Unit-V Magnetism and Superconductivity

Engineering Physics

Prof. G. V. Khandekar

HOD FE

Syllabus

- **Superconductivity**
- Introduction to Superconductivity
- Properties of superconductors (zero resistance, Meissner effect, critical fields, persistent currents)
- isotope effect

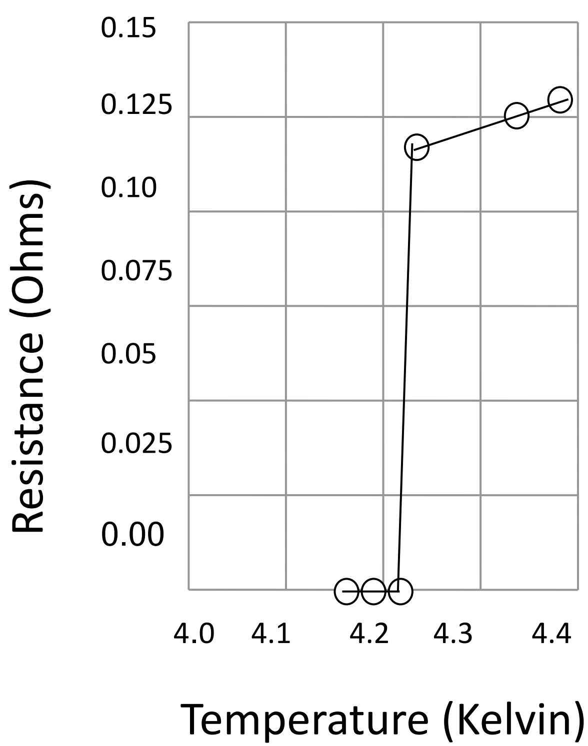
Syllabus

- **Physics of Nanoparticles**

Introduction, Nanoparticles, Properties of nanoparticles: Optical, electrical (quantum dots, quantum wires), magnetic, structural, mechanical, brief introduction to different methods of synthesis of nanoparticles such as physical, chemical, biological, mechanical. Synthesis of colloids, Growth of nanoparticles, Synthesis of metal nanoparticles by colloidal route, Application of nanotechnology electronics, energy, automobiles, space & defense, medical, environmental, textile, cosmetics.

Introduction

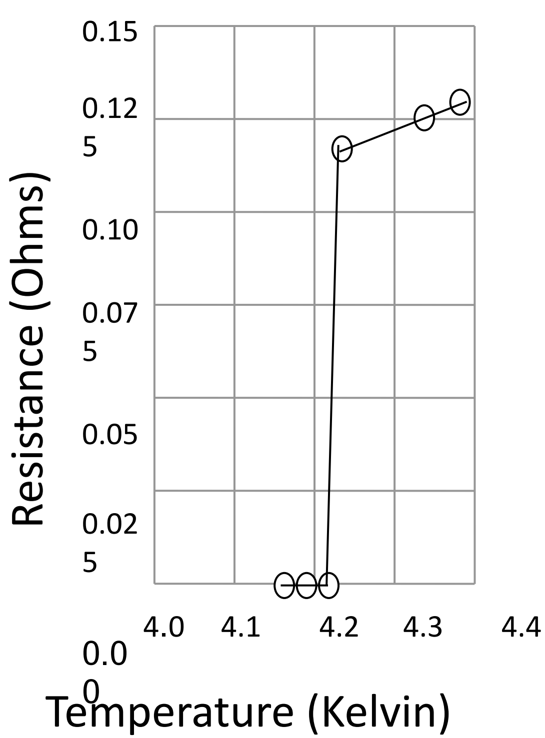
Superconductivity was first discovered in 1911 by the Dutch Physicist, "Heike Kammerlingh Onnes". He investigated the electrical properties of metals at extremely cold temperature.



Onnes, passed a current through Mercury wire and lowered the temperature of the wire gradually.

At 4.2 K he found that the resistance of the Mercury wire suddenly vanished. Current was flowing through Mercury and nothing was stopping it.

