Department of Physics

Providence Women's College

E-Content of III Sem MSc Physics

Paper Name: Solid State Physics

Chapter: Superconductivity

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Super Conductivity

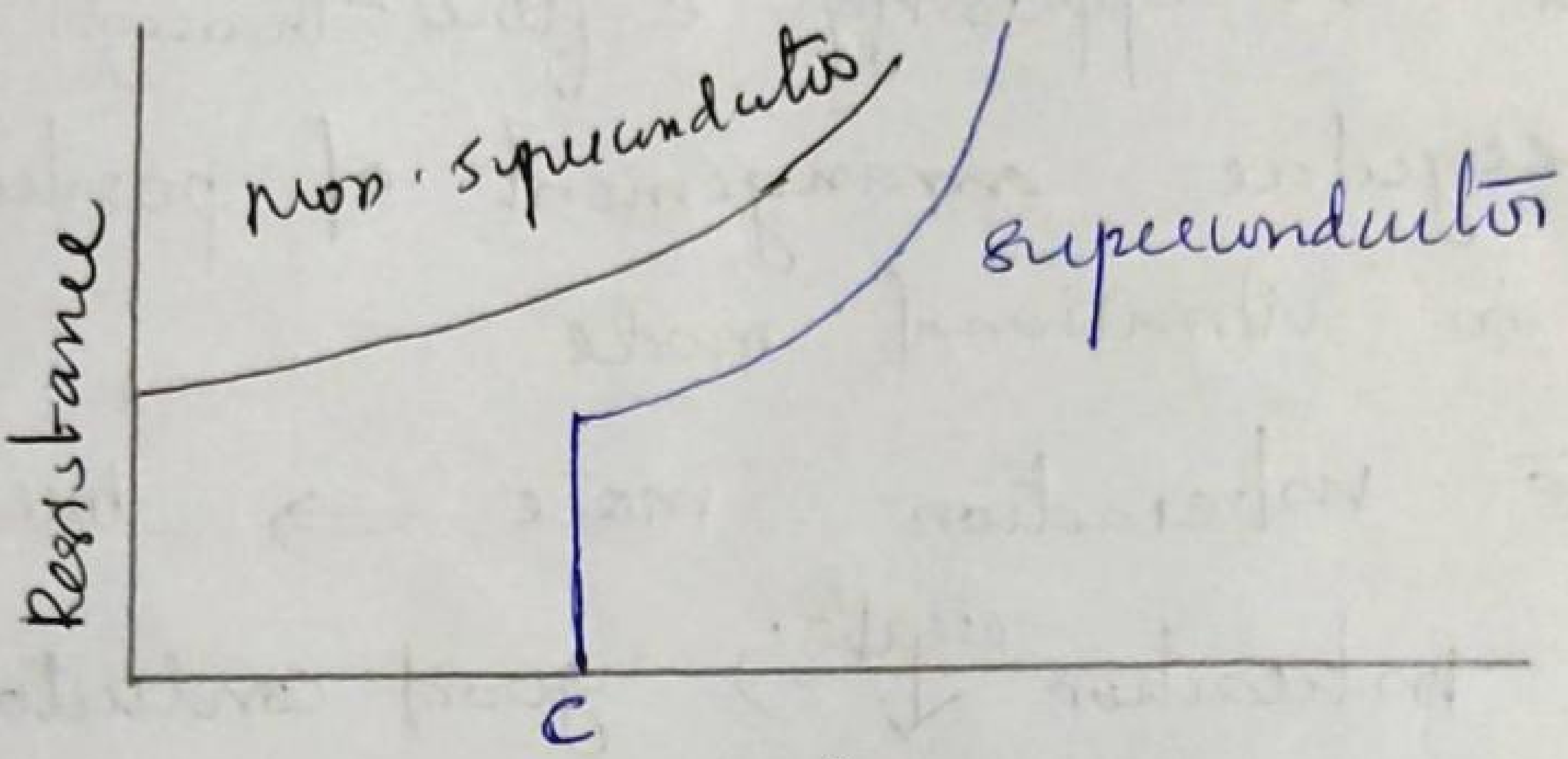
- SC was discoverd in 1911 by Heike Kammerlingh Onnes.
- Metals / material - Temp lowering - Resistance decreased.
- lattice will be opposing ē flow-through it
- lattice - regular arrangement of positive charged ions.
- lattice is in vibrational mode
- lattice - ē interaction more ⟹ more (insulator) resistance
- lattice - ē interaction weak ↓ ⟹ good conductor
- Temp ↓ - lattice - ē interaction ↓ weak - Resistance ↓.
- In the case of mercury he observed sudden change in resistance observed at a particular temp.
  - temp below absolute zero ≈ 4.18 K.
- The resistance of mercury is coming to zero.
- This phenomena he named - Superconductivity.

Superconductors are the material having almost zero resistivity and behave as diamagnetic below the superconducting transition temperature.

(diamagnetic material opposing applied electric / mag field)

superconductivity is the flow of electric current without resistance in certain metals, alloys and ceramics at temperatures near absolute zero, and in some cases at temperatures hundreds of degrees above absolute zero = −273°K. (reversible process - normal conductor to super conductor)

- As temperature decreases, A superconducting material's resistance gradually decreases until it reaches critical temperature. At this point resistance drops off, often to zero, As shown in the Graph at Right.



C = critical temperature.

- <u>Critical Temperature</u> (T_c) The temperature at which a material electrical resistivity drops to absolute zero is called the Critical Temperature or Transition Temperature
  - T_c CT - function of impurity of the material.
- Below Critical Temp, material is said to be in superconducting and above this it is said to in normal state. Below this temperature the superconductor also exhibits a variety of several astonishing magnetic and electrical properties.

  Hg = $T_c(K) = 4.15$ (adding impurity Tc changes)

<u>General Properties of Superconductors</u>

- Electrical resistance: Virtual zero electrical resistance.
- Effect of impurities: when impurities are added to superconducting elements, the superconductivity is not loss

but the T_c is lowered.
(impurities increase the width of SC)
line gradually decrease.

- Effects of pressure and stress : certain materials exhibits superconductivity on increasing the pressure in superconductors, the increase in stress results in increase of the T_c value.

Effect of Magnetic Field

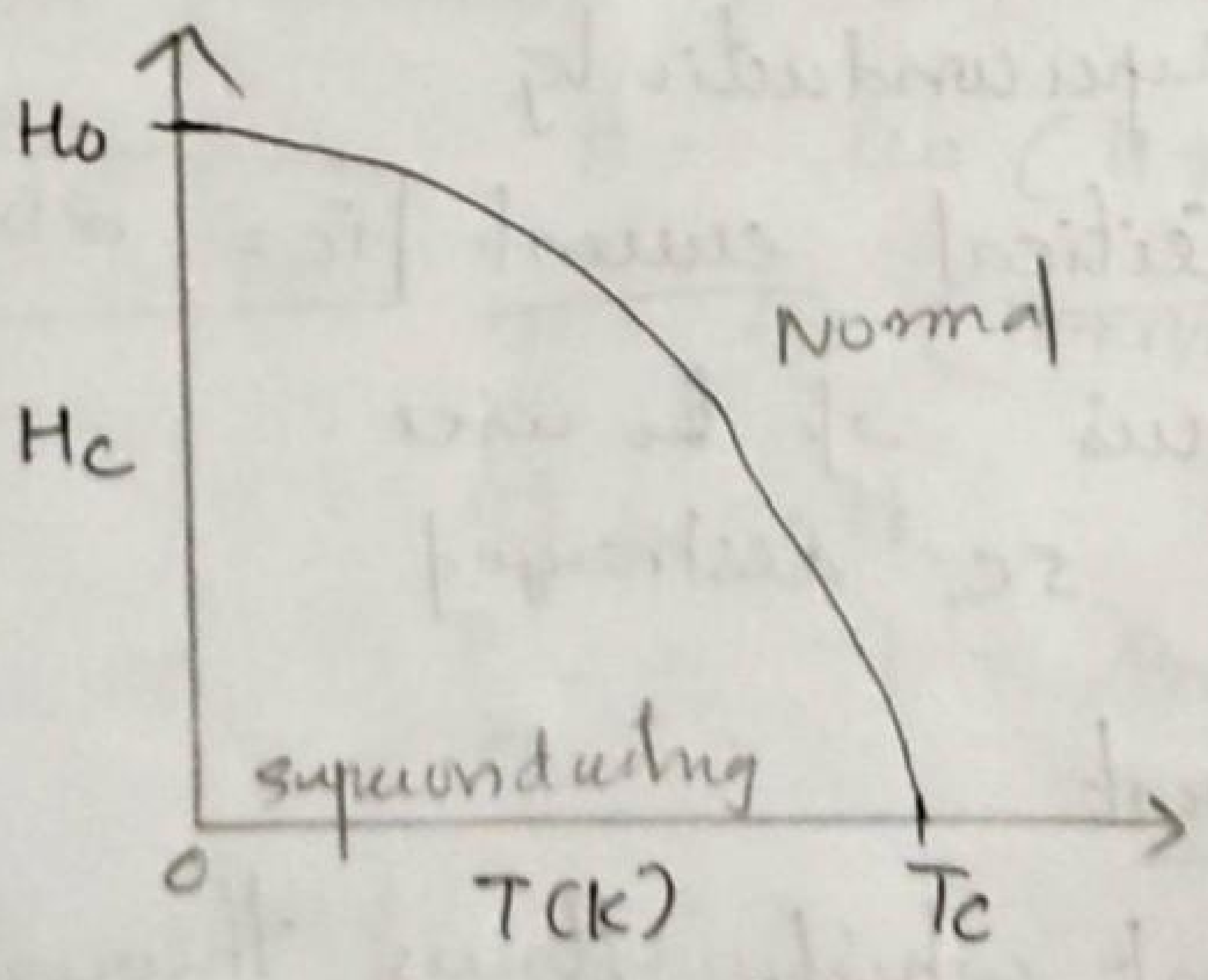
Critical Magnetic Field (H_c) :- minimum magnetic field required to destroy the superconducting property at any temperature.

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

element	H_c
Nb =	198
Pb =	80.3
Sn =	30.9

H_0 = critical field at 0K
T = Temp below T_c
T_c = Transition temperature.

0 – Tc
max H applied to destroy SC
after Tc
already normal conductor



(levitation)

- Superconductor showing diamagnetic property, superconductors always try to oppose the external magnetic field
- Superconductor will be cutting the external mag flux lines.
- Current will be induced, when flux is cut.
- That current will be flowing outside the SC on the

surface of superconducting material the current will be flowing - screening current

- Due to screening current it will be producing a magnetic field.
- Direction of this Mag Field will be oppo to the direction of external mag. F.
- If we keep on increasing ext mag field, screening current also will be increasing so the opposition also will increase.
- After a certain point, the mg Field started penetrating inside the body.
- At a particular value of magnetic field the full flux lines will be started penetrating inside the body.
- The S.C property can be destroyed.

Effect of Electric Current

- Large electric current - induces magnetic field - destroys superconductivity
- Induced Critical current $\boxed{i_c = 2\pi r H_c}$

  r = radius of the wire.

  after i_c - SC destroyed

Persistent Current

- steady current which flows through a superconducting ring without any decrease in strength even after the removal of the field.
- Diamagnetic property.

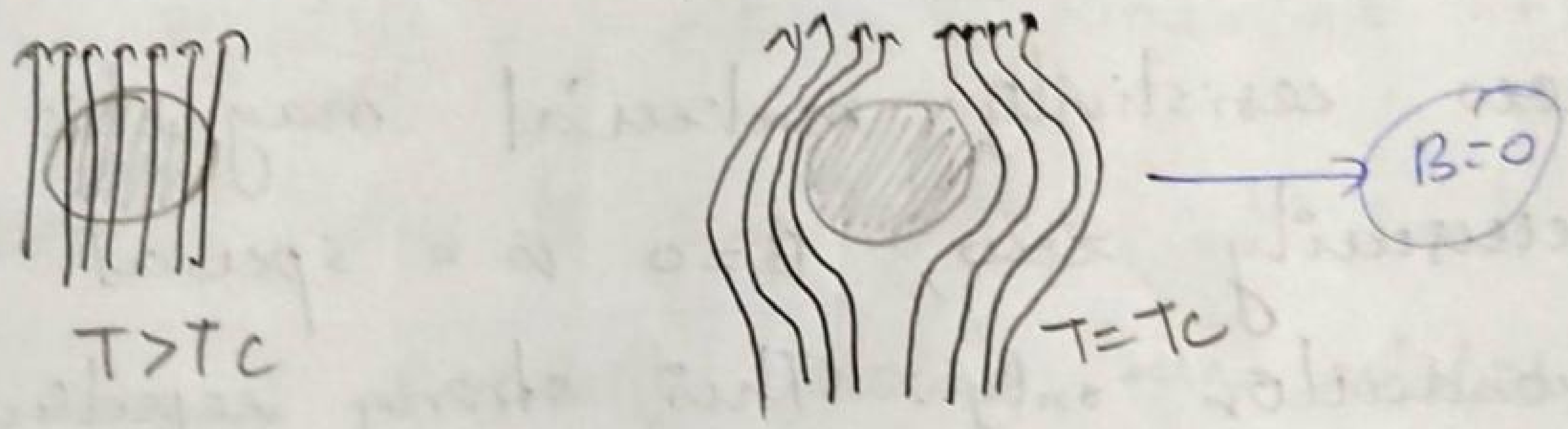
Meissner effect

superconductor is not ideal conductor

- when superconducting material cooled below its T_c it becomes resistanceless & perfect diamagnetic.
  (induced mag field $B = 0$ inside material).

when superconductor placed inside a magnetic field at T_c all magnetic flux is expelled out of it the effect is called Meissner effect.

- Perfect diamagnetism arises from some special magnetic property of superconductor.



- If there is no magnetic field inside the superconductor relative permeability or diamagnetic constant $\mu_r = 0$
- Total magnetic induction B is zero.
- $\Rightarrow$ $B = 0 \Rightarrow B = \mu_0 (H + M)$

$$0 = \mu_0 (H + m)$$

$$M = -H$$

(Perfect diamagnetic material) $\Leftarrow$ $\therefore \frac{M}{H} = -1 = \chi_m$ magnetic ~~super~~ susceptibility

H = applied field

M = magnetisation ~~induced~~ produced m > H

- Ideal case – Temp ↓ Resistance ↓ reach zero value
- superconductor obeys the ideal case.

Superconductor ideal case or not?

diamagnetism is essential property of SC but all diamags are not SCs.

Meisner effect = zero resistivity ?

$B=0 \Rightarrow \rho=0$?

For zero resistivity too occur $B=0$, not need.

$B=0$, does not follow from zero resistivity ($\rho=0$)

from ohms law $J=\sigma E$ — $J=\sigma E$, $E=\frac{J}{\sigma}=\rho J$

$$E=\rho J$$

If $\rho\to 0$, J is finite, current density

$$\Rightarrow E=0.$$

maxwell's em equation $\Rightarrow$ $\nabla\times E=-\frac{\partial B}{\partial t}$

$$\Rightarrow \frac{\partial B}{\partial t}=0$$

or B is constant, so $B\neq 0$ always.

for a zero resistivity material magnetic induction is not necessarily zero; $B=0$ is a special property of superconductor only. This strong repulsion of external magnetic field is called Levitation Effect.

