SUPERCONDUCTIVITY

Extraordinary electrical and magnetic property

***ρ = 0 (perfect conductivity) ➡ no power loss**

***B = 0(perfect diamagnetism) ➡ strong repulsion in magnetic fields**

Historical background:

- First observed by Kamerlingh Onnes in 1911, while studying the electrical resistivity of Mercury (Hg)
- Resistivity of Hg continuously decreased from 233K to 4.2K(the liquid Helium range)
- Later similar behavior was observed for lead(Pb) and Tin (Sn) also
- Resistance being zero, persistent current flows indefinitely

without attenuation

- They are called superconductors and

 the phenomenon is named super conductivity

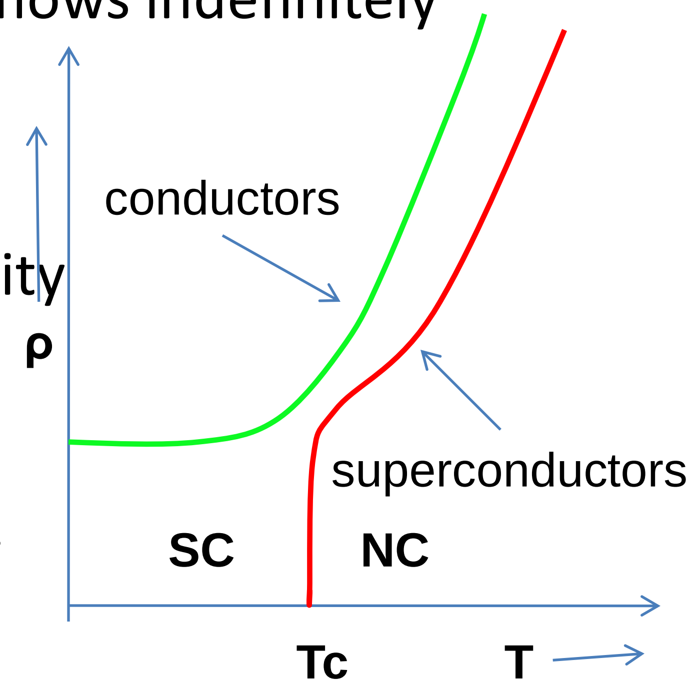
- The temperature at which resistivity

becomes zero, and material transforms

from normal conducting to superconducting

Phase is called **TRANSITION or CRITICAL**

TEMPERATURE (Tc)



- The observed transition temp. is to low (liquid helium range) which is difficult and expensive to achieve
- Longtime research yielded a transition temp. 23K in an intermetalic compound Nb3Ge (1977)
- In 1986 for a ceramic La-Ba-Cu-O the transition temp. Reached was 34K
- 1987--- $YBa_2Cu_3O_7$--- 90K
- 1988---Th cuprate-----125K
- The above materials are oxide ceramics superconductors and sowed high transition temp.----called high Tc superconductors
- A cuprate of Hg showed Tc= 138K

Important observations:

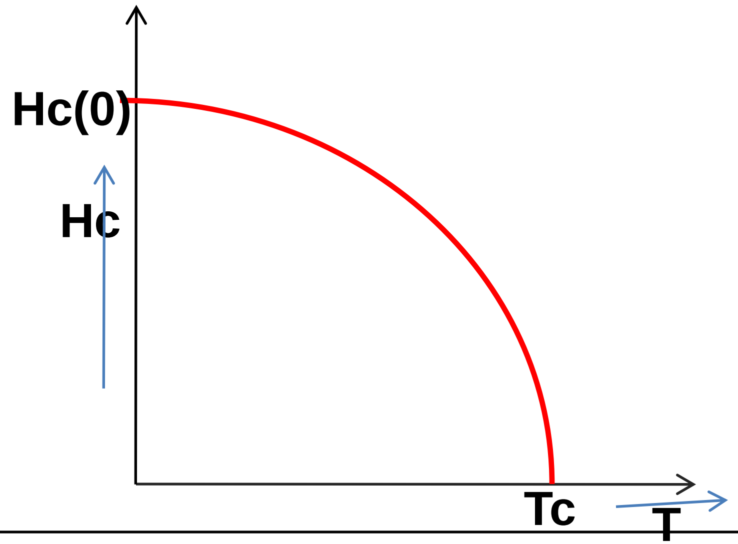
1. All good conductors like Cu, Au… are not superconductors
2. All good superconductors like Zn,Pb… are not good conductors
3. Nonmagnetic impurity has no effect on Tc value of a SC

- Magnetic impurity added drastically lowers the Tc value of a SC
- Sometimes application of pressure changes a normal conductor to super conductor
- Tc value----0.001K(Rh)………………. 138K(Hg-Ba-Ca-Cu-O
- A superconductor when placed in ext. magnetic field, at a particular value looses its superconducting property.

