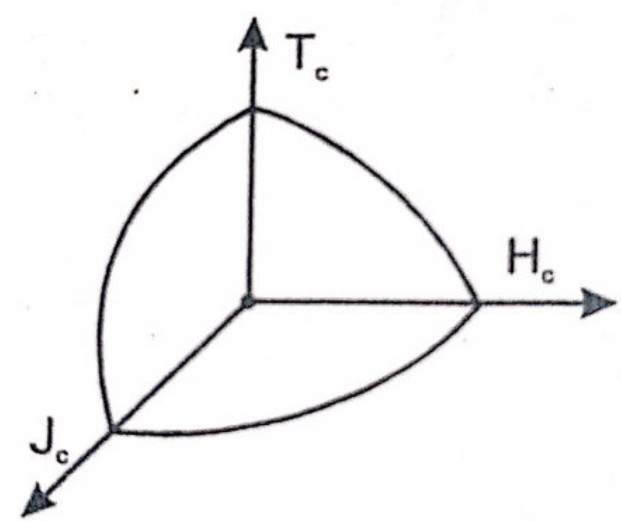
Critical Current Density (Jc) and Critical Current (Ic)

When the current density through a superconducting sample exceeds a critical value Jc, the superconducting state is found to disappear in the sample. This happens because the current through the superconductor itself generates a magnetic field and at a sufficiently high current density the magnetic field will start exceeding the critical magnetic field Hc, thereby making the superconducting state to disappear in the material.

Hence, **the critical current density can be define as the maximum current that can be permitted in a superconducting material without destroying its superconductivity state.** The critical current density is a function of temperature, i.e., colder the temperature for a superconductor the more is the current it can carry.

For a thin long cylindrical superconducting wire of radius r, the relation between critical current Ic and critical magnetic field Hc is given by , $\boxed{\mathbf{Ic=2\pi r\ Hc}}$

Similarly, the relation between critical current density Jc and critical current Ic is given by **Jc=Ic/A**, where A is the supercoducting specimen's cross section area



Meissner Effect (Diamagnetic Property): The **Meissner effect** (or **Meissner–Ochsenfeld effect**) is the expulsion of a magnetic field from a superconductor during its transition to the superconducting state when it is cooled below the critical temperature.

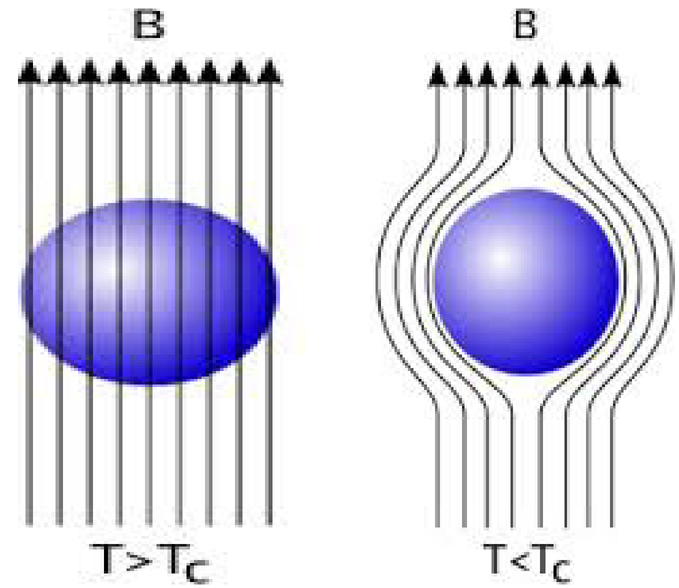
The German physicists **Walther Meissner and Robert Ochsenfeld** discovered this phenomenon in **1933** by measuring the magnetic field distribution outside superconducting tin and lead samples.

Walter Meissner

Robert Ochsenfeld

When a superconducting material is placed in a magnetic field at room temperature, the magnetic field is found to penetrate normally throughout the material.

However, if the temperature is lowered below Tc and with H<Hc the material is found to reject all the magnetic field penetrating through it .



The above process occurs due to the development of surface current, which in turns results in the development of magnetization M within the superconducting material. Hence, as the developed magnetization and the applied field are equal in magnitude but opposite in direction they cancel each other everywhere inside the material. This below Tc a superconductor is perfectly diamagnetic substance.

The Meissner effect is a distinct characteristics of a superconductor from a normal perfect conductor.

In addition, This effect is exhibited by the superconducting materials only when the applied field is less than the critical field Hc.

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

where μ_o is the permeability of free space

M is the intensity of magnetisation

and H is the applied magnetic field.