- (strongly opposing mag F., mag F levitate above S.C).

TP → SC - zero resistivity & meisner effect, - cannot explained by maxwell eq^n & ohm's law.

London Equation

- two fluid eq^n.
- According to London's theory there are two type of electrons in SC
  - super electrons (at 0°K) & Normal electrons (at Tc)
- At 0°k there are only super electrons.

- with increasing temp. super electron ↓
Normal electron ↑.

- Normal $\bar{e}$ have resistance (resistance = lattice vibration)
- Super $\bar{e}$ - NO resistance
- The current carried by super $\bar{e}$ >>> current carried by normal $\bar{e}$.

n_n = number density of normal $\bar{e}$
u_n - drift velocity of normal $\bar{e}$
n_s = no. density of super $\bar{e}$
u_s = drift velocity of super $\bar{e}$

Equation of motion of super electron under electric field is

$$m\frac{du_s}{dt} = -eE \quad (ma = qE = F)$$

(contribution of due to super $\bar{e}$ >> contn due to normal $\bar{e}$)

Now current & drift velocity are related as

current $I_s = (-)n_s e A u_s$ $\qquad A$ = area

$\therefore$ $J_s = (-)n_s e u_s$

$$\therefore \quad u_s = \frac{-\vec{J}_s}{n_s e}$$

$$m\frac{d}{dt}\left(\frac{-\vec{J}_s}{n_s e}\right) = -e\vec{E}$$

$$\therefore \quad \boxed{\frac{dJ_s}{dt} = \frac{n_s e^2 E}{m}}$$ London's first equation. prove zero resistivity

If $E = 0$ $\quad \frac{dJ_s}{dt} = 0 \Rightarrow J$ = constant (finite)
current density constant

without any external (electric) field, there will be persistent current will be flowing.

$$\vec{E} = \frac{d\vec{J_s}}{dt} \quad \frac{m}{n_s e^2}$$ $E = -\frac{dA}{dt}$ vector potential

$$\frac{d\vec{J_s}}{dt} \cdot \frac{m}{n_s e^2} = -\frac{d\vec{A}}{dt}$$

$$\frac{d}{dt}\left(\frac{m}{n_s e^2}\vec{J_s}\right) = -\frac{d\vec{A}}{dt}$$

$$\therefore \quad \frac{m}{n_s e^2}\vec{J_s} = -\vec{A}$$

$$\boxed{J_s = -\frac{n_s e^2 \vec{A}}{m}}$$ london's second equation

Topperw

- T.P meisner effect.

Again from Amperes law,

$$\bar{\nabla} \times \bar{B} = \mu_0 \vec{J_s}$$

$$\bar{\nabla} \times \bar{B} = \mu_0 \left(-\frac{n_s e^2}{m}\vec{A}\right)$$

Take curl on both sides.

$$\bar{\nabla} \times \bar{\nabla} \times \bar{B} = \mu_0 \left(-\frac{n_s e^2}{m} \bar{\nabla} \times \bar{A}\right)$$

Now

$$\bar{\nabla} \times \bar{\nabla} \times \bar{B} = \bar{\nabla} \times \bar{\nabla} \cdot \bar{B} - \nabla^2 \vec{B} \qquad \& \quad \bar{\nabla} \times \bar{A} = B$$

$$\bar{\nabla} \cdot \bar{\nabla} \cdot \bar{B} - \bar{\nabla}^2 \bar{B} = \mu_0 \left(-\frac{n_s e^2 \bar{B}}{m}\right)$$

so $\bar{\nabla} \cdot \bar{\nabla} \cdot \bar{B} = (\nabla \cdot \nabla \cdot \nabla \times A) = 0$

$$\therefore \quad \nabla^2 B = \frac{\mu_0 n_s e^2 \vec{B}}{m}$$

Assume $\mu_0 \times \frac{n_s e^2}{m} = \frac{1}{\lambda^2} = \frac{\mu_0 n_s e^2}{m}$

$$\nabla^2 B = \frac{1}{\lambda^2}\vec{B}$$

or $$\boxed{\nabla^2 \vec{B} - \frac{1}{\lambda^2}\vec{B} = 0}$$ λ is called london penetration length.

from london's eq^n

$$\boxed{B(x) = B_0\, e^{-x/\lambda_L}}$$ (-ve sign indicates decreasing)

(for thin film, flux penetration will be there, they do not obey meissner effect)

Penetration depth is the distance upto which magnetic lines penetrate through the material, when placed in a magnetic field.

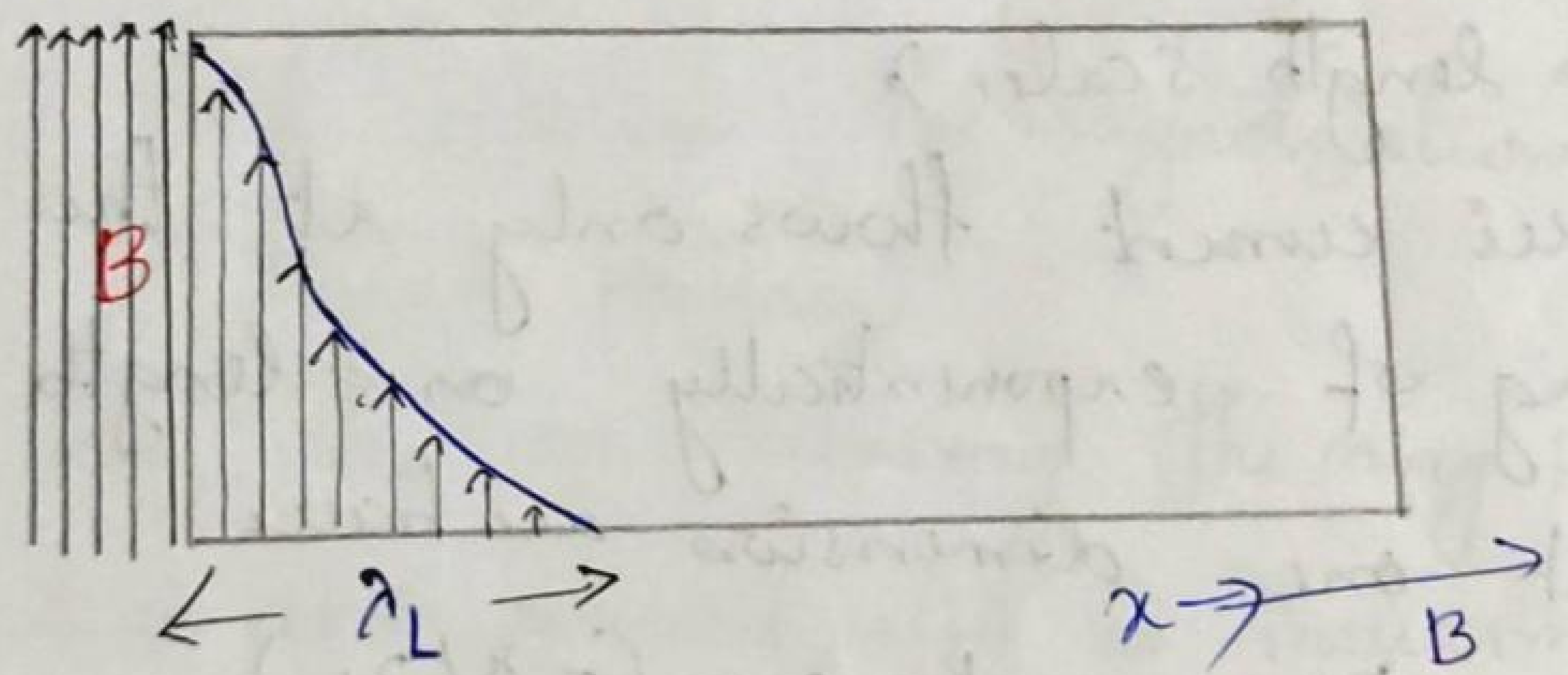
λ_L = penetration depth (considering x direction)

$= (m/nq^2\mu_0)^{1/2}$

$B(x)$ = mag field at any position x

$B(0)$ - mag field at $x=0$ (starting point)

small x ∝ surface thermal



coherence length:

where coherence length is the range in a super conductor in which superconducting electrons remain in the same state in a spatially varying magnetic field.

The resistivity of the superconductors suddenly falls to zero indicates that all the electrons in the material come to the same state suddenly (10^{-4}cm) a long range order.

(length sups ξs can travel)

8|9|21 Superconductivity can be destroyed by
- increasing temp
- increasing magnetic field
- increasing current.

Summary of London equations

The London's produced a phenomenological model of superconductivity which provided equations which described but did not explain superconductivity.

Starting with with the observation that superconductors expel all magnetic flux from their interior, they demonstrated the concept of the Penetration depth; showing that
- flux does penetrate, but falls of exponentially on a length scale, λ.
- electric current flows only at the surface, again falling of exponentially on a length scale, λ.

So, in just one dimension we have

$$B(x) = B_A \exp(-x/\lambda_L)$$

$$J_y(x) = J_A \exp(-x/\lambda_L)$$

with $\lambda_L = \sqrt{m/\mu_0 n_s e^2}$ London penetration depth

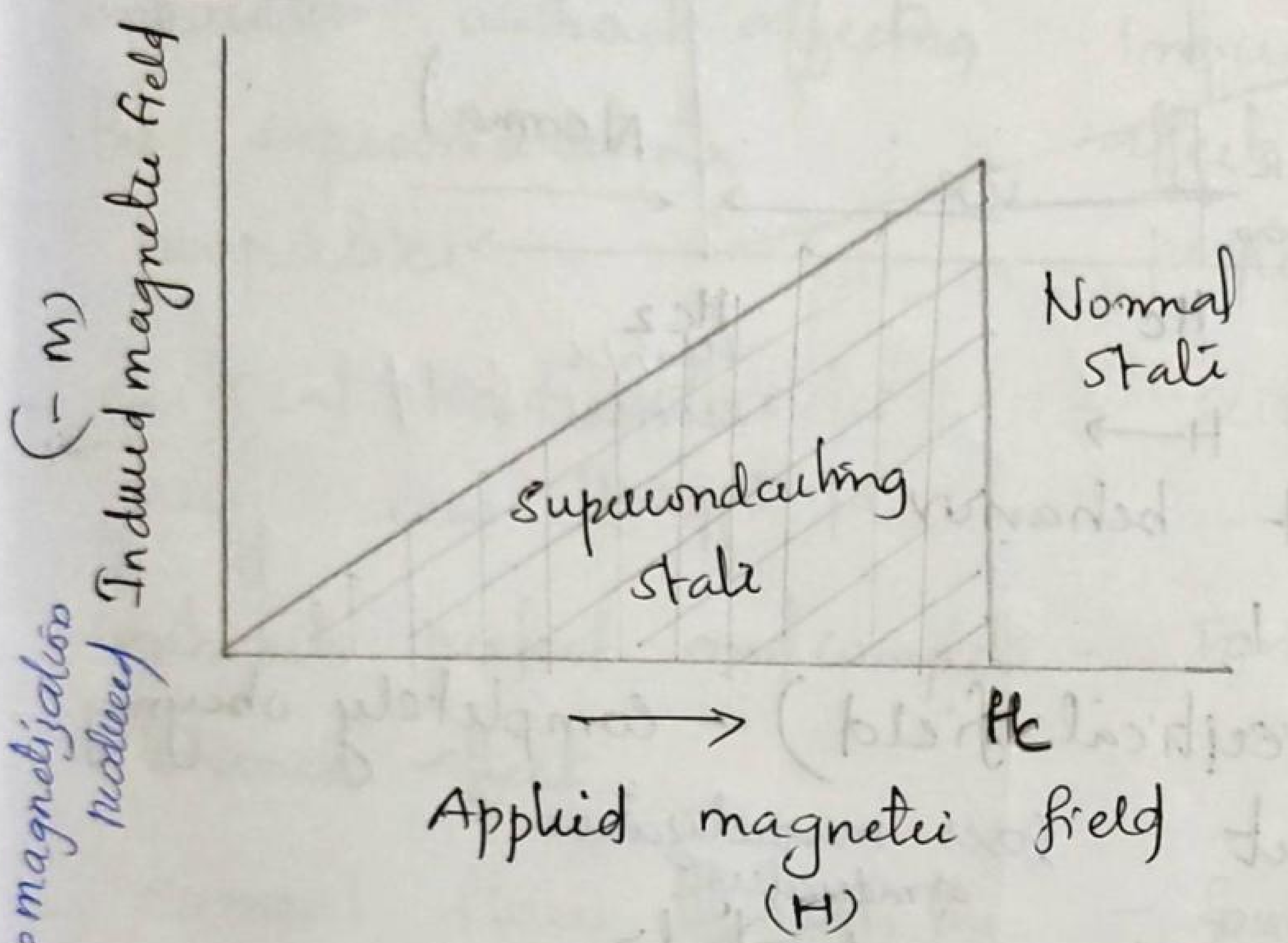
λ_L is very small $\Rightarrow$ flux will be penetrating on the surface only over a small thickness

Inside the material flux $= 0$.