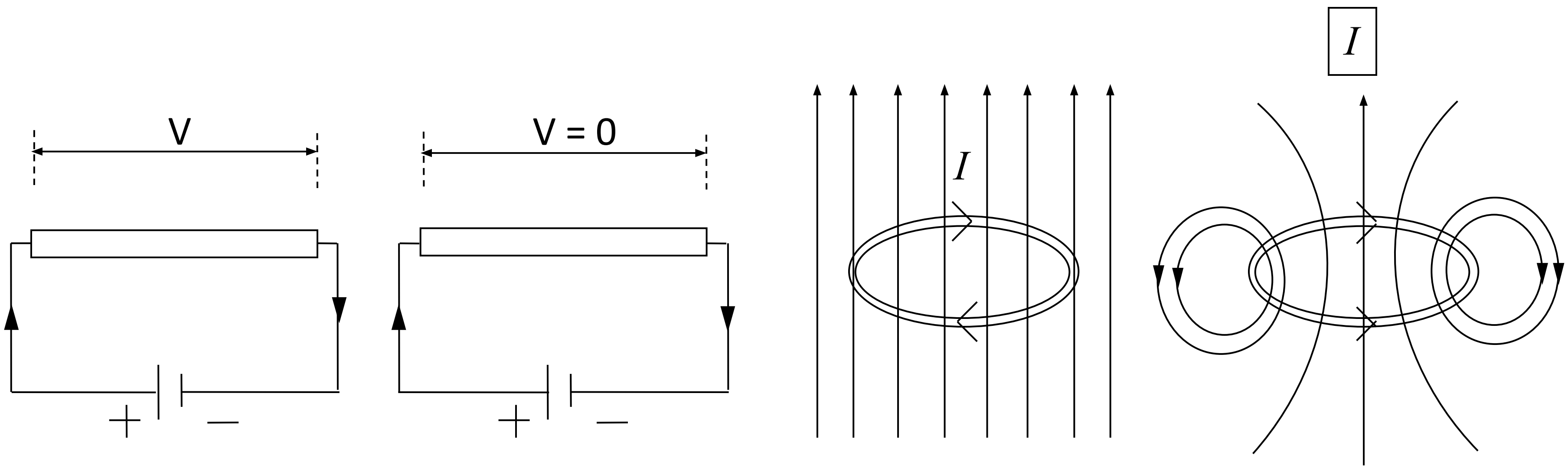
According to Onnes "Mercury has passed into a new state, on account of its extraordinary electrical properties may be called the superconductive state".



When a material is cooled below certain temperature called as 'critical temperature' (T_C); the resistance of the material becomes zero called as '*superconductivity*'.

Properties of Superconductors

1. Zero Electrical Resistance:



At $T > T_C$ | At $T < T_C$ | At $T > T_C$ | At $T < T_C$

When the external field is switched off, a current is induced in the ring had finite resistance R. The current circulating in the ring would decrease according to equation,

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$$I\,(t) = I(0)\,e^{-Rt/L}$$ where L is the inductance of ring

The decrease in the current is monitored by a change in the magnetic flux through a test coil held close to the superconducting ring.

Any change in the magnetic flux of superconducting ring will induce an e.m.f. in the test coil.

Careful measurements further show that the resistivity of the superconductor may be assumed to be zero.

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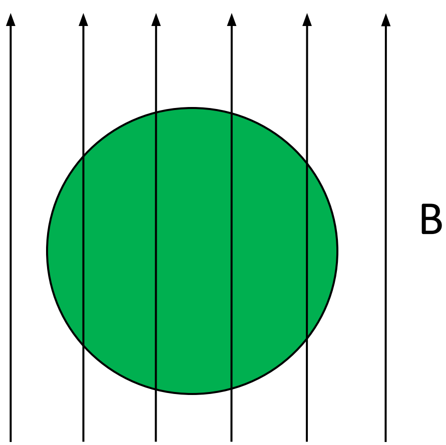
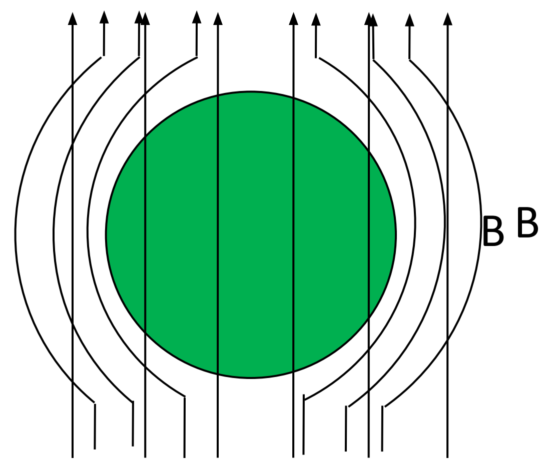
2. The Meissner Effect or Perfect Diamagnetism:

In 1938, two German Physicist, Meissner and Ochsenfeld, observed that, a superconductor expels magnetic flux completely. This phenomenon is known as *Meissner effect*.