Critical magnetic field : The magnetic field responsible for the destruction of superconducting property is called critical magnetic field (Hc), is also a function of temp.

at Tc, Hc is zero, i.e., Hc(Tc)= 0

$$Hc = H_0 (1 - T^2/Tc^2)$$



H0 is the magnetic field at 0K

Hc is the magnetic field at TK

Tc is critical temp.

- **Hence, SC state is stable for definite ranges of magnetic field and temp.**
- **Normal conducting state is more stable at high temp. and high magnetic field**

Critical current density : when the current through a SC exceeds a certain critical value superconducting property is destroyed.

Current density corresponding to critical magnetic field is called critical current density Jc

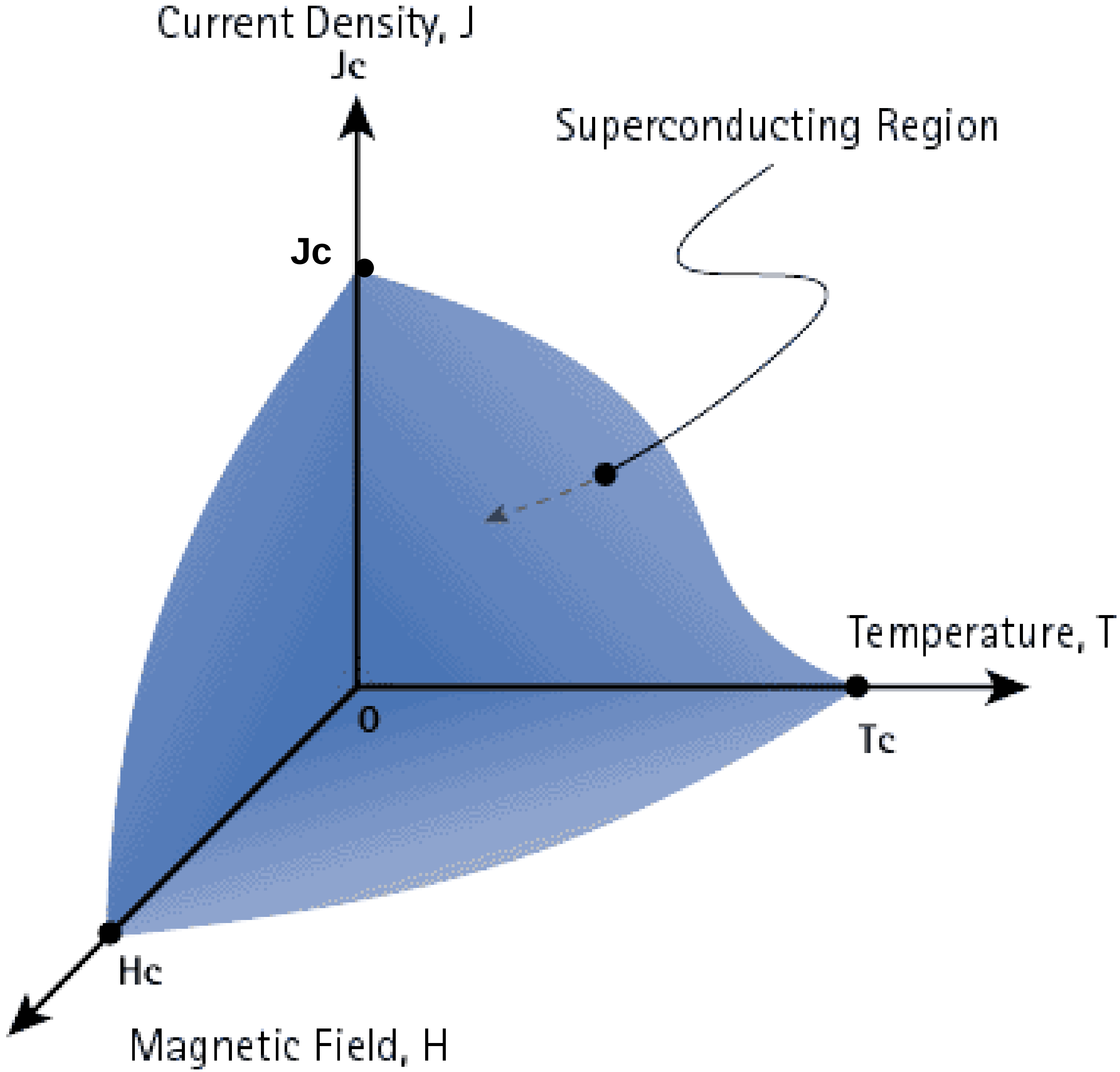
As, $B = \mu_0 I / 2\pi r$

hence, $I_c = 2\pi r B_c / \mu_0$

So, $\boxed{J_c = 2B_c / \mu_0 r}$

Critical temp. '**Tc**' , critical mag. Field '**Hc**' and critical current density '**Jc**' are the three parameters to decide SC property