{ If the thickness of the film is comparable to the penetration depth, you can observe that inside the superconducting material there will be flux. This is not obeying the meisner effect)

On the basis of meisner effect . SCrs can be classified into two 1) Type I
2) type II

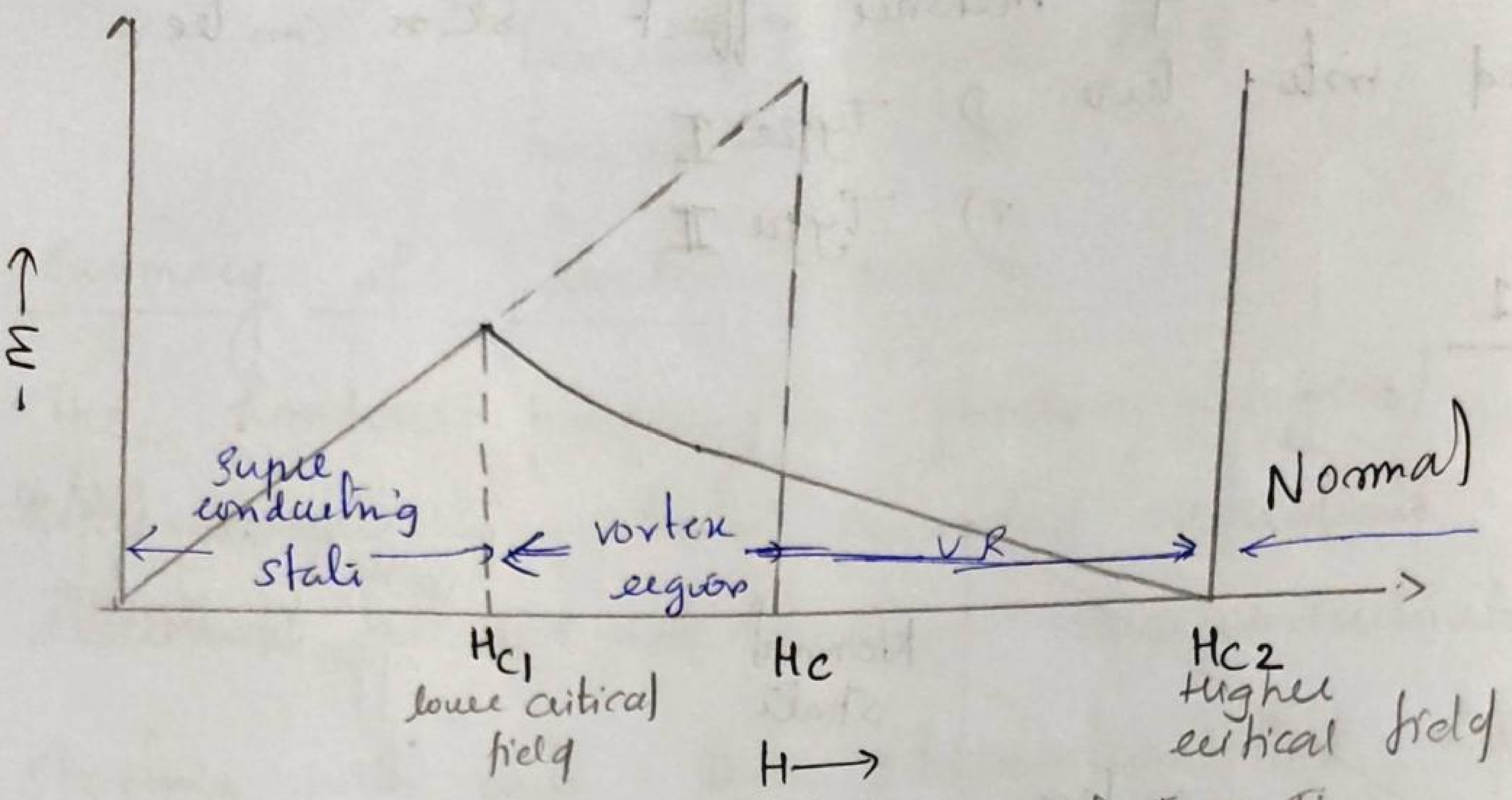
Type 1



induced mag field is opposite direction

- As the field increases the magnetization (induced) also will increase (linear increase).
- If you are keep on increasing the mag Field the magnetization ~~also~~ induced will be increasing in the opposite manner.
- magnetization is induced to the surface current (screening current)
- the induced (opposite) mag field and Applied mag Field are equal up to the Critical Field Hc.
- above Hc = Normal state.
- upto Hc = obeys meisner effect (no flux inside the material).
- magnetic field produced by the super conducting material are not allowing the external field to enter inside the body.

Type 2



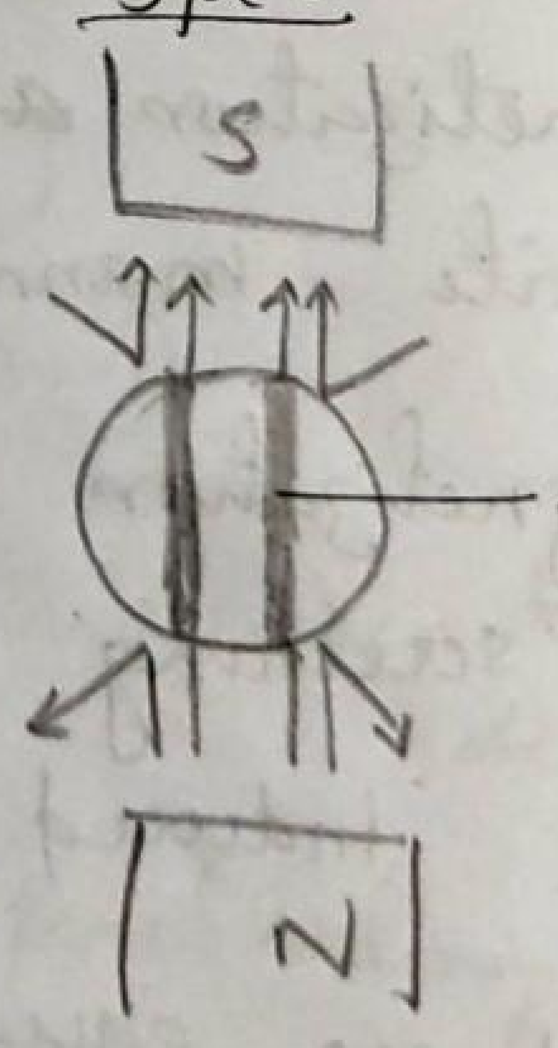
- Solid line represent behavior of Type II
- dotted line Type I
- upto H_{C1} (lower critical field) - completely obeying the meisner effect

loses magnetization gradually

- b/w H_{C1} & H_{C2} (vortex region) - obeying mixed state
  - flux will be penetrating through the body, but as well as behaving like a superconductor

Type 1

Type 2



- do not allow mag Fields to penetrate.
- Above H_C - lose their superconducting properties.

- allow magnetic fields to penetrate b/w H_{C1} & H_{C2}.
- lose their SC properties above H_{C2}
- flux tubes :- a normal non superconducting region in a

Type II S.C ns b/w H_{c1} & H_{c2}.

Type 1	Type 2
- Soft Superconductors are those which can tolerate impurities without affecting the superconducting properties	- Hard Superconductors are those which cannot tolerate impurities, i.e, the impurities affects the superconducting property.
- critical Field value is very low.	- critical field value is very high.
- exhibits perfect and complete Meissner effect	- Don't exhibit perfect and complete meissner effect
- current flows through the surface only	- found that current flows throughout the material.
- These materials have limited technical applications because of very low field strength values (0.2 Tesla)	- These materials have wider technology of very high field strength value. - carry high current density (40 Tesla)

Isotope effect

- evidence of S.C effect = isotope effect & energy gap.
- observed by Maxwell in 1950.
- critical temp of SC varies with isotopic mass.
- (isotopes - same no. of p & e, neutron number changing
- $\bar{e}$ number not changing, - lattice not changing
n change - material behaviour change.)

- Transition temp of mercury changes from 4.185 K to 4.146 K as the isotopic mass M varies from 199.5 to 203.4.
- T_c varies with the isotopic Mass M as

$$\boxed{T_c \propto M^{-\alpha}} \qquad \alpha = 1/2$$

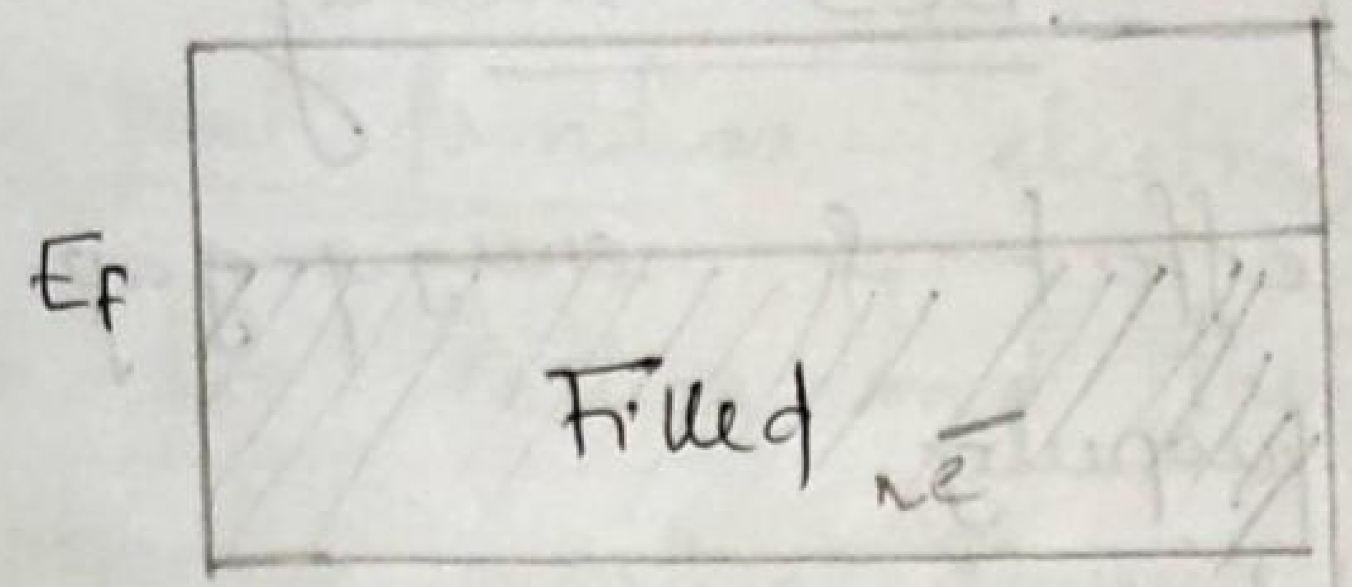
$$\boxed{T_c M^{1/2} = \text{constant}}$$

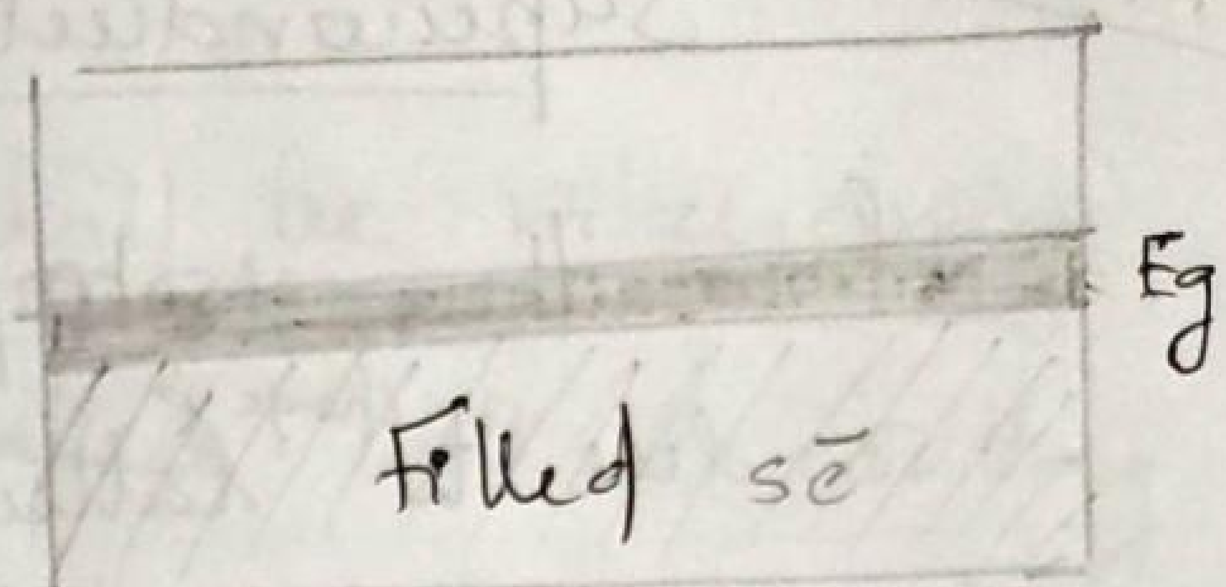
- The isotopic mass can enter in the process of the formation of the superconducting phase of the electron states only through the electron - phonon interaction.
  (phonon - lattice vibrational wave)

Energy Gap.

[The energy gap b/w super ē and normal ē or
- The energy needed to convert super ē to normal ēs
- EG. not a fixed value. EG chang w.r.t Temp
- At T=0 - gap will be maximum - only s. electrons.
- When T ↑, gap ↓ , T = Tc = EG = 0
- In SC EG attached with Fermi level.)]
- The energy gap in superconductors are attached to the fermi gas.
- current flows despite the presence of a gap (current flows due to super ēs).
-
- The energy gap has no effect ~~has no effect~~ upon the behaviour of the special electrons that carry current in SC.
- (There will be a gap b/w filled state & unfilled state - EG)

At T=0K





- ~~The energy~~ conduction band in normal state

Energy gap at the fermi level in the superconducting state.

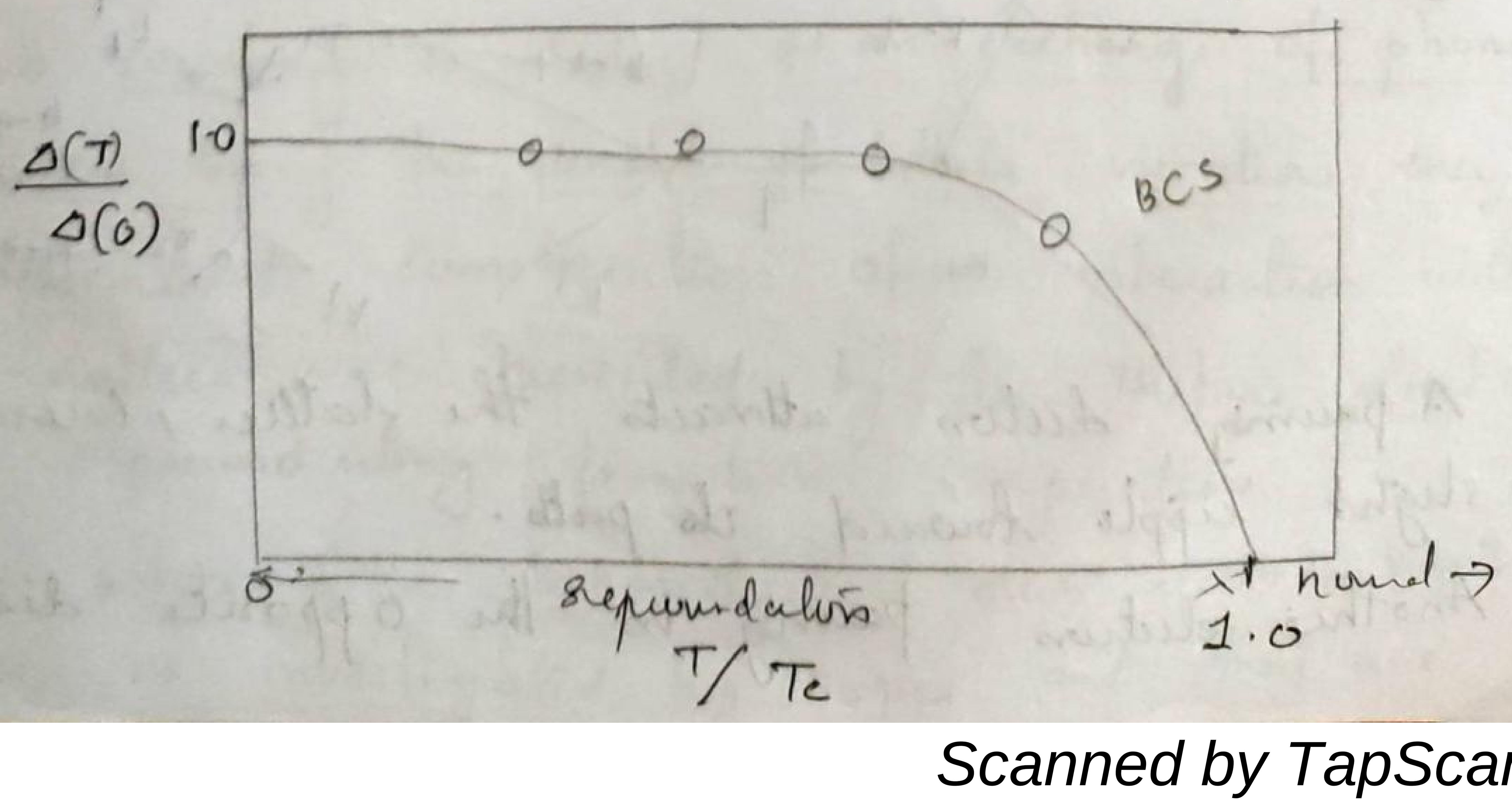
- The energy gap varies with temperature Unlike insulators and semiconductors.
- Max at 0K and decreases continously to zero as the temp is increased to the Tc.
- At T = Tc, all the SC electrons ~~bcle~~ become normal electrons.
- The gap decreases from a value of about 3.5 $k_B T_c$ at 0K to zero at the Tc.