$T > T_c$ (Normal State)



$T < T_c$ (Superconducting State)

$T > T_c$ (Normal State)

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They also demonstrated that, the effect is reversible. When the temperature is raised from below T_C , the flux suddenly penetrates the specimen after it reaches T_C and the substance is in normal state.

Perfect Diamagnetism:

When a magnetic material is placed in a external magnetic field it acquire feeble magnetization opposite in the direction of the external magnetic field and cancels out each others effect. Such materials are called as diamagnetic materials.

The magnetic induction inside the substance is given by,

$$B = \mu_0 (H + M) \text{ ------- } (1)$$

Where, H = external intensity of magnetic field.

M = magnetization of the medium.

μ_0 = magnetic permeability.

$$B = \mu_0(1 + \frac{M}{H})\, H$$

$$B = \mu_0(1 + \chi)\, H \qquad \therefore \chi = \text{magnetic susceptibility} = \frac{M}{H}$$

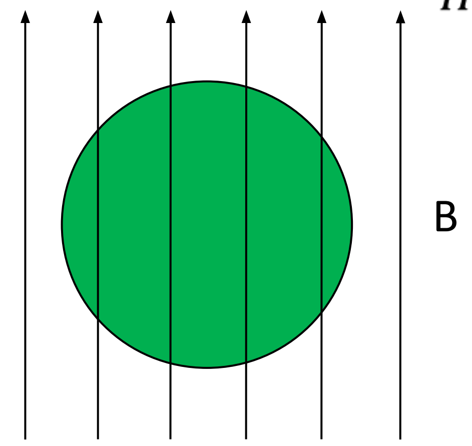
But , in the superconducting state, $B = 0$.

Therefore equation (1) becomes,

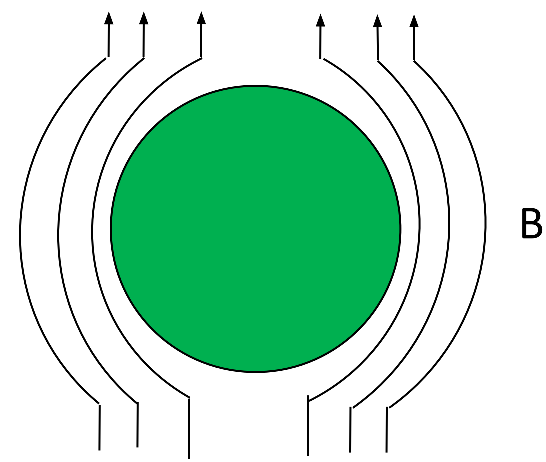
$$M = -H \qquad Or \qquad \chi = -1$$

This means that, magnetization is equal and opposite of magnetic field intensity. The medium is therefore diamagnetic.

Such a condition in which the magnetization cancels the external magnetic field intensity exactly is referred as *"perfect diamagnetism"*.



$T > T_C$ (Normal State)



$T < T_C$ (Superconducting State)

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3. Critical Field: (H_C)

It was found that the superconductivity can be destroyed by application of magnetic field.

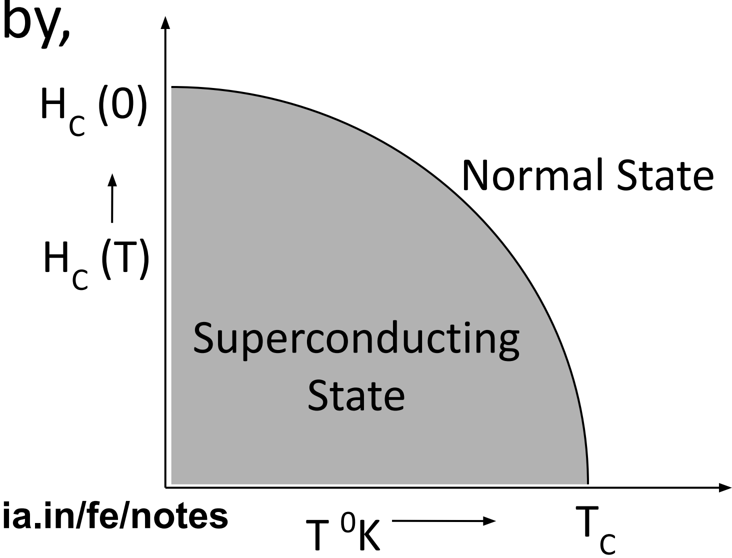
When the magnetic field applied to the superconducting specimen is greater than certain value called as 'critical field', it becomes normal and recovers its normal resistivity even at $T < T_C$.