But, we know that for a superconductor $B = 0$

Therefore, equation (1) can be written as

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

$$\because \quad \mu_o \neq 0$$

$$M + H = 0$$

or

$$M = -H$$

or

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

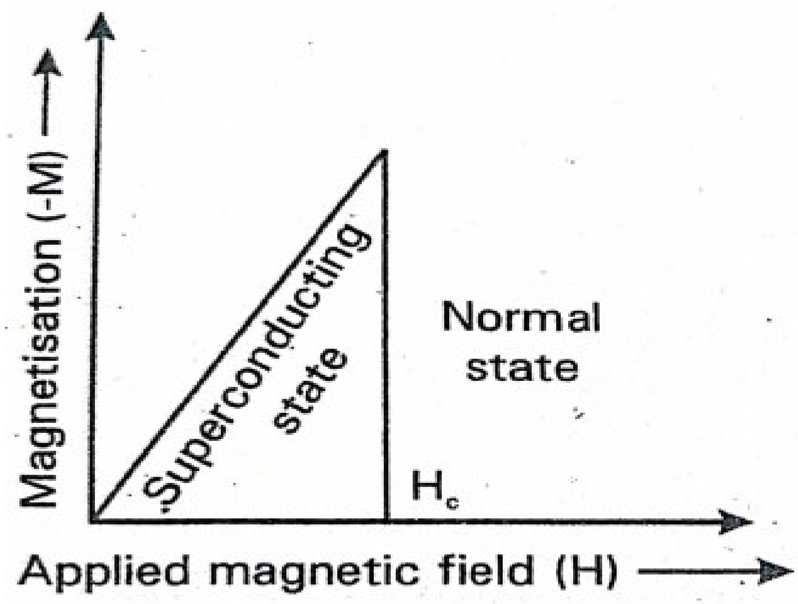
Hence, $\chi_m = -1$ *where* $\chi_m = \dfrac{M}{H}$ *is called the magnetic susceptibility.* Thus this means tl for a superconductor the susceptibility is negative and maximum, i.e., a *superconductor exhib perfect diamagnetism.*

Types of Superconductors

Based on the behavior of superconducting materials in an applied magnetic field, the superconductors are classified into type I and II superconductors.

Type I Superconductors

Type I superconductors exhibit complete Meissner effect, i.e., they are completely diamagnetic. The magnetization curve for type I superconductor is shown in figure. The values of Hc for type of I superconducting materials are always too low.



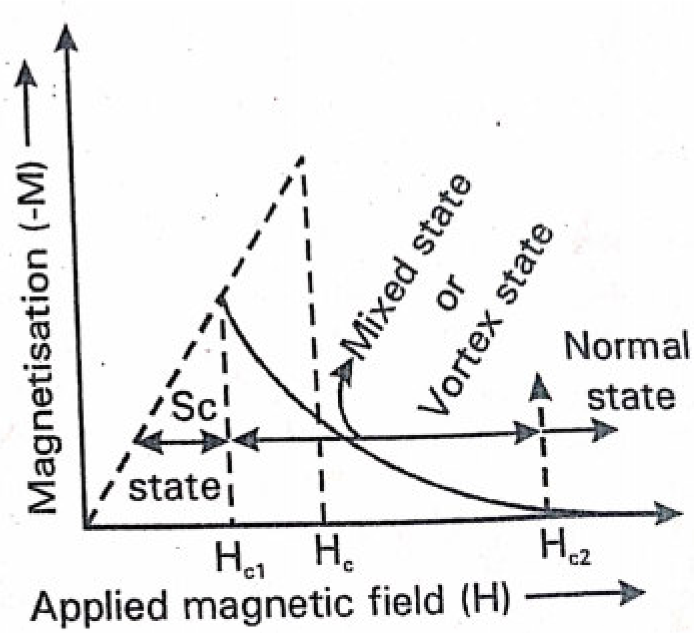
The magnetization curve shows that the transition at Hc is reversible. This means that if the magnetic field is reduced below Hc, the material again acquires superconducting property and the field is expelled.

Type I superconductors are also called as soft superconductors because of their tendency to allow the field penetration even for a lower applied field.

Many pure elements, alloy and some compound superconductors exhibit type I behavior.

Type II Superconductors

Type II superconductors behave defiantly in increasing field, as shown in figure. For an applied field below Hc1, the material is perfectly diamagnetic and hence the field is completely excluded. **Hc1 is called as lower critical field**. At Hc1, the field start to thread the specimen and this penetration increases until Hc2 is reached at which the magnetization vanishes and the specimen becomes normal. **Hc2 is called the upper critical field**.