k_B = Boltzmann constant
Tc = Critical Temp.

$$\boxed{\begin{array}{l} E_g = 2\Delta = 2b\, k_b T_c \\ E_g / k_B T_c = 2b \end{array}}$$

max T_c < 35 K, 20 K

$T = T_c \rightarrow \Delta(T) = 0$ gap energy = 0



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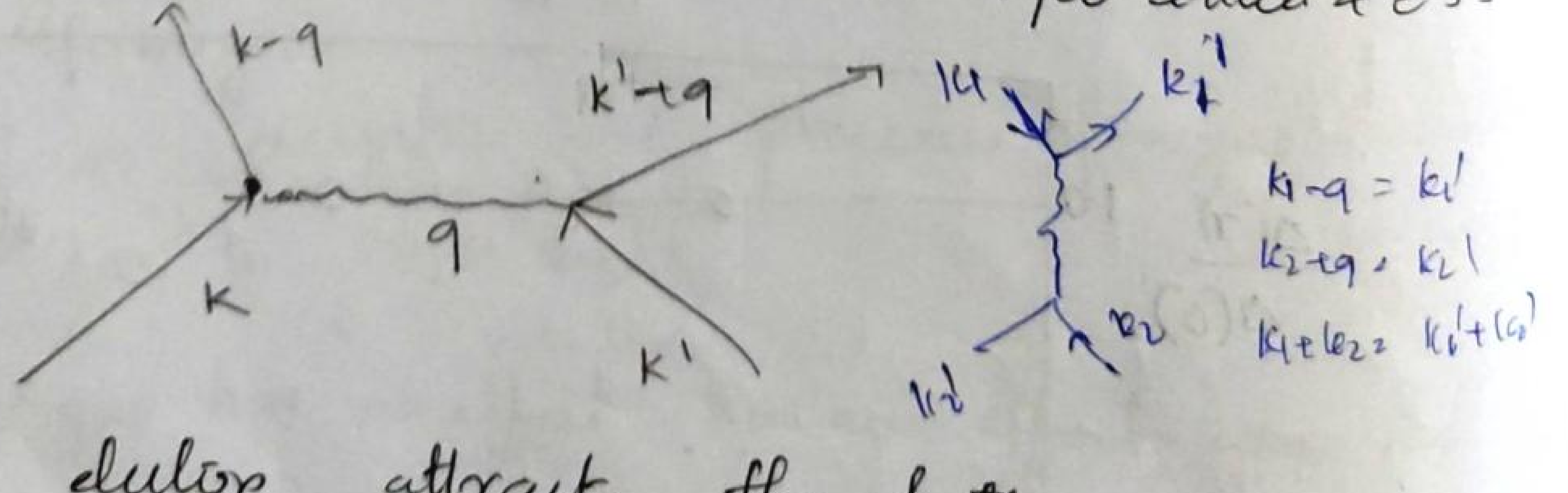
Superconductivity - BCS Theory

- from the isotopic effect & energy gap -
  - SC due to change in lattice property
  - crystal structure not changing

BCS Theory

- Bardeen, Cooper, Schrieffer attributed the cause of superconductivity to pair of electrons formed by the interaction b/w two ēs via an exchange of a phonon.
- This is an electron - phonon - electron interaction which is attractive and bind two electrons together forming a pair called ~~call~~ "Cooper pair".
- One electron interact with a positive ion in the lattice and deforms the lattice, a second electron with compatible momentum passing nearby interacts with the same ions in the distorted lattice so as to minimise its energy.
- (phonon - lattice - interaction) - strong interaction - more resistance)
- good conductors - weak interactions b/w lattice & ēs.



- A passing electron attracts the lattice, causing a slight ripple toward its path.
- Another electron passing in the opposite direction

is attracted to that displacement.

coopee pair formation - electrons will be interacting with the lattice and the lattice will be emitting a phonon, another ē will be interacting with the same lattice will be absorbed by that phonon, so the total momentum will be conserved.

Cooper pairs

- The transition of a metal from the normal to the superconducting state has the nature of a condensation of the electrons into a state which leaves a band gap above them.
- This kind of condensation is seen with super fluid helium, but helium is made up of bosons -- multiple electrons can't collect into a single state because of the pauli exclusion principle.
- Froehlich was first to suggest that the electrons act as pairs coupled by lattice vibrations in the material.
- This coupling is viewed as an exchange of phonons, phonons being the quanta of lattice vibration energy
- Experimental corroboration of an interaction with the lattice was provided by the isotope effect on the superconducting transition temperature.
- The boson-like behaviour of such electron pairs was in investigated by Cooper and they are

called Cooper pairs.

- The condensation of cooper pairs is the foundation of the BCS theory of superconductivity.

((energy gap - energy needed to break cooper pair bond)

- coherence length - how long it can move with bond (together).

{ not obey paulis exclusion principle, large no. of cooper pair can accomodate 1 energy state.

- have integral spin: acts like bosons.

- All will occupy in the BCS ground state. Fermi level is reduced.]

- The electrons forming cooper pair have equal and opposite momentum one in spin up and the other in spin down state.

- If the state with spin up (↑) and +k is occupied then the corresponding state with down spin (↓) and -k is also occupied. Similarly if the state with spin up (↑) and +k is vacant, then the corresponding state with down spin (↓) and -k is also vacant.

- Net spin of the cooper pair is zero.

- They condense into a quantum mechanical ground state with a long range order called coherence length.

- Total energy of the system minimizes and a small energy gap 'Δ' is formed near the fermi energy E_{f},

$$\boxed{\Delta \approx 1.4\, k_{\beta} T_c}$$

(ēs in boson form, many cooper pairs sharing the same energy level, all try to go to ground state of BCS level. Fermi level reduced (position). Gap b/w fermi level & upper state).

- At T = 0K energy gap is maximum as pairing is max. (cooper pairs max)
- At T = Tc, SC and energy gap disappears as all pairing are broken - C pair → normal e' (NC).
- Single electrons are scattered by the vibrating ions and experience opposition, hence $\rho \neq 0$, but cooper pairs are not scattered by the vibrating ions, so $\rho = 0$ (Cooper pair slide through lattice.)

Elements of BCS Theory.

- BCS theory of Superconductivity.

(drawback = max transition temp is 135 K at present. According to BCS theory Tc < 20 K).
BCS- for low temp S conductor.)

- The properties of Type 1 Superconductors were modelled successfully by the efforts of John Bardeen, Leon Cooper, and Robert Schrieffer in what is commonly called the BCS theory.
- A key conceptual element in this theory is the pairing of electrons close to the fermi level into

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cooper pair through interactions with the crystal lattice.

(~~cooper~~ electron → cooper pair. from the surface moving to inside the BCS level, this process continuous). trying to reduce energy).

- This pairing results from a slight attraction b/w the electrons related to lattice vibrations; the coupling to the lattice is called a phonon interaction

- Pairs of electrons can behave very differently from single electrons which are fermions and must obey the Pauli exclusion principle.

- The pair of electrons act more like bosons which can condense into the same energy level.

- The electron pairs have a slightly lower energy and leave an energy gap above them on the order of 0.001 eV which inhibits the kind of collision interactions which lead to ordinary resistivity.

- For temperature such that the thermal energy is less than the band gap, the material exhibits zero resistivity.

- B, C, & S received Nobel prize in 1972 for the development of the theory of superconductivity

- In the normal state of a metal, electrons move independently, whereas in the BCS state, they are bound into "Cooper pairs" by the attractive interaction. The BCS formalism is based on the reduced potential for the electrons attraction.

- you have to provide energy equal to the energy gap to break apart, to break one pair you have to change energies of all other pairs.

- This is unlike the normal metal, in which the state of an electron can be changed by adding a arbitrary small amount of energy

- The energy gap is highest at low temperature but does not exist at temperature higher than the transition temperature

- The BCS Theory gives an expression of how the gap grows with the strength of attractive interaction and density of states.

- The BCS theory gives the expression of the energy gap that depends on the Temp T and Critical Temp Tc and is independent of the material:

$$\boxed{E = 3.52\, k_B\, T_c \left(1 - \left(T/T_c\right)\right)^{1/2}}$$

$k_B = 1.38 \times 10^{-23}\ m^2\, kg\, s^{-2}\, K^{-1}$

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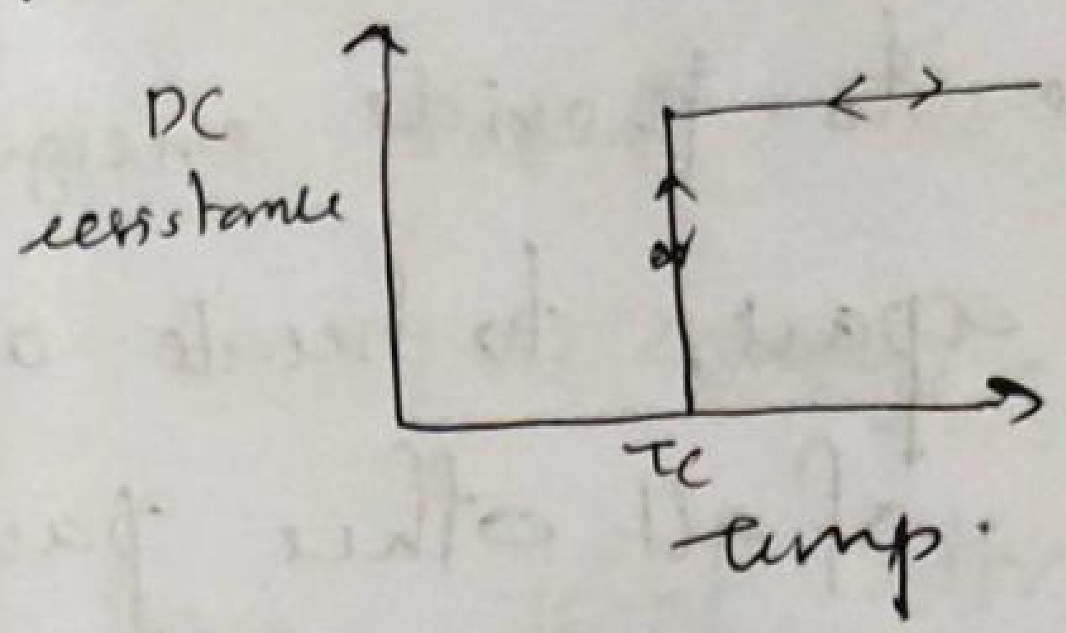
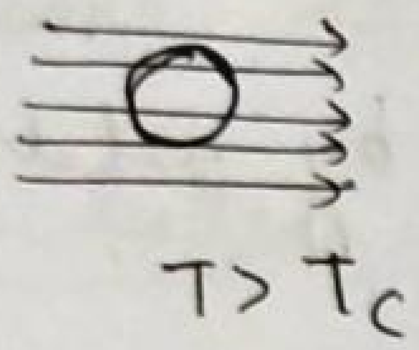
Flux Quantisation & Tunneling

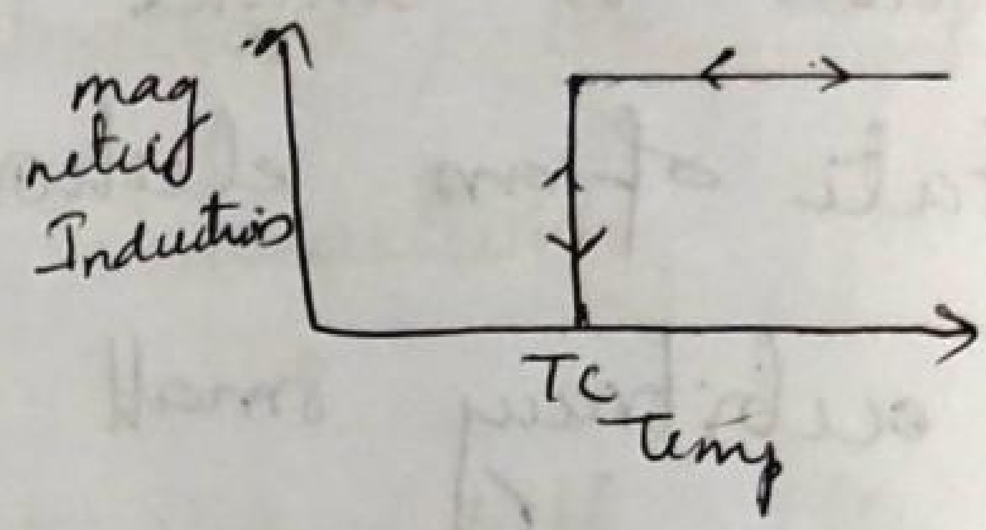
Three hallmarks of superconductivity

1) Zero resistance

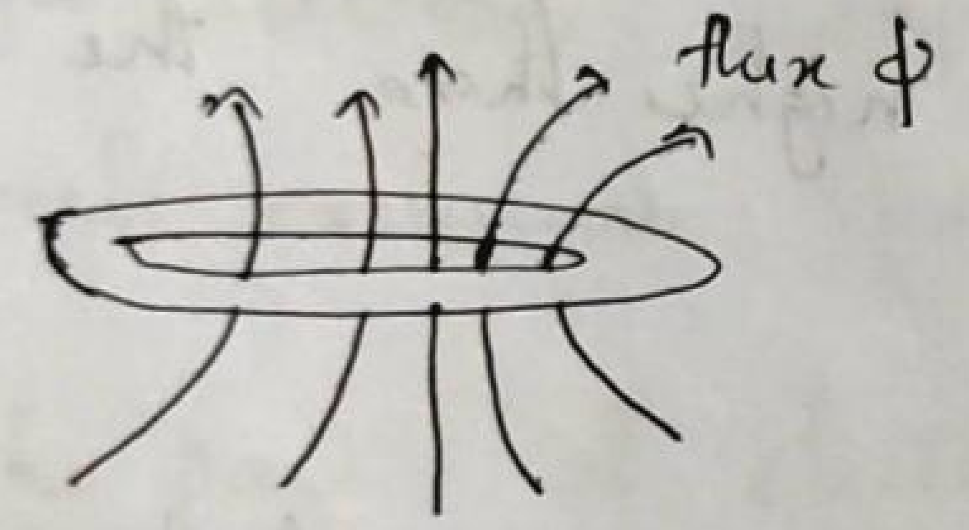


2) complete Diamagnetism (Meissner effect)





3) Macroscopic Quantum Effects.



flux quantization $\phi = n\phi_0$

Josephson Effects.