The critical field depends on temperature for a given substance.

The variation of critical field is represented by,

$$H_c(T) = H_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

The variation of $H_c(T)$ against T is as shown,



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4. Critical Current: (I_c)

The critical field need not be external.

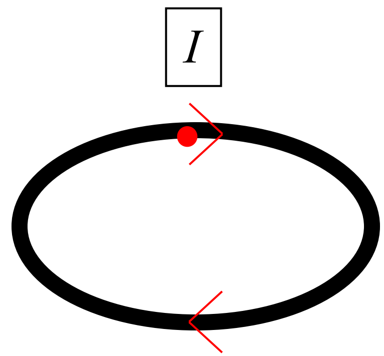
A current flowing in a superconductor creates its own magnetic field and the current is large enough so that its own field reaches the critical value, then superconductivity is also destroyed.

This places a limitation on the strength of the current which may flow in a superconductor.

"The minimum current flowing in a superconductor at which, the magnetic field developed around it is equal to the critical field (i.e. $H = H_C$) is called the critical current".

This is, in fact, the primary limitation in the manufacture of high field superconducting magnets.

5. Persistent Current: (I_c)



At $T > T_c$ (Normal State)

At $T < T_c$ (Superconducting State)

When the current is passed through a loop of a conductor, there is a resistance, which opposes the flow of current.

But when the temperature of the loop is lowered below its critical temperature it is converted into superconductor and the current keeps flowing for years without any significant loss.

This current is called as *'persistent current'*.

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6. Isotope Effect

The critical temperature T_c of a superconductor varies with isotopic mass. This is called as Isotope effect.

The dependence of T_c on the atomic mass reveals that lattice vibrations and hence electron phonon interactions is deeply involved in the superconductivity.

Based on experimental results it is found that,

$$T_c \propto M^{-\alpha} \qquad or \qquad T_c M^{\alpha} = cons\tan t$$

Here, M is the atomic mass, T_c is the critical temperature and α = 0.49 ± 0.01.

In view of this value of α it was thought that α = 0.5 (1/2) is valid for most of the materials.

$$T_c M^{1/2} = Cons\tan t$$

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Unit-V Magnetism and Superconductivity

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Syllabus

- **Superconductivity**

- BCS theory
- Type I & Type-II Super conductors

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Flow of Current through ordinary conductors

Superconductors have the ability to conduct electricity without the loss of energy.

To understand how current flows in the superconductor, first we must know how current flows in an ordinary conductor.

When current flows → In ordinary conductor → Some energy is lost → Light or Heat

↓

Migration of electrons through lattice set it into vibration.

↓

When the electrons moves through lattice they bump into the obstacles like tiny impurities or imperfections they fly off in all directions and lose energy in the form of heat.

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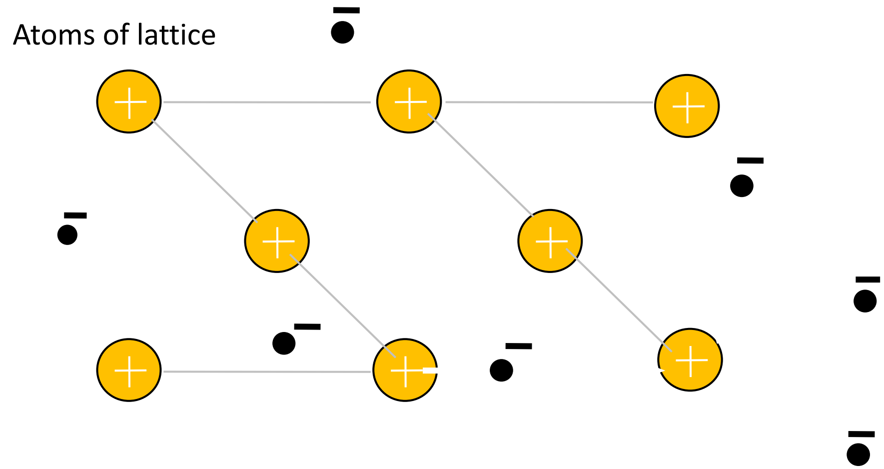
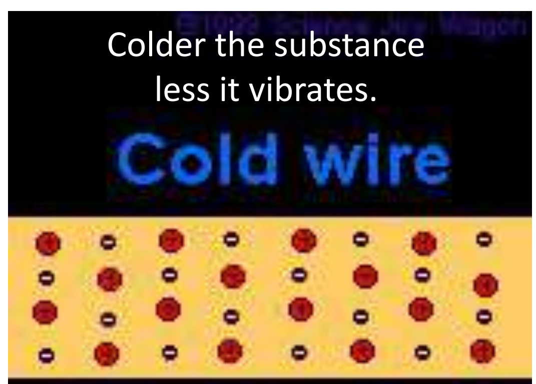