In the region between Hc1 and Hc2 the material is in the **mixed state or the vortex state**.

The value Hc2 for type II may be **100 times more** or even higher than that of type I superconducting material. As Hc2 and Tc of type II superconducting material are higher than that of type I superconductor, the type II superconducting materials are most widely used n all engineering applications.

Type II superconducting materials are also called as **hard superconductors** because of relatively large magnetic field requirement to bring them back to their normal state.

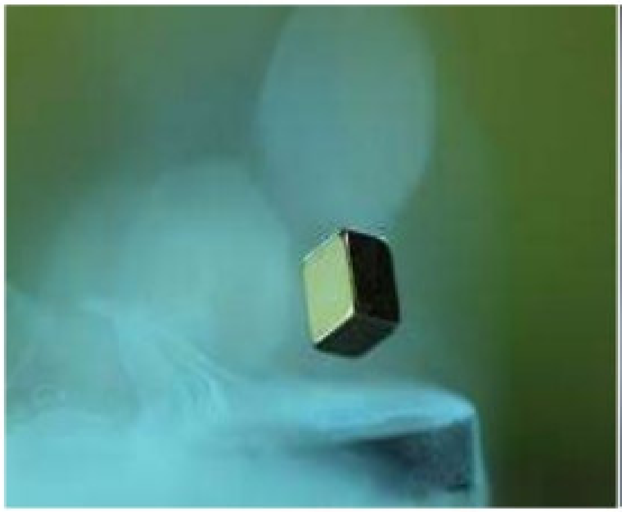
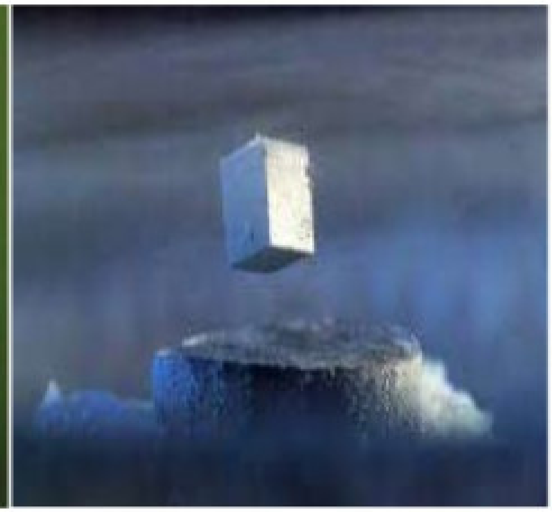
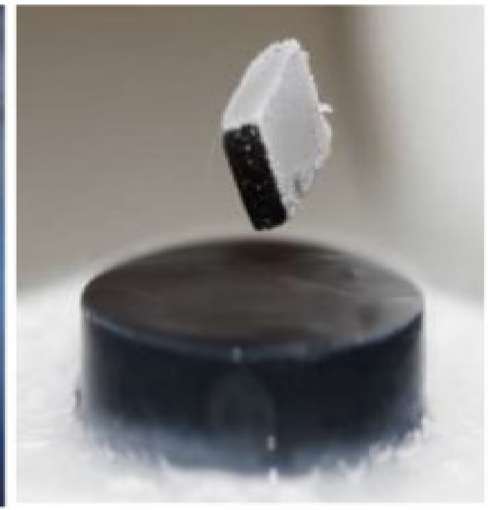
Examples for type I and type II superconducting materials with their Hc values are listed in below table.

Type I		Type II	
Material	Hc in Tesla	Material	Hc in Tesla
Pb	0.08	Y1Ba2Cu3O7	300
Hg	0.014	Nb3Sn	24.5
Sn	0.030	Nb3Ge	38

Sr.Nos.	Type I Superconductors	Type II Superconductors
1	Soft superconductors	Hard Superconductors
2	Only one critical field (Hc)	Two critical field Hc1 and Hc2
3	Very low critical field value	Very high critical field value
4	Exhibit perfect and complete Meissner effect	Do not exhibit a perfect and complete Meissner effect
5	Limited technical application because of very low field strength value.	Wider technological application because of very high field strength value.
6	Examples: Pb,Hg, Zn, etc.	Examples:Y1Ba2Cu3O7, Nb3Sn,Nb3Ge

Applications

Magnetic levitation or maglev is the process by which an object is suspended above another object with no other support but magnetic field.

We know that a diamagnetic substance repels a magnetic field. This, the perfect diamagnetic properties of superconductors make them suitable for achieving frictionless motion in motors and bearing.