(. The material should be in the form of ring or hollow cylinder. The material in normal state and we are applying mag. field. flux line will be everywhere inside outside ring. Once decrease the temp, reach Tc, the flux lines on ring expel out of ring. The flux lines inside the ring is trapped. That fluxlines will be quantized).

To prove flux lines are quantised,

Let $\psi(r)$ be the super state wave function.

(cooper pair is represented by wavefunction ψ)

$n =$ particle density / number density

$= \psi^* \psi$

($n =$ no. of cooper pair / unit volume)

$\psi = \sqrt{n}\, e^{i\theta(r)}$ & $\psi^* = \sqrt{n}\, e^{-i\theta(r)}$

$\psi^+\psi = n$ particle density

θ = phase of wave.

$\psi = \sqrt{n} e^{i\theta(r)}$

velocity Operator $v = \frac{1}{m}\left(P - \frac{q}{c}A\right)$

(p = momentum, A = vector potential)

$P = mv$

$v = \frac{(p - q/c\,A)}{m}$

velocity $v = \frac{1}{m}\left(\frac{\hbar}{i}\nabla - \frac{q}{c}A\right)$

particle flux: $\psi^* v \psi$

$$= \frac{n}{m} e^{-i\theta}\left(\frac{\hbar}{i}\nabla - \frac{q}{c}A\right)e^{i\theta} = \frac{n}{m}\left[e^{-i\theta}\frac{\hbar}{i}\, i e^{i\theta}\nabla\theta \right.$$

$$\left. - \frac{n}{m} e^{-i\theta}\frac{q}{c}A e^{i\theta}\right)$$

$$= \frac{n}{m}\left(\hbar\nabla\theta - \frac{q}{c}A\right)$$

Electric current density: $j = q\psi^* v\psi$

$$\boxed{j = \frac{nq}{m}\left(\hbar\nabla\theta - \frac{q}{c}A\right)}$$

$\nabla \times \nabla\theta = 0$

$\lambda_L = \left(\frac{m}{nq^2\mu_0}\right)^{1/2}$

$$\nabla \times j = \frac{nq}{m}\left(-\frac{q}{c}\nabla\times A\right) = -\frac{nq^2 B}{mc}$$

$\left(\mu_0 = \frac{4\pi}{c^2}\right)$

london eq^n with $\lambda_L = \sqrt{\frac{mc^2}{4\pi n q^2}}$

According to meissner effect, mag field = 0, $B = 0$

$\therefore$ The mag flux lines cannot peneteate inside the body

Therefore $j = 0$. The current will be flowing only on the surface of sc'ing material not inside.

Inside S.C $B = j = 0$,

$$\Rightarrow j = \frac{nq}{m}\left(\hbar\nabla\theta - \frac{q}{c}A\right) = 0 \Rightarrow \hbar\nabla\theta = \frac{q}{c}A$$

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take closed integral on b.s ; w.r.t dt

$$\int_C \hbar \nabla\theta \cdot dl = \frac{q}{c}\int_C A \cdot dl$$

$\nabla \to \Delta$

$$\hbar \Delta\theta = \frac{q}{c}\int_S \nabla \times A \, d\sigma = \frac{q}{c}\int_S B \cdot d\sigma \quad \text{(using stokes law)}$$

$$\hbar \Delta\theta = \frac{q}{c}\phi$$

ψ measurable $\to$ ψ single valued $\to$ $\Delta = 2\pi s$.

$\int \nabla\theta \cdot dl = 2\pi n$

$$\frac{h}{2\pi} \cdot 2\pi s \cdot \theta = \frac{q}{c}\phi$$

s = integer

$$\boxed{\phi = \frac{hc}{q} s}$$

q = total charge of cooper pair $= -2e$

(s=1)

$$\boxed{\phi_0 = \frac{hc}{2e} \approx 2.0678 \times 10^{-7} \text{ gauss cm}^2}$$

= fluxoid or fluxon. quantum of flux

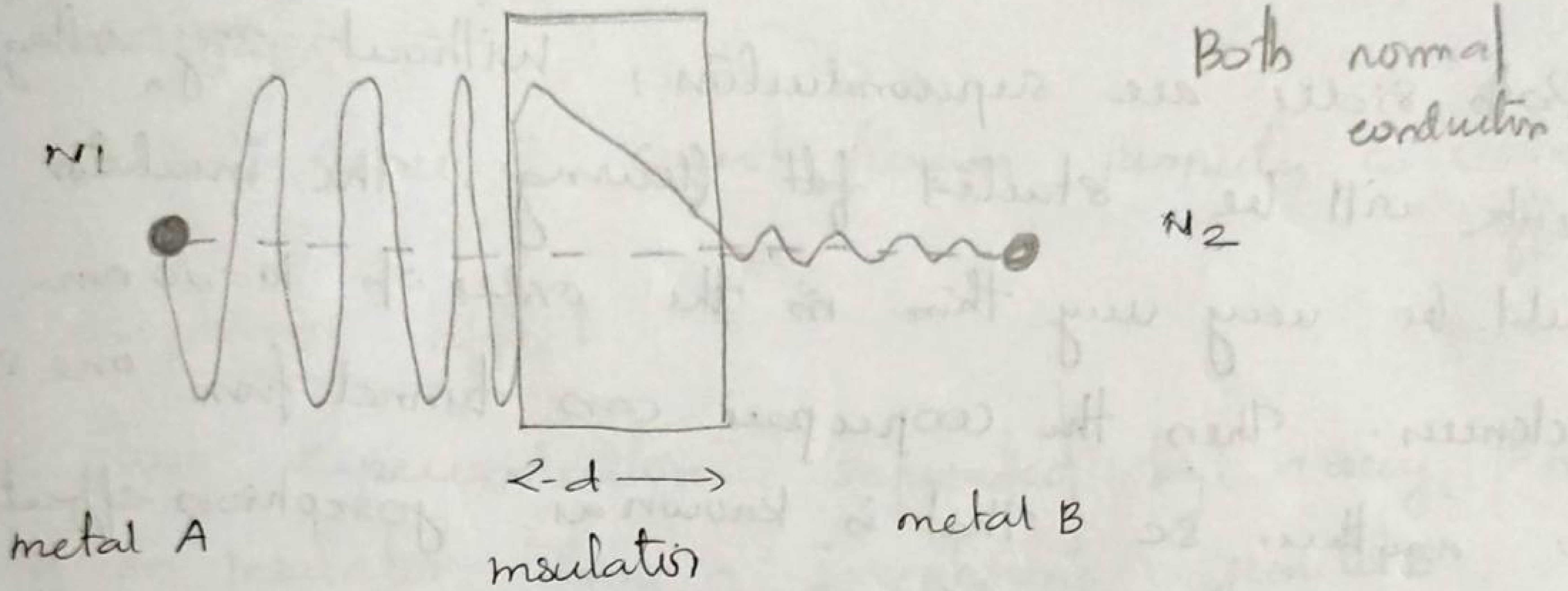
flux through ring : $\phi = \phi_{ext} + \phi_{sc} = s\phi_0$

ϕ_{ext} not quantized $\to$ ϕ_{sc} must adjust

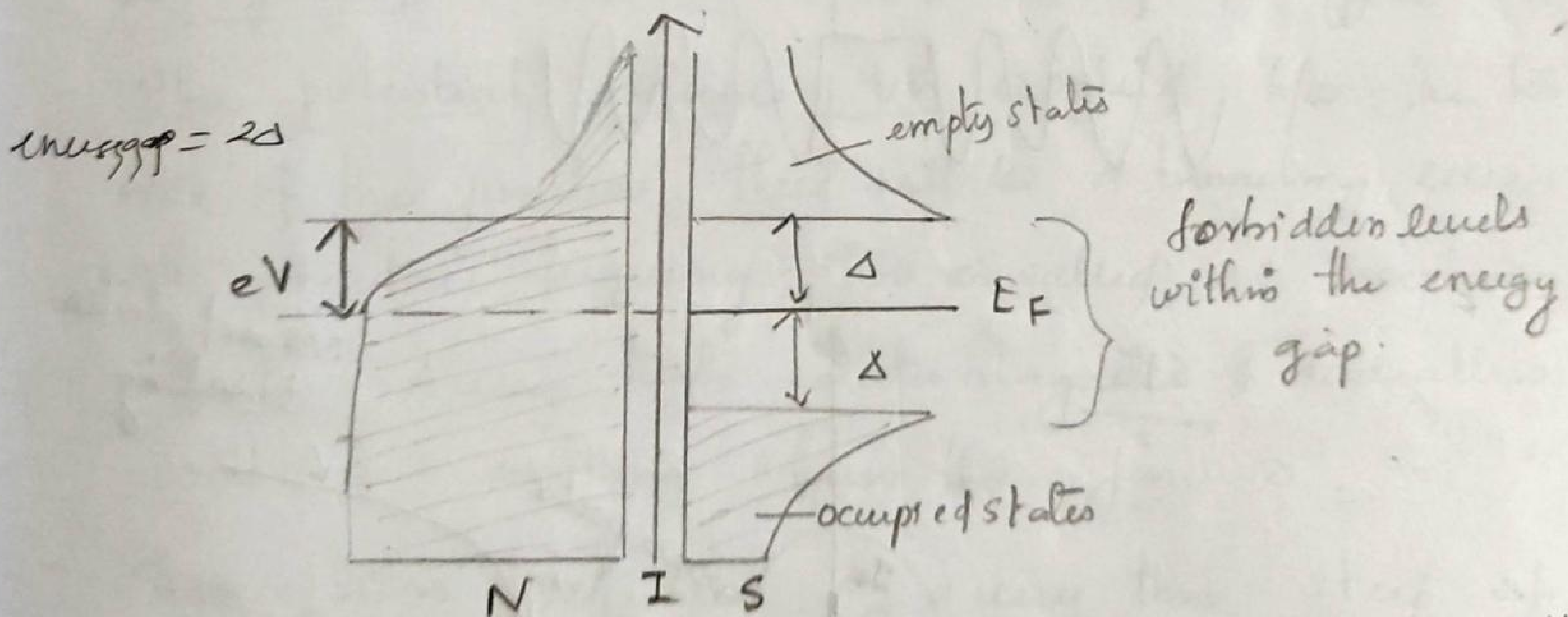
Tunneling in Solid state systems

The award is for their discoveries regarding tunneling phenomena in solids. Half of the prize is divided equally b/w Esaki and Giaever for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors respectively. The other half is awarded to josephson for his theoretical predictions of properties is a supercurrent flowing through a tunnel barrier, in particular the phenomena generally known as the Josephson effects.

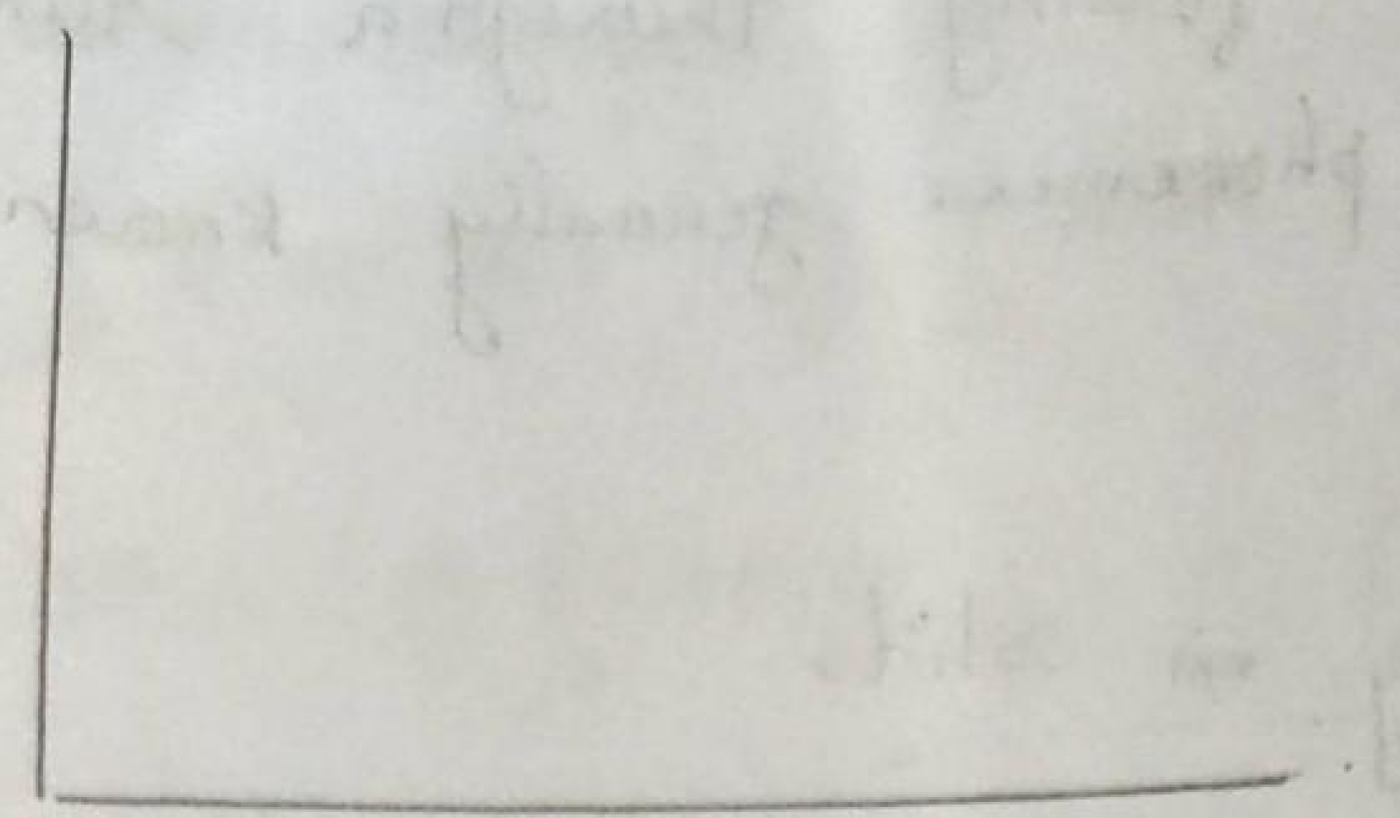
Electron tunneling in solids.