Normal State

When current flows → In superconductor → No energy is lost → Unobstructed current flow

The ability of electrons to pass through superconducting material unobstructed has puzzled scientists for many years.



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Early researchers suggested that fewer atomic vibrations would permit electrons to pass more easily.

But this predicts a slow decrease of resistivity with temperature.

It soon became apparent that these simple ideas could not explain superconductivity. It is much more complicated than that.

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BCS Theory of Superconductors

The understanding of superconductivity was advanced in 1957 by three American Physicists, John Bardeen, Leon Cooper, and John Schriffer through their theory of superconductivity, known as the **BCS theory**.

The BCS theory explains superconductivity at temperatures close to absolute zero.

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Atomic lattice vibrations were directly responsible for unifying the entire current. They forced the electrons to pair up into teams that could pass all the obstacles which caused resistance in the conductor.

Phonons

Packets of sound waves present in the lattice as it vibrates.

This lattice noise cannot be heard, but its role as a moderator is indispensable.

“Cooper pairs”.

Electrons normally repel one another. But in superconductors they feel an overwhelming attraction.

This happen because of phonons

The electron pair is alternatively pulled together and pushed apart without collision with the atoms of the lattice i.e. without resistance.

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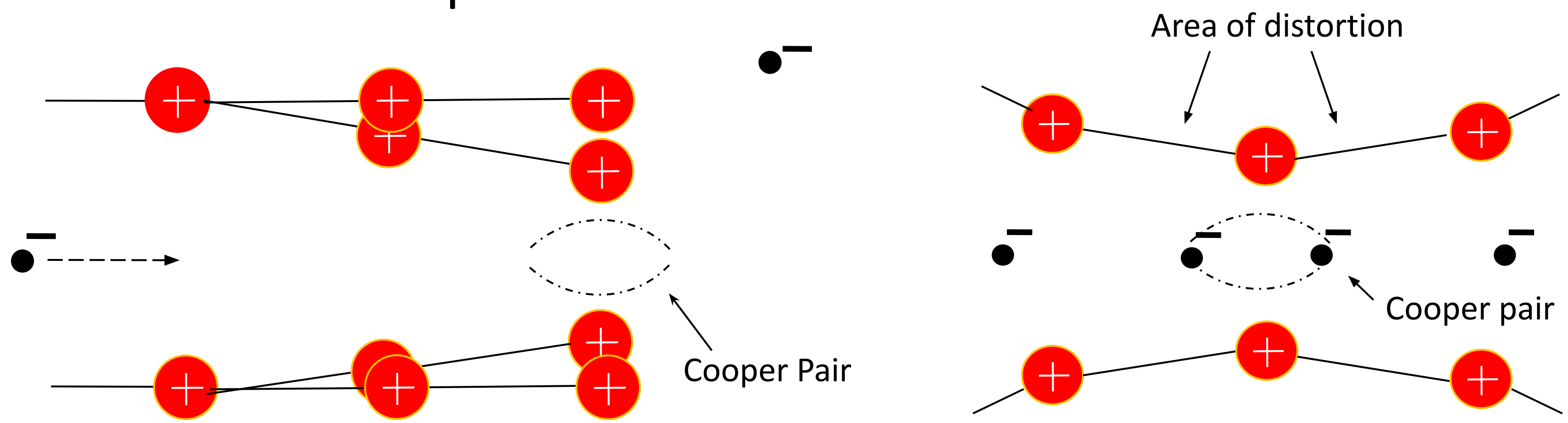
Formation of Cooper Pairs:



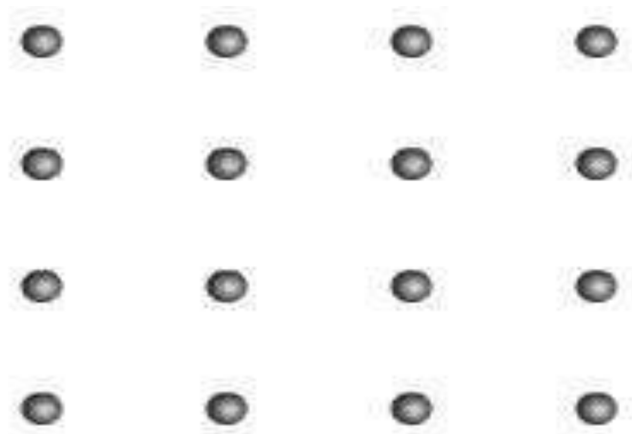
The electron emits a phonon and the other electron absorbs that phonon. This is how cooper pairs are formed.

The electron pairs are coherent with one another as they pass through the conductor in unison.

It is the exchange of phonons that keeps the Cooper pairs together.

The electron pair is alternatively pulled together and pushed apart without collision with the atoms of the lattice i.e. without resistance.

The electron pairing is favorable because it has the effect of putting the material into a lower energy state. When electrons are linked together in pairs, they move through the superconductor in an orderly fashion without any hindrance.



Type I and Type II Superconductor

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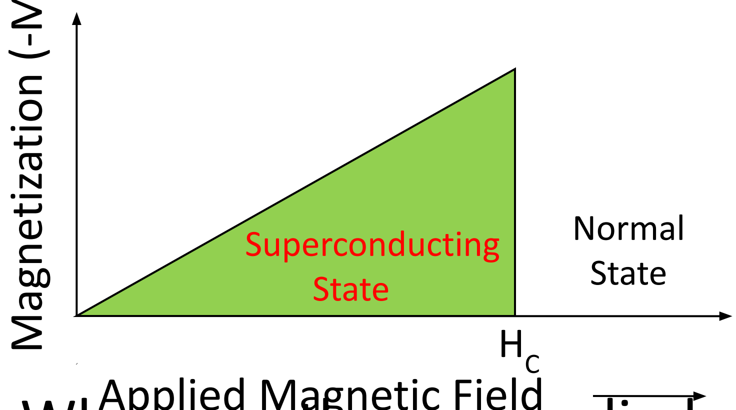
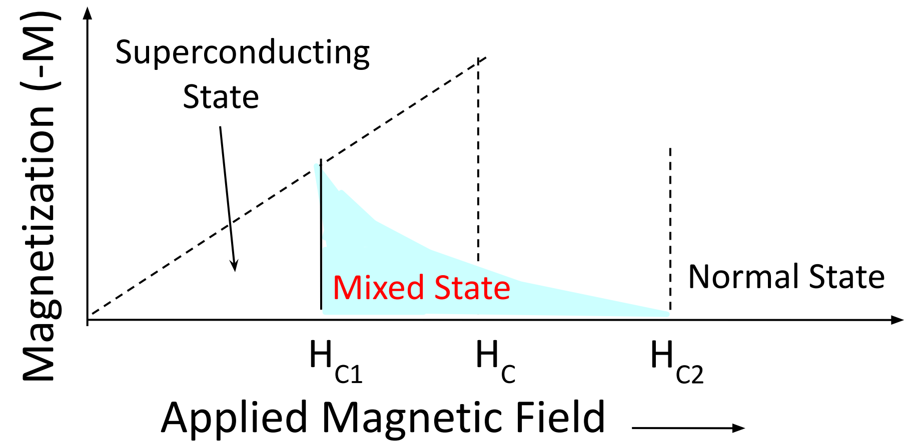
Type - I superconductor



1. When the applied magnetic field is equal to critical magnetic field (H_C) of that superconductor then the material suddenly (abrupt change) looses its superconductivity and converted into normal