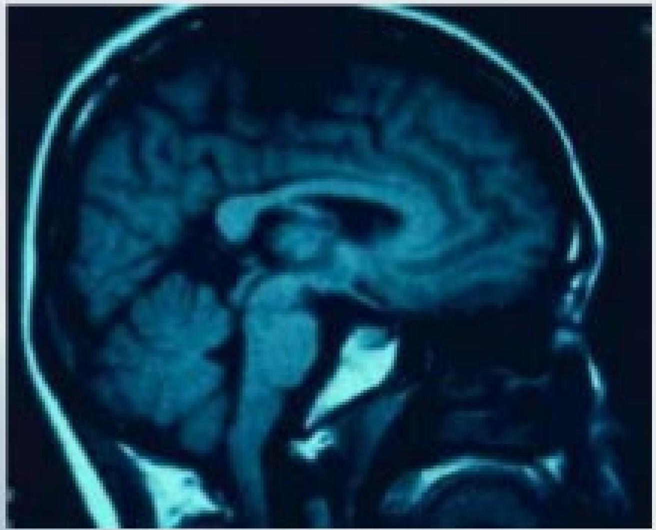
The phenomena of magnetic levitation is based on Meissner effect.

1. Superconductor can be used to transmit electrical power over very long distance without any power loss or any voltage drop.
2. Superconducting generators has the benefits of small size and low energy consumption than conventional generators.
3. Superconducting coils are used in N.M.R. imagine equipments which are used in hospitals for scanning the whole body to diagnose medical problems.
4. Very strong magnetic field can be generated with coils made of high Tc superconducting materials.
5. Superconductors can act as relay or switching system in a computer. They can be used as memory or storage element in computers.
6. Very fast and accurate computer can be constructed using super conductors and power consumption is also very low.
7. Ore separation can be done by efficiently using superconducting magnet.
8. SQUID- Superconducting Quantum Interference Device detectors are used to be measure the levels of iron in liver.

Application of Superconductors

- Particle Accelerators
- Generators
- Transportation
- Power Transmission
- Electric Motors
- Military
- Computing
- Medical
- B Field Detection (SQUIDS)

The Yamanashi MLX01 MagLev train



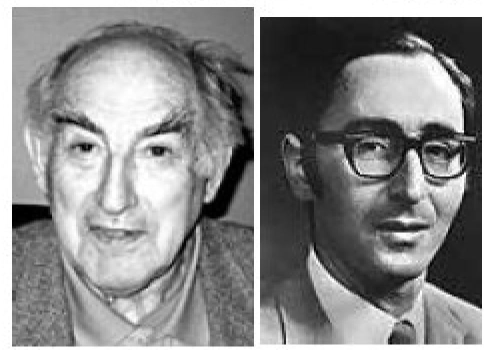
100 years in superconductivity

Discovery of superconductivity H. Kamerlingh Onnes(1911) in Hg
1913 Nobel prize

Perfect diamagnetism: Meissner and Ochsenfeld(1933)

London equation: F. and H. London(1933)

Ginzburg-Landau theory: 1950s
2003 Nobel prize (with Abrikosov)



Isotope effect: H. Frohlich(1950)

BCS theory: J. Bardeen, L. Cooper and J.R. Schrieffer(1957) 1972 Nobel prize

Tunneling: Josephson (1957) 1973 Nobel prize

Hi-Tc superconductivity: J. G. Bednorz and K. A. Muller(1986) in Ba-La-Cu-O system. 1987 Nobel prize

Problems

1. For mercury of mass number 202 and transition temperature is 4.2 K. find the transition temperature for the isotope of mercury of mass number 200.
2. The critical temperature for a metal with isotopic mass 199.5 is 4.185 K. Calculate the isotopic mass if the critical temperature falls to 4.133 K.
3. The critical temperature of Nb is 9.15 K. At 0K the critical field is 0.196 T. Calculate the critical field at 6 K.
4. Calculate the critical current through a long thin superconducting wire of radius 0.5 mm. The critical magnetic field is 7.2 x 10^3 A/m.
5. Superconducting Sn has a critical temperature of 3.7 K at zero magnetic field and a critical field of 0.0306 T at 0 K. Find the critical field at 2 K.
6. Calculate the critical current for a superconducting wire of lead having a diameter of 1 mm at 4.2 K. Critical temperature for lead is 7.18K and H_o=6.5x10^4 A/m.
7. The critical field for vanadium is 10^5 A/m at 8.58 K and 2 x 10^5 A/m. Determine the Tc value.