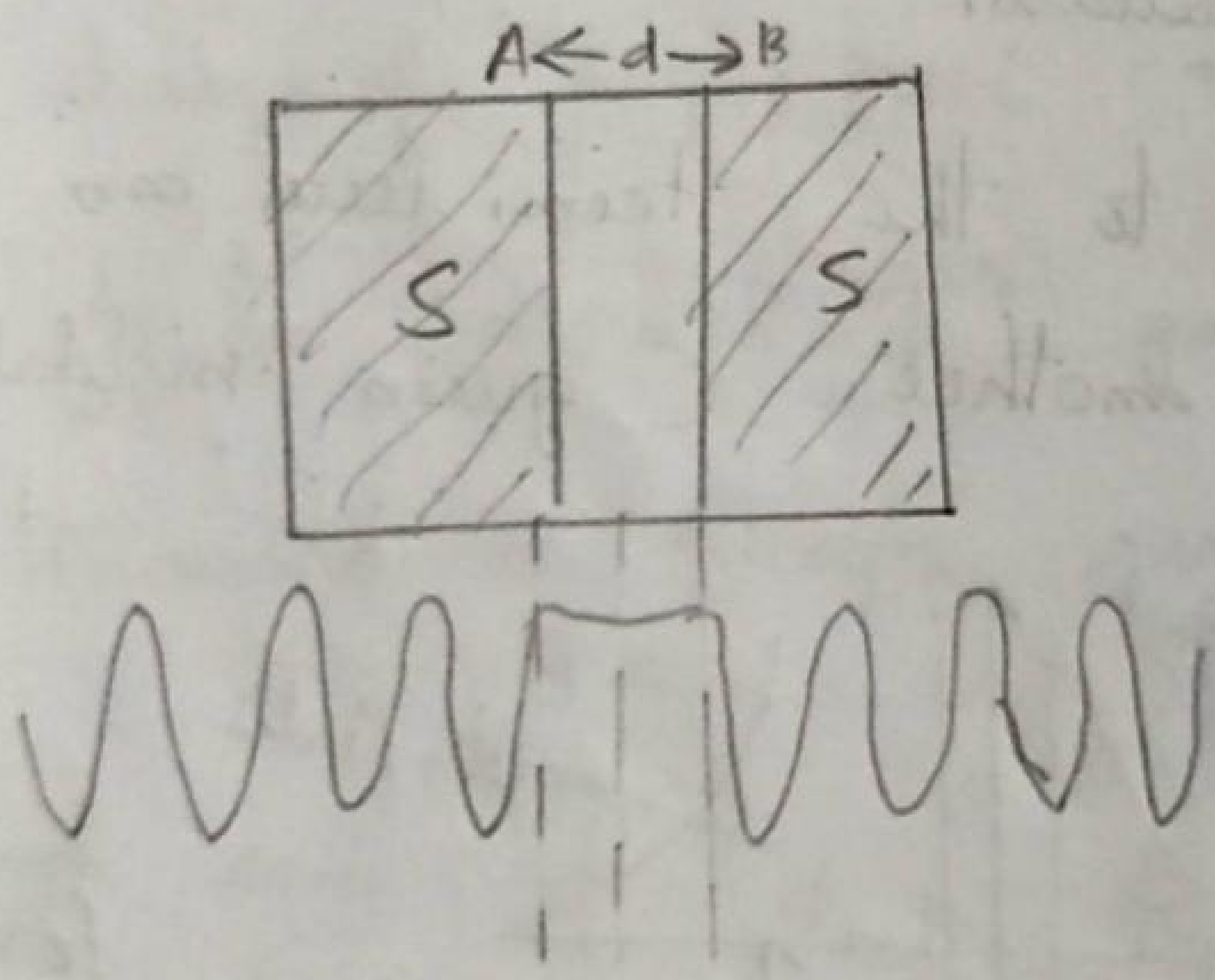
Electrons close to the Fermi level can tunnel from one metal to another. (given insulator is very thin)

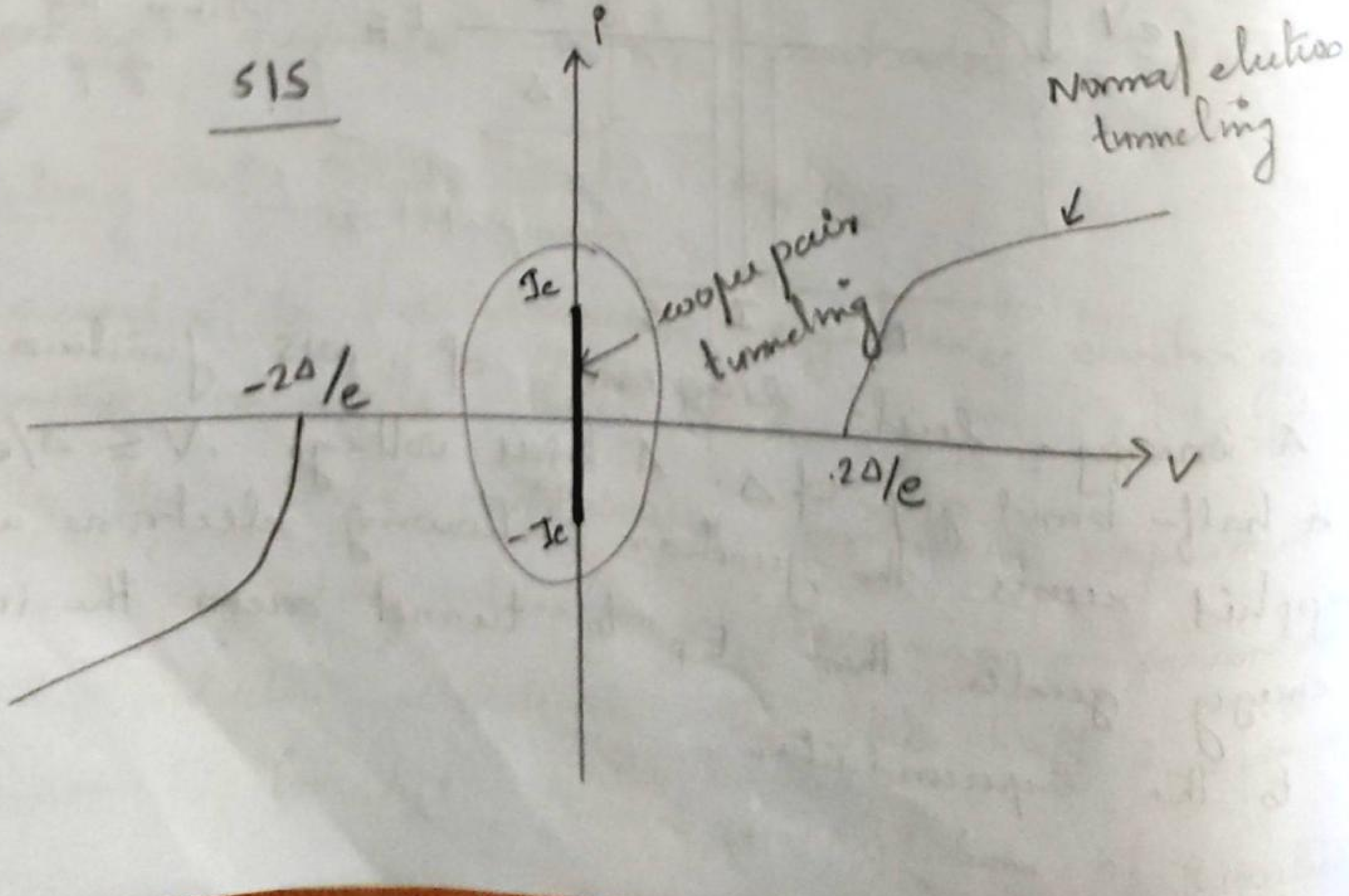


A energy-level-diagram of a NIS junction with a half-band gap of Δ. A bias voltage, $V \geq \Delta/e$, is applied across the junction, allowing electrons with an energy greater than E_F to tunnel across the insulator to the superconductor.



If Both sides are superconductors, without any external voltage, current will be started ~~flt~~ flowing; The insulator should be very very thin in the order of 10-20 nm. thickness. Then the cooper pair can tunnel from one sc to another sc. That is known as josephson effect.





- from the graph, without any (applied) external voltage (v=0) current is flowing) from $-i_c$ to $+i_c$ = DC current
- maximum current flowing without applying voltage.
- normal $\bar{e}$ starts tunneling only when voltage is equal to ($2\Delta/e$) energy required to break the cooper pair. - AC!

(2Δ gap)

- SIS - super $\bar{e}$ current flowing property is Josephson effect.

Josephson Effect

- Two superconductors separated by a very thin strip of an insulator form a josephson's junction.
- As a consequence of the tunneling of electrons across the insulators without applied voltage, there is a net current across the junction. This is called DC Josephson effect.
- If a potential difference V is applied b/w the two side of the junction, there will be a tunneling current with angular frequency. This is called AC Josephson effect. A very high electromagnetic radiation will be emitting from the junction.
- Two SCrs separated by a very thin strip of an ~~installer~~ insulator forms a josephson junction.
- The wave nature of moving particles make electrons to tunnel through the barrier. As a consequence of tunneling of electrons across the insulator there is net current across the junction. This is called d.c josephson effect. The current flows even in absence of

potential difference.

- The magnitude of current depends on the thickness of the insulators, the nature of the materials and temperature.

- (superconducting bar - connected with voltmeter shows zero voltage. Bcoz, zero resistance $V=IR$, $V=0$.

- Break superconducting bar .. voltmeter deflect).

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Theory of DC josephson effect.

Let ψ_1 be the probability amplitude of $\bar{e}$ pair on one side of the junction & ψ_2 be the probability amplitude on the other side. And assume that both the Scrs are identical and suppose both are in zero potential

The time dependent sch eqn

$$i\hbar \frac{\partial \psi}{\partial t} = H\psi$$ can be applied to the two Scrs having amplitude ψ_1 & ψ_2. As

$$i\hbar \frac{\partial \psi_1}{\partial t} = (\hbar T)\,\psi_2 \quad \text{—} (1)$$

$$i\hbar \frac{\partial \psi_2}{\partial t} = (\hbar T)\,\psi_1 \quad \text{—} (2)$$

where $\hbar T$ represent the effect of electron pair coupling or the transfer interaction across the insulator

- T is the measure of leakage of ψ_1 into the region II. and ψ_2 in the region I.

- suppose the gap b/w the two Scr is large, then $T=0$ (Thickness of insulator large)

$$\psi_1 = \sqrt{n_1}\, e^{i\theta_1} \quad \& \quad \text{——} ③$$

$$\psi_2 = \sqrt{n_2}\, e^{i\theta_2} \quad \text{——} ④ .$$

$\delta = \theta_2 - \theta_1$

where n_1 & n_2 are the number densities of SCrs of region I & II.

Substitute ③ & ④ in ① & ②.

$$i\cancel{\hbar}\frac{\partial}{\partial t}\left(\sqrt{n_1}e^{i\theta_1}\right) = \cancel{\hbar}T\psi_2$$

$$\frac{\partial}{\partial t}\left(\sqrt{n_1}e^{i\theta_1}\right) = -iT\psi_2 .$$

$$\frac{1}{2\sqrt{n_1}}\frac{\partial n_1}{\partial t}e^{i\theta_1} + \sqrt{n_1}\, i e^{i\theta_1}\frac{\partial \theta_1}{\partial t} = -iT\psi_2$$

$$\frac{1}{2\sqrt{n_1}}\frac{\partial n_1}{\partial t}e^{i\theta_1} + i\psi_1\frac{\partial \theta_1}{\partial t} = -iT\psi_2 \quad \text{——} ⑤$$

substituting ④ in ②,

$$i\hbar\frac{\partial}{\partial t}\left(\sqrt{n_2}e^{i\theta_2}\right) = \hbar T\psi_1$$

$$\frac{\partial}{\partial t}\left(\sqrt{n_2}e^{i\theta_2}\right) = -iT\psi_1$$

$$\frac{1}{2\sqrt{n_2}}\frac{\partial n_2}{\partial t}e^{i\theta_2} + \sqrt{n_2}\, i e^{i\theta_2}\frac{\partial \theta_2}{\partial t} = -iT\psi_1$$

$$\frac{1}{2\sqrt{n_2}}\frac{\partial n_2}{\partial t}e^{i\theta_2} + i\psi_2\frac{\partial \theta_2}{\partial t} = -iT\psi_1 \quad \text{——} ⑥$$

multiply ⑤ with $\sqrt{n_1}e^{-i\theta_1}$

$$\cancel{\sqrt{n_1}}\cancel{e^{-i\theta_1}}\left(\frac{1}{2\cancel{\sqrt{n_1}}}\cancel{e^{i\theta_1}}\right)\frac{\partial n_1}{\partial t} + \sqrt{n_1}e^{-i\theta_1}\left(i\psi_1\frac{\partial \theta_1}{\partial t}\right) = -iT\sqrt{n_2}e^{i\theta_2}\sqrt{n_1}e^{-i\theta_1}$$

$$\frac{1}{2}\frac{\partial n_1}{\partial t} + \sqrt{n_1}\cancel{e^{-i\theta_1}}\, i\sqrt{n_1}\cancel{e^{i\theta_1}}\frac{\partial \theta_1}{\partial t} = -iT\sqrt{n_1 n_2}\, e^{i(\theta_2-\theta_1)}$$

$$\frac{1}{2}\frac{\partial n_1}{\partial t} + i n_1\frac{\partial \theta_1}{\partial t} = -iT\sqrt{n_1 n_2}\, e^{i(\theta_2-\theta_1)} \quad \text{——} ⑧$$

$$\frac{1}{2}\frac{\partial n_1}{\partial t} + i n_1\frac{\partial \theta_1}{\partial t} = -iT\sqrt{n_1 n_2}\left(\cos(\theta_2-\theta_1) + i\sin(\theta_2-\theta_1)\right)$$

$$\frac{1}{2}\frac{\partial n_1}{\partial t} + i n_1\frac{\partial \theta_1}{\partial t} = -iT\sqrt{n_1 n_2}\cos\delta + T\sqrt{n_1 n_2}\sin\delta \quad \text{——} ⑦$$

multiply ⑥ with $\sqrt{n_2}\, e^{-i\theta_2}$

$$\cancel{\sqrt{n_2}\, e^{-i\theta_2}}\left(\frac{1}{2\sqrt{n_2}}\, \cancel{e^{i\theta_2}}\right)\frac{\partial n_2}{\partial t} + \left(\sqrt{n_2}\, \cancel{e^{-i\theta_2}}\right) i\sqrt{n_2}\, \cancel{e^{+i\theta_2}}\;\frac{\partial \theta_2}{\partial t} = -iT\sqrt{n_1}\, e^{i\theta_1} \times \sqrt{n_2}\, e^{-i\theta_2}$$

$$\frac{1}{2}\frac{\partial n_2}{\partial t} + i n_2 \frac{\partial \theta_2}{\partial t} = -iT\sqrt{n_1 n_2}\, e^{i(\theta_1-\theta_2)}$$

$$= -iT\sqrt{n_1 n_2}\, e^{-i(\theta_2-\theta_1)}$$

$$= -iT\sqrt{n_1 n_2}\left(\cos(\theta_2-\theta_1) - i\sin(\theta_2-\theta_1)\right)$$