Type - II superconductor

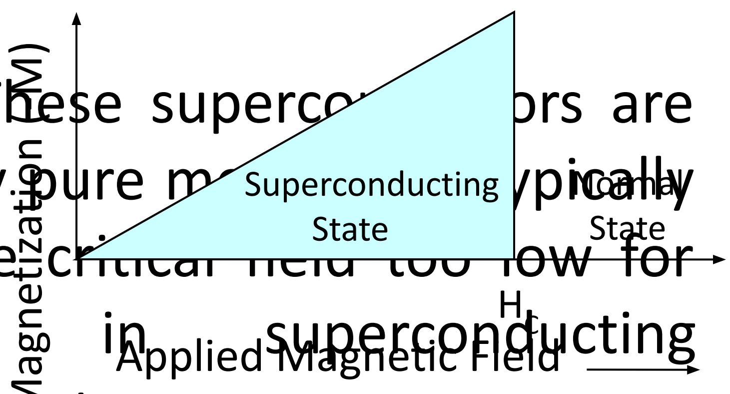


1. When the applied magnetic field approaches to critical magnetic field (H_C) of that superconductor then the material start loosing is superconductivity gradually and loses it completely above its critical magnetic field value and converted into normal state.

Type - I superconductor

2. These superconductors have only one critical field (H_c) value, below which they are superconductors and above they are normal conductors.

3. These superconductors are very pure metals typically have critical field too low for use in superconducting magnets.



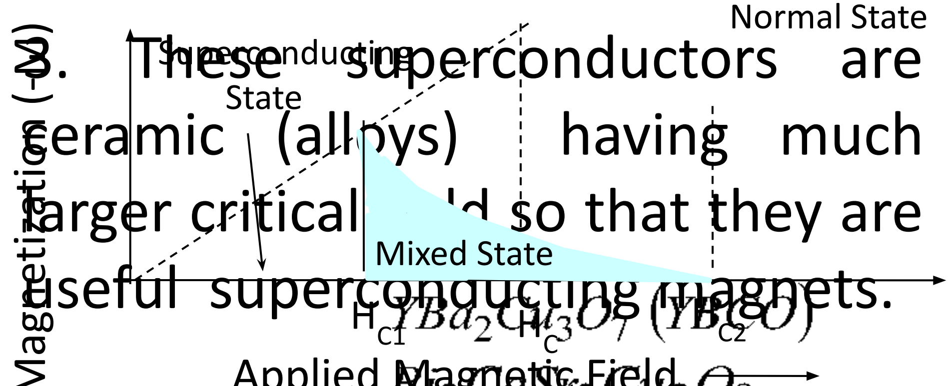
Type - II superconductor

2. These superconductors have two critical field values (H_{c1} and H_{c2}). Below H_{c1} they are superconductors and above H_{c2} they are normal conductor and between H_{c1} & H_{c2} they are in mixed state.

3. These superconductors are ceramic (alloys) having much larger critical field so that they are useful superconducting magnets.

$YBa_2Cu_3O_7$ (YBCO)

$Bi_2CaSr_2Cu_2O_9$



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4. Examples: Lead, Mercury , Tin etc.

5. The strongest type-I super--conductor pure Lead has a critical field of about 800 gauss.

4.Examples: $YBa_2Cu_3O_7$ $(YBCO)$

5. *YBCO* superconductors have upper critical field values as high as 100 Tesla.

Unit-V Magnetism and Superconductivity

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Syllabus

- **Superconductivity**
- DC & AC Josephson Effect.
- Applications (super conducting magnets, transmission lines etc.)

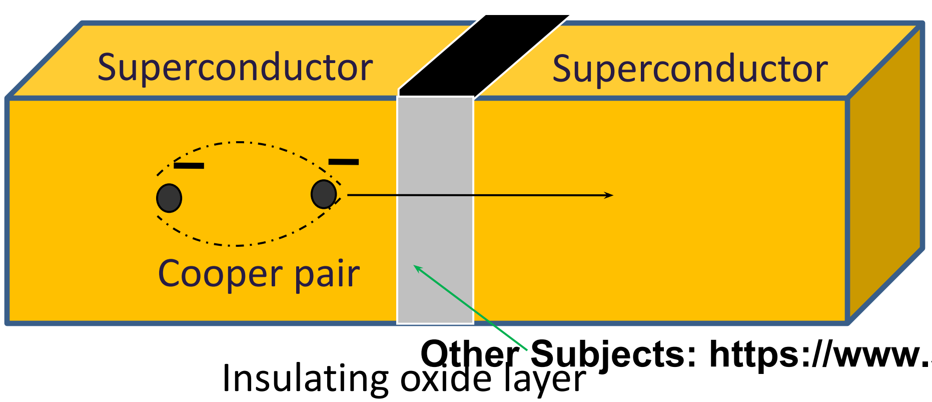
DC and AC Josephson Effect

The *'Josephson effect'* is the phenomenon of flow of electric current across two weakly coupled superconductors, separated by a very thin insulating barrier.

This arrangement two superconductors linked by a non-conducting barrier is known as a *'Josephson junction'.*

The current that flow crosses the barrier is the *'Josephson current'*.

It has important applications in quantum-mechanical circuits such as SQUIDs or RSFQ digital electronics.



Two superconductors are joined together, separated only by a thin insulating barrier such as an oxide layer 10 to 20 A^0 thick.

If a voltage is applied across the junction, a small oscillating current starts flowing back and forth through the junction, without equilibrating the two sides. This is known as the *'a.c. Josephson effect*'.

The frequency of this a.c. current is, $\upsilon = \dfrac{2eV}{h}$

The Josephson effect has found wide usage, for example in the following are as:

1. SQUIDs, or superconducting quantum interference devices, are very sensitive magnetometers that operate via the Josephson effect. They are widely used in science and engineering.

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2. In precision metrology the Josephson effect provides an exactly reproducible conversion between frequency and voltage.
3. Single electron transistors are often constructed of superconducting materials, allowing use to be made of the Josephson effect to achieve novel effects. The resulting device is called a "superconducting single-electron transistor".
4. RSFQ digital electronics is based on shunted Josephson junctions. In this case, the junction switching event is associated to the emission of one magnetic flux quantum that carries the digital information: the absence of switching is equivalent to '0', while one switching event carries a '1'.

5. Josephson junctions are integral in Superconducting Quantum Computing such as in a Flux qubits or others schemes where the phase and charge act as the Conjugate variables.
6. STJs (Superconducting Tunnel Junction) detectors may become a viable replacement for CCDs (charge-coupled devices) for use in astronomy and astrophysics in a few years. These devices are effective across a wide spectrum from ultraviolet to infrared, and also in x-rays. The technology has been tried out on the William Herschel Telescope in the SCAM instrument.

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Applications of Superconductivity

1. Superconducting cables can be used to transmit electric power over long distances without power losses.
2. Superconductors can be used to check unwanted magnetic flux by using their diamagnetic property.
3. By using superconductors, very fast and accurate computers can be developed.
4. Superconducting wires can be used to carry the large currents in high field electromagnets. Such superconducting magnets are widely used in modern particle accelerators. They are also used in Magnetic Resonance Imaging (MRI) in medicine.
5. The **S**uperconducting **QU**antum **I**nterference **D**evices (SQUID) may be configured as a magnetometer to detect incredibly small magnetic fields in living organism. (Change in magnetic fields in brain).

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7. Highly powerful strong field superconductor electromagnets are fabricated using liquid helium superconductors. These electromagnets are used in NMR spectrometers and NMR imaging that are employed in medical diagnosis.
8. Superconductor electromagnets are used for **MAG**netically **LEV**itating (MAGLEV) world's fastest trains.
9. Now it has been possible to design ceramic superconductors which can act at temperature > 77 K, i.e. it can act as hi-T_c superconductors. These superconductors have advantage over low-T_c superconductors because liquid nitrogen can be used as a coolant, which is cheaper and has better cooling due to its high thermal capacity.

10. Other industrial applications of superconductors are through magnets, sensors, transducers and magnetic shielding.
11. Superconductors also have applications in power generation, energy storage, fusion, transformers and transducers.

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Questions

1. What are superconductors? Define critical temperature. [2]
2. What is the significance of critical temperature, critical magnetic field for superconductors? [4]
3. Explain the following terms : [2 each]
   i) Zero Electrical resistance
   ii) Persistent current.
   iii) Meissner effect.
   iv) Critical magnetic field
4. Explain the isotope effect & its significance. [3]
5. Explain the Meissner effect. [4]
6. Give the applications of superconductors. [4]

4. Explain the Meissner effect. What important property of superconductors it explain? [4]
5. Explain the perfect diamagnetism in superconductors. [4]
6. Distinguish between Type I & Type II superconductors. [4]
7. Explain Type I & Type II superconductors with examples. [6]
8. What is superconductivity? Explain the BCS theory of Superconductors. [6]
9. Explain the perfect diamagnetism in superconductors. [4]
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