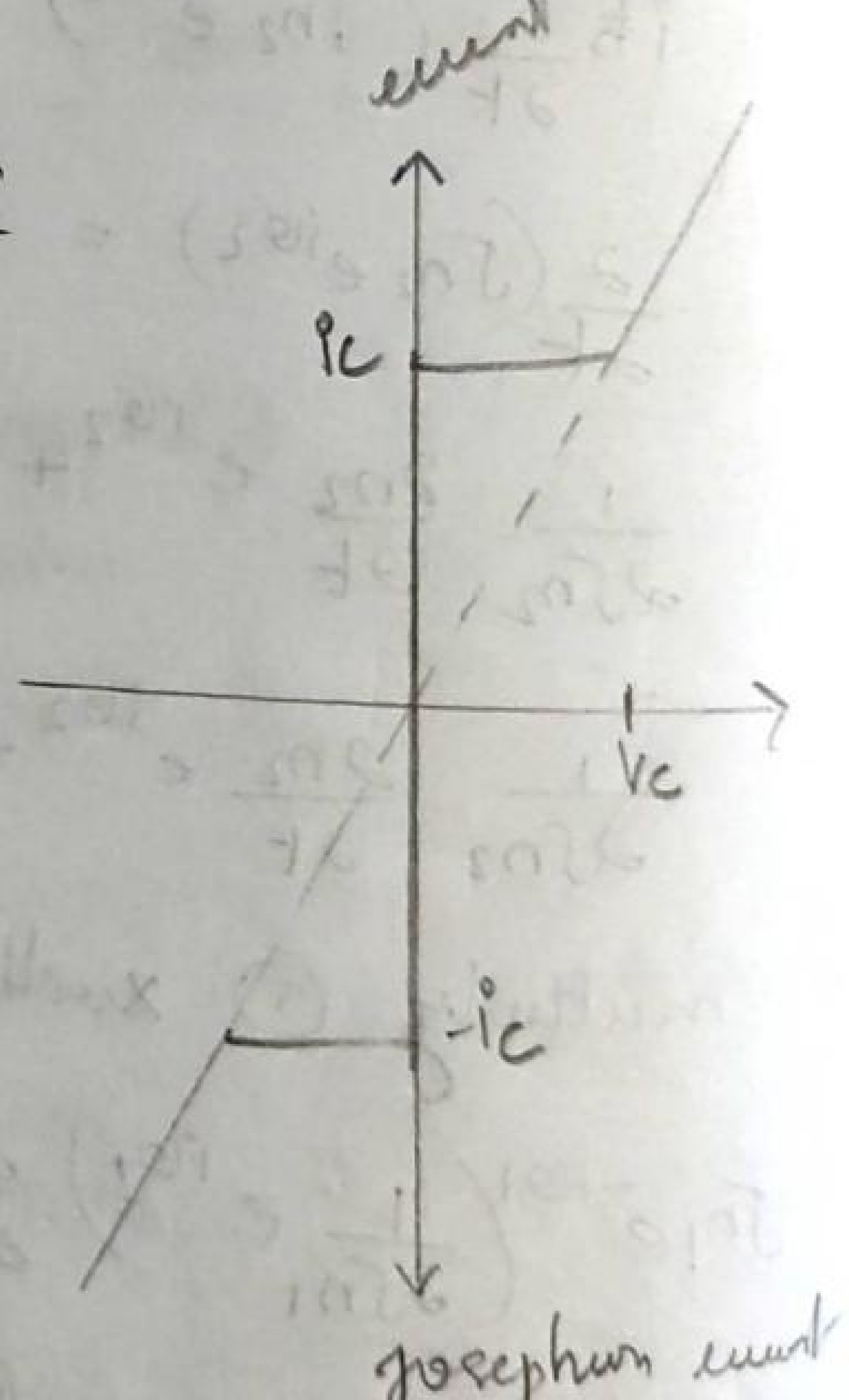
$$\frac{1}{2}\frac{\partial n_2}{\partial t} + i n_2 \frac{\partial \theta_2}{\partial t} = -iT\sqrt{n_1 n_2}\cos\delta - T\sqrt{n_1 n_2}\sin\delta \quad \text{— ⑧}$$

separating into real & imaginary parts

from ⑦ Real part,

$$\frac{1}{2}\frac{\partial n_1}{\partial t} = T\sqrt{n_1 n_2}\sin\delta$$

$$\boxed{\frac{\partial n_1}{\partial t} = 2T\sqrt{n_1 n_2}\sin\delta} \quad \text{— I}$$



imaginary part,

$$n_1\frac{\partial \theta_1}{\partial t} = -T\sqrt{n_1 n_2}\cos\delta$$

$$\boxed{\frac{\partial \theta_1}{\partial t} = -T\sqrt{\frac{n_2}{n_1}}\cos\delta} \quad \text{— II}$$

from ⑧ Real part,

$$\frac{1}{2}\frac{\partial n_2}{\partial t} = -T\sqrt{n_1 n_2}\sin\delta$$

$$\boxed{\frac{\partial n_2}{\partial t} = -2T\sqrt{n_1 n_2}\sin\delta} \quad \text{— III}$$

imaginary part,

$$n_2\frac{\partial \theta_2}{\partial t} = -T\sqrt{n_1 n_2}\cos\delta$$

$$\boxed{\frac{\partial \theta_2}{\partial t} = -T\sqrt{\frac{n_1}{n_2}}\cos\delta}$$

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for two identical superconductors $n_1 = n_2$

$$\frac{\partial n_1}{\partial t} = 2Tn\sin\delta \qquad \frac{\partial n_2}{\partial t} = -2Tn\sin\delta$$

1 to 2

$$\frac{\partial n_2}{\partial t} = -\frac{\partial n_1}{\partial t}$$ current flow from the junction is proportional to $\frac{\partial n_2}{\partial t}$ or $-\frac{\partial n_1}{\partial t}$.

current flow $\propto \frac{\partial n_1}{\partial t}$.

$$\frac{\partial \theta_1}{\partial t} = -T\cos\delta \qquad \frac{\partial \theta_2}{\partial t} = -T\cos\delta$$

$$\frac{\partial \theta_1}{\partial t} = \frac{\partial \theta_2}{\partial t} \Rightarrow \frac{\partial}{\partial t}(\theta_2 - \theta_1) = 0$$ (phase difference is time independent)

$$\frac{\partial}{\partial t}\delta = 0 \Rightarrow \delta = \text{constant}$$

$\therefore$ we can conclude that superconducting pairs current J of the superconductor pairs across the junction depends on the phase difference δ. $\boxed{J = J_0\sin\delta}$

Since δ is a constant $\therefore$ J will be a constant DC current & J_0 is proportional to T & here we have taken the voltage applied as zero & the current flowing is a constant current. This implies that without applying any voltage a DC current flowing through the junction with maximum value of $-J_0$ to $+J_0$. Depending on the value of $\theta_2 - \theta_1$ and this effect is known as DC Josephson effect.

So plotting a graph current density Vs θ.

$+J_0$ at $\sin 90$

$-J_0$ at $\sin 270$

- no phase change in DC J Effect.. (

T = Transfer interaction.

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AC Josephson effect

Let a voltage V is applied to the Josephson junction, an $\bar{e}$ pair experience a ~~to~~ potential difference qV on passing across the junction where $q = -2\times e$. [bcoz Cooper pair consists of $2\bar{e}$] instead of $\bar{e}$ tunneling, Cooper pair is tunneling.

So we can say that a pair on one side has a potential of $-eV$ and a pair on the other side has a potential of $+eV$. So that potential difference will become $-2eV$. So the eqn of motion become.

$$i\hbar \frac{\partial \psi_1}{\partial t} = \hbar T \psi_2 - eV \psi_1 \quad —(1)$$

$$i\hbar \frac{\partial \psi_2}{\partial t} = \hbar T \psi_1 + eV \psi_2 \quad —(2)$$

$\psi_1 = \sqrt{n_1}\, e^{i\theta_1}$ $\quad$ $\psi_2 = \sqrt{n_2}\, e^{i\theta_2}$. $\quad$ $\delta = \theta_2 - \theta_1$ phase difference

$$(1) \Rightarrow \; i\hbar \frac{\partial(\sqrt{n_1} e^{i\theta_1})}{\partial t} = \hbar T \sqrt{n_2} e^{i\theta_2} - eV \sqrt{n_1} e^{i\theta_1}$$

$$\left(i\hbar \left[\frac{1}{2\sqrt{n_1}} \frac{\partial n_1}{\partial t} \times e^{i\theta_1} + \sqrt{n_1}\, i\, e^{i\theta_1} \frac{\partial \theta_1}{\partial t}\right)\right) = \hbar T \sqrt{n_2} e^{i\theta_2} - eV \sqrt{n_1} e^{i\theta_1} \; \cancel{\times \sqrt{n_1} e^{-i\theta_1}} \quad —(3)$$

~~ihs~~ $(3) \times \sqrt{n_1}\, e^{-i\theta_1}$

$$i\hbar \frac{\sqrt{n_1}\, \cancel{e^{-i\theta_1}}\, \cancel{e^{i\theta_1}}}{2\sqrt{n_1}} \frac{\partial n_1}{\partial t} - \hbar \sqrt{n_1}\, i\, \cancel{e^{i\theta_1}} \cdot \sqrt{n_1}\, \cancel{e^{-i\theta_1}} \frac{\partial \theta_1}{\partial t}$$

$$= \hbar T \sqrt{n_1}\sqrt{n_2}\, e^{i\theta_2} \cdot e^{-i\theta_1} - eV \sqrt{n_1}\sqrt{n_1}\, \cancel{e^{i\theta_1}}\, \cancel{e^{-i\theta_1}}$$

$$i\hbar \frac{1}{2} \frac{\partial n_1}{\partial t} - \hbar n_1 \frac{\partial \theta_1}{\partial t} = \hbar T \sqrt{n_1 n_2}\, e^{i(\theta_2 - \theta_1)} - eV n_1$$

$$i\hbar \frac{1}{2}\frac{\partial n_1}{\partial t} - \hbar n_1 \frac{\partial \theta_1}{\partial t} = \hbar T\sqrt{n_1 n_2}\, e^{i\delta} - eV n_1$$

$$i\hbar \frac{1}{2}\frac{\partial n_1}{\partial t} - \hbar n_1 \frac{\partial \theta_1}{\partial t} = \hbar T\sqrt{n_1 n_2}\,(\cos\delta + i\sin\delta) - eV n_1$$

$$i\hbar \frac{1}{2}\frac{\partial n_1}{\partial t} - \hbar n_1 \frac{\partial \theta_1}{\partial t} = \hbar T\sqrt{n_1 n_2}\cos\delta + i\hbar T\sqrt{n_1 n_2}\sin\delta - eV n_1$$

Real part

$$-\hbar n_1 \frac{\partial \theta_1}{\partial t} = \hbar T\sqrt{n_1 n_2}\cos\delta - eV n_1$$

$$-\hbar \frac{\partial \theta_1}{\partial t} = \hbar T \frac{\sqrt{n_2}}{\sqrt{n_1}}\cos\delta - eV$$

$$\boxed{\frac{\partial \theta_1}{\partial t} = -T\sqrt{\frac{n_2}{n_1}}\cos\delta + \frac{eV}{\hbar}} \quad \text{— I.}$$

Imaginary part

$$\hbar \frac{1}{2}\frac{\partial n_1}{\partial t} = \hbar T\sqrt{n_1 n_2}\sin\delta .$$

$$\boxed{\frac{\partial n_1}{\partial t} = 2T\sqrt{n_1 n_2}\sin\delta} \quad \text{— II.}$$

$$(2) \Rightarrow i\hbar \frac{\partial \sqrt{n_2}\, e^{i\theta_2}}{\partial t} = \hbar T\sqrt{n_1}\, e^{i\theta_1} + eV\sqrt{n_2}\, e^{i\theta_2} .$$

$$\left(i\hbar\left(e^{i\theta_2}\frac{1}{2\sqrt{n_2}}\frac{\partial n_2}{\partial t} + \sqrt{n_2}\cdot i e^{i\theta_2}\cdot\frac{\partial \theta_2}{\partial t}\right) = \hbar T\sqrt{n_1}\, e^{i\theta_1} + eV\sqrt{n_2}\, e^{i\theta_2}\right) \times \sqrt{n_2}\, e^{-i\theta_2}$$

$$= i\hbar \frac{\cancel{\sqrt{n_2}}\,\cancel{e^{-i\theta_2}}\cdot \cancel{e^{i\theta_2}}}{2\cancel{\sqrt{n_2}}}\frac{\partial n_2}{\partial t} - \hbar\sqrt{n_2}\sqrt{n_2}\,\cancel{e^{-i\theta_2}}\,\cancel{e^{i\theta_2}}\frac{\partial \theta_2}{\partial t}$$

$$= \hbar T\sqrt{n_1 n_2}\, e^{-i(\theta_2-\theta_1)} + eV\sqrt{n_2}\sqrt{n_2}\,\cancel{e^{i\theta_2}}\,\cancel{e^{-i\theta_2}}$$

$$\frac{i\hbar}{\alpha}\frac{\partial n_2}{\partial t} - \hbar n_2 \frac{\partial \theta_2}{\partial t} = \hbar T\sqrt{n_1 n_2}\, e^{-i\delta} + eVn_2$$

$$\frac{i\hbar}{\alpha}\frac{\partial n_2}{\partial t} - \hbar n_2 \frac{\partial \theta_2}{\partial t} = \hbar T\sqrt{n_1 n_2}\left(\cos\delta - i\sin\delta\right) + eVn_2 .$$

Real part,

$$-\hbar n_2 \frac{\partial \theta_2}{\partial t} = \hbar T\sqrt{n_1 n_2}\cos\delta + eVn_2$$

$$\frac{\partial \theta_2}{\partial t} = -T\frac{\sqrt{n_1 n_2}\cos\delta}{n_2} - \frac{eV}{\hbar}$$

$$\boxed{\frac{\partial \theta_2}{\partial t} = -T\sqrt{\frac{n_1}{n_2}}\cos\delta - \frac{eV}{\hbar}} \quad \text{--- (III)}$$

imaginary part

$$\frac{\hbar}{\alpha}\frac{\partial n_2}{\partial t} = -\hbar T\sqrt{n_1 n_2}\sin\delta$$

$$\boxed{\frac{\partial n_2}{\partial t} = -2T\sqrt{n_1 n_2}\sin\delta} \quad \text{--- (IV)}$$

$$\frac{\partial n_1}{\partial t} = 2T\sqrt{n_1 n_2}\sin\delta$$

$$\frac{\partial \theta_1}{\partial t} = -T\sqrt{\frac{n_2}{n_1}}\cos\delta + \frac{eV}{\hbar}$$

$$\frac{\partial n_2}{\partial t} = -2T\sqrt{n_1 n_2}\sin\delta$$

$$\frac{\partial \theta_2}{\partial t} = -T\sqrt{\frac{n_1}{n_2}}\cos\delta - \frac{eV}{\hbar}$$

for identical scrs $n_1 = n_2$

$$\frac{\partial n_1}{\partial t} = 2T n \sin\delta \qquad \frac{\partial n_2}{\partial t} = -2Tn\sin\delta$$

$$\frac{\partial n_2}{\partial t} = -\frac{\partial n_1}{\partial t}$$

$$\frac{\partial \theta_1}{\partial t} = -T\cos\delta + \frac{eV}{\hbar}$$

$$\frac{\partial \theta_2}{\partial t} = -T\cos\delta - \frac{eV}{\hbar}$$

$$\frac{\partial \theta_2}{\partial t} - \frac{\partial \theta_1}{\partial t} = -\frac{2eV}{\hbar}$$

$$\frac{\partial(\theta_2-\theta_1)}{\partial t} = -\frac{2eV}{\hbar}$$

$$\frac{\partial \delta}{\partial t} = \frac{-2eV}{\hbar} \cdot = \int_0^t \partial\delta = \int_0^t -\frac{2eV}{\hbar}\, dt$$

$$\cancel{\delta(\theta) = \delta(0) - (}$$

$$\cancel{\delta(\delta} \quad \delta(t) - \delta(0) = -\frac{2eV}{\hbar}t$$

$$\delta(t) = \delta(0) - \frac{2eVt}{\hbar}$$

(δ = phase is time dependent)

$$J = J_0 \sin\delta = J_0 \sin\left(\delta(0) - \underset{(-\omega t)}{\frac{2eVt}{\hbar}}\right).$$

current oscillates with frequency (A very high electromagnetic radiation will be emitted with freq ω)

$$\boxed{\omega = \frac{2eV}{\hbar}} \Rightarrow \hbar\omega = 2eV$$

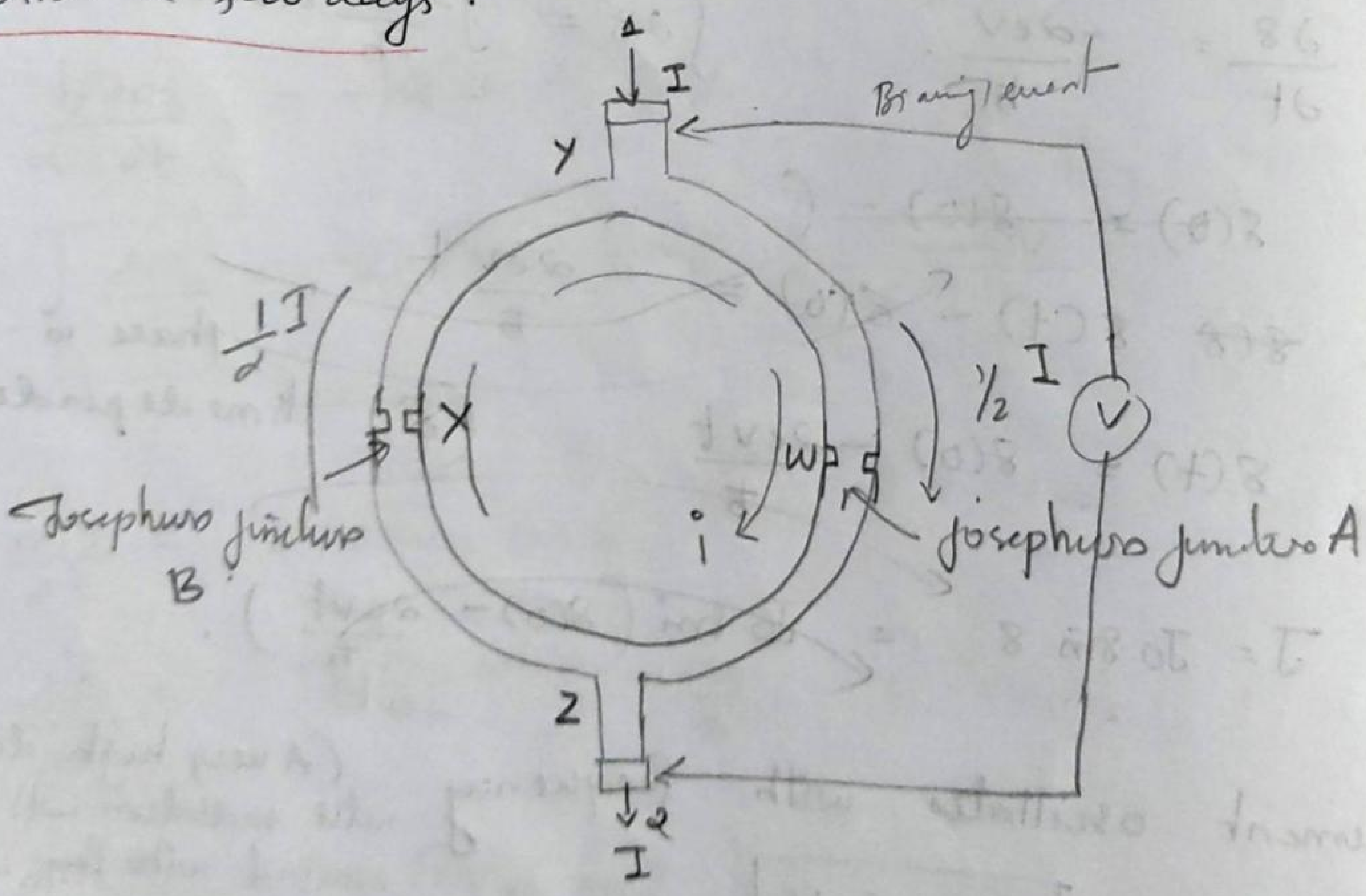
This is the ac josephson effect. A dc voltage of 1 μV produces a frequency of 483.6 MHz. The ~~eradiation~~ relation says that a photon of energy $\hbar\omega = 2eV$ is emitted or absorbed when an electron pair crosses

the barrier.
- To be used for a precise measurement of h/e

(e/h)

SQUIDS.

Superconducting Quantum Interference Device
— They are type of extremely sensitive magnetometer that contains a josephson junction.
(two scrs - closed one - two shells, joining positions insulator (junction))
— They are so sensitive that they can detect a field change of 5×10^{-14} gauss ($1/10^{13}$ of the earth's mag field) within a few days.



(There will no effect of external mag field inside squid)

Principle

phase change due to mag Field → current flows → voltage change.

- DC squids are a current loop with two Josephson junctions in it that will carry a current of $I/2$ (one) in each branch in the absence of an external magnetic field.
- In the presence of a field there is a secondary current produced that increases the current in one branch and decreases the current of another branch.
- This will continue until there is a critical current reached that will then cause the magnetic field to switch and thus the current to change.
- (~~joseph~~ – a voltage will be appearing on the josephson junctions
- One branch exceeding critical ~~mean~~ current means. it is a normal conductor, flux will be started penetrating inside the body.) ~~phase change occurs~~

(One period of voltage variation corresponds to an increase of one flux quantum).

Let the phase difference b/w points 1 and 2 taken on a path through junction A(B) be $\delta A(\delta B)$.
A & B be δA & δB.

when no external ~~applied~~ field is applied, $\phi = 0$

$$\delta_A = \delta_B.$$

phase differ

when ext field applied $\phi \neq 0 \Rightarrow \delta_B - \delta_A = \frac{2e}{\hbar c}\phi$

The phase difference around a closed circuit which encompasses a total magnetic flux ϕ.

$$\delta_B = \delta_0 + \frac{e}{\hbar c}\phi \quad , \quad \delta_A = \delta_0 - \frac{e}{\hbar c}\phi$$

The total current. $J_{total} = \cancel{J_c} J_0 \sin \delta_0$

$$I_{total} = I_A + I_B$$

$$= I_c \left[\sin\left(\delta_0 + \frac{e}{\hbar}\phi\right) + \sin\left(\delta_0 - \frac{e}{\hbar}\phi\right) \right]$$

$$= 2 I_c \sin \delta_0 \cos\left(\frac{e}{\hbar}\phi\right)$$

$J_{total} = 2(J_0 \sin \delta_0) \cos \frac{e\phi}{\hbar c}$

The current varies with ϕ and has maxima when

$$\frac{e}{\hbar}\phi = s\pi, \quad s = \text{integer}.$$

1. A superconducting quantum interference device (SQUID) is a mechanism used to measure extremely weak signals.
2. Super current changes periodically with magnetic flux.
3. Junction region have much lower value than the rest of the superconducting ring.
4. When the current in the junction exceeds the critical value, the junction become normal, then the fluxons penetrate through the link.
5. So the current falls to critical value and then the link reverts to SCing state.
6. Then the junction act as a gate.

Applications
- Type II SCrs used as very powerful magnet. used in Hospitals for NMR. Nuclear magnetic resonance
- maglev trains - magnetic levitation trains.

Sc magnet above scr levitate.

Scr leg. ~~trans~~ magnet force applied.

- Starting ignition - initial trigger.

to stop. use force. no external energy is required.

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High Temperature Superconductors

- based on the Temp which it showing SCtivity.
- liquify the materials.
- almost HT are Type II scrs.
- 1911 , 1st scrs transition temp was 4K.
- To reduce T - we can use cryogen - difficult.
- need liquified gas He- 4K.

Till 1986 - scr near 20 K. used liq He

In 1986 - cuprate scrs discovered, $T_c > 77K$. Ni = 77K.

- liq Nitrogen - can be used for cooling - cheap.

- discovered by Bednorz & Muller. = Ba-La-Cu-O.

HTSC

- High temperature superconductors have high Tc values.
- They are not metal or intermetallic compounds but oxides of copper in combination with other elements.

(cations -)

- In 1983, 1987 & 1988, material with Tc up to 40k, 93 k, and 125 k have been discovered respectively.
- The HTSC compounds are represented by simplified notations as 1212, 1234 etc. These notation are based on

number of atoms in each metal element.

- They are brittle and easy to form wires and tapes.
  (form of powder - convert to pellet shape.
  or putting powder in silver tube - elongate silver tube to long wire ~~being~~ by heating, silver do not ~~destroy/situating~~ SCing property).

- HTSC wires / tapes provide transmission of electrical power over a long distance without any resistive loss.

- copper oxygen layer is reason for SCivity.

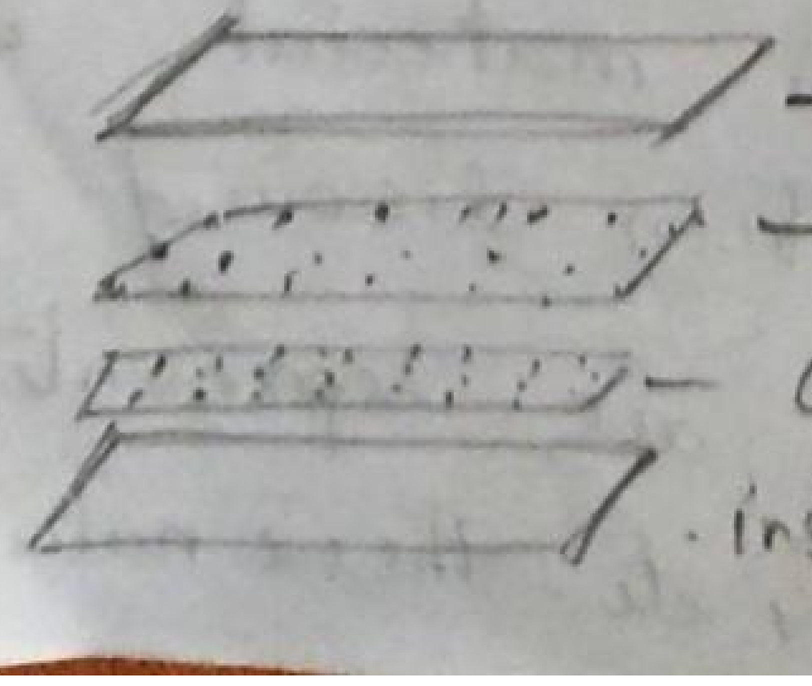
eg:

compound		T_C(K)	
$YBa_2Cu_3O_{7-\delta}$	Y-123	92	- (itrium)
$Bi_2Sr_2CaCu_2O_8$	Bi-2212	84	
$Bi_2Sr_2Ca_2Cu_3O_{10}$	Bi-2223	110	
$TlBa_2Ca_2Cu_3O_{10}$	Tl-1223	125	
$HgBa_2Ca_2Cu_3O_{10}$	Hg 1223	133	(mercury)

Perovskite Structure

- ceramics - layered perovskite material
  CuO_2 - planes responsible for superconductivity
- properties show high anisotropy.

CuO_2 - plane -



- They are Type II SCrs high H_{c_2} value.

cuprates

- The resistivity in the normal state varies linearly with temperature.
- Vanishingly small isotope effect ($\alpha = 0 - 0.2$) is considered an important evidence of non-phononic SC vity.
- Observed energy gap is very large. nearly 20-30 meV.
- $\Delta(0)/k_B T_c = 3$ to 4, which is greater than BCS estimated value (1.764)
- The Hall coefficient is temperature dependent.
- An inverted parabolic relation b/w T_c and hole concentration (holes are responsible for HTSCr)
- cuprate SCrs are generally considered to be quasi-2D materials with their SC ing properties determined by electrons moving within weakly coupled Copper-oxide (CuO_2) layers.
- Neighbouring layer containing ions such as Lanthanum, barium, Strontium, or other atoms act to stabilize the structure and doped es or holes onto the copper-oxide layers.
- The cuprate Scrs adopt a Perovskite structure.
- The CuO_2 planes are checkerboard lattices with squares of O_2^- ions with Cu^{2+} ion at the center of each

square. chemical formulae of superconducting materials generally contains fractional numbers to describe the doping required for SC'ng.

- There are several families of cuprate SCrs and they can be categorized by the elements they contain and the number of adjacent copper-oxide layers in each SCing block

- eg YBCO , BSCCO ~~or~~
 Y123 (Bi-2201, Bi 2212, Bi 2223)

~~$HgBa_2Ca_2Cu_3O_x$ = Tc~~

- max T_c = $HgBa_2Ca_2Cu_3O_x$ = 133 k.
 high Pressure 165 k.

Iron Based SCrs

- Ib SCrs contains layers of iron & a pnictogen such as arsenic or phosphorus or a chalcogen.
- This is currently the family with the 2nd highest critical temp, behind cuprates.
- most undoped iron-based SCrs show a tetragonal orthorhombic structural phase transition followed at lower temperature by magnetic ordering, similar to cuprate SCrs
- poor metals
- LaFePO - 4k , LaFeAs - 43k (under pressure)
- LnFeAs - 56 k

MgB_2

- Magnesium diboride is occasionally referred to as a H.TSC because its $T_c \approx 39k$.

- Fulleride Scrs when alkali metals are intercalated into C60 molecules show scivity at temp of up to 38k.

- Some organic Scrs and heavy fermion compounds are considered to be high-temperature Scrs because of their high Tc values relative to their Fermi energy, despite the Tc values being lower than for many conventional Scrs.