PHASE DIAGRAM



- <u>Isotope effect:</u>

At Tc , transition from normal state to superconducting state occurs. This temperature of a material varies with the isotopic mass

$$T_c \propto 1 / M^{1/2} \qquad \text{or, } M^{1/2} T_c = \text{const.}$$

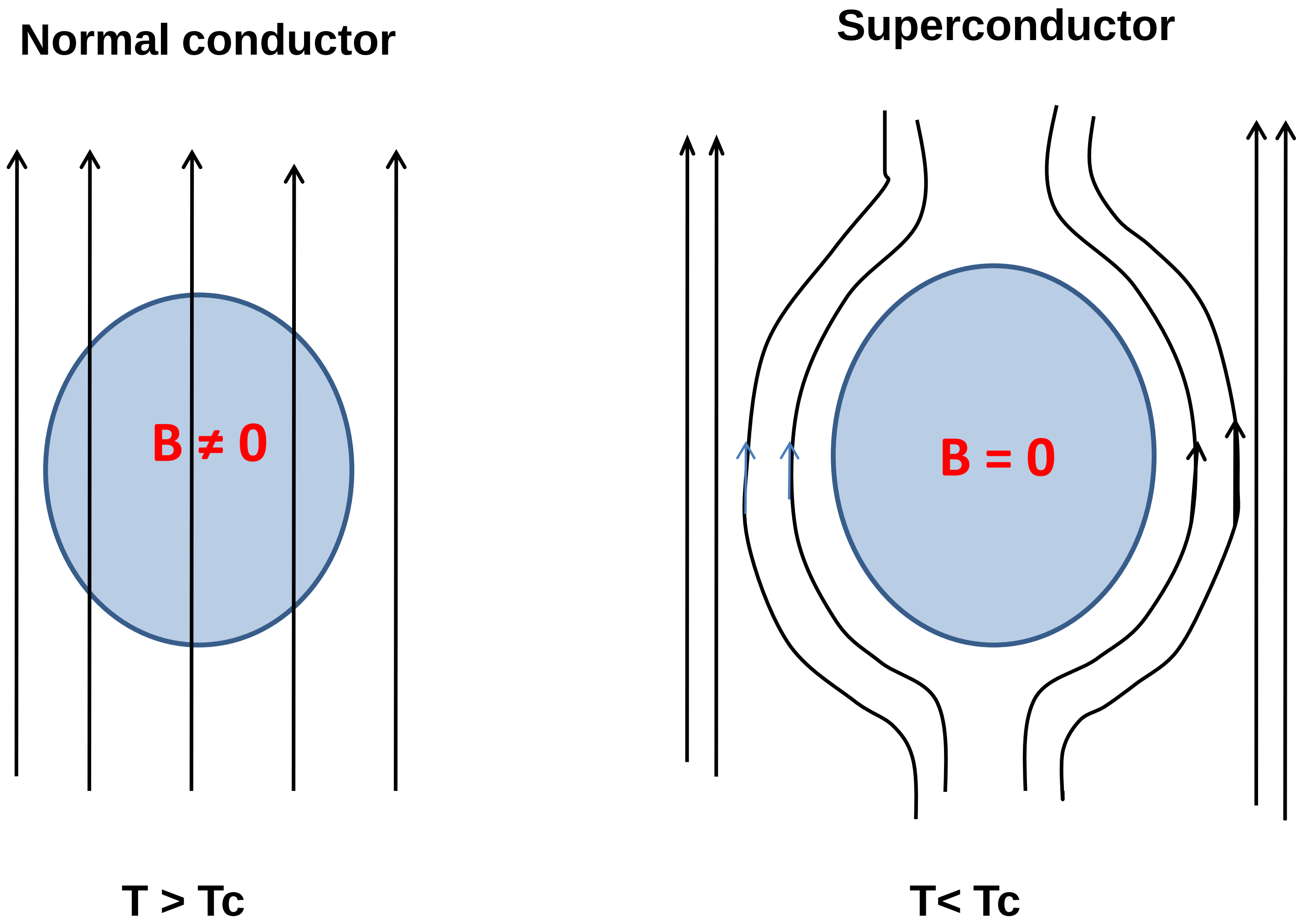
<u>Meissner Effect</u>: Meissner and Ochsenfeld in 1933 observed—

When a superconducting material at temp. T> Tc, is placed in ext. magnetic field, lines of magnetic induction pass through its body, but when it is cooled below the critical temp. i.e., T< Tc , these lines of induction are pushed out of the superconducting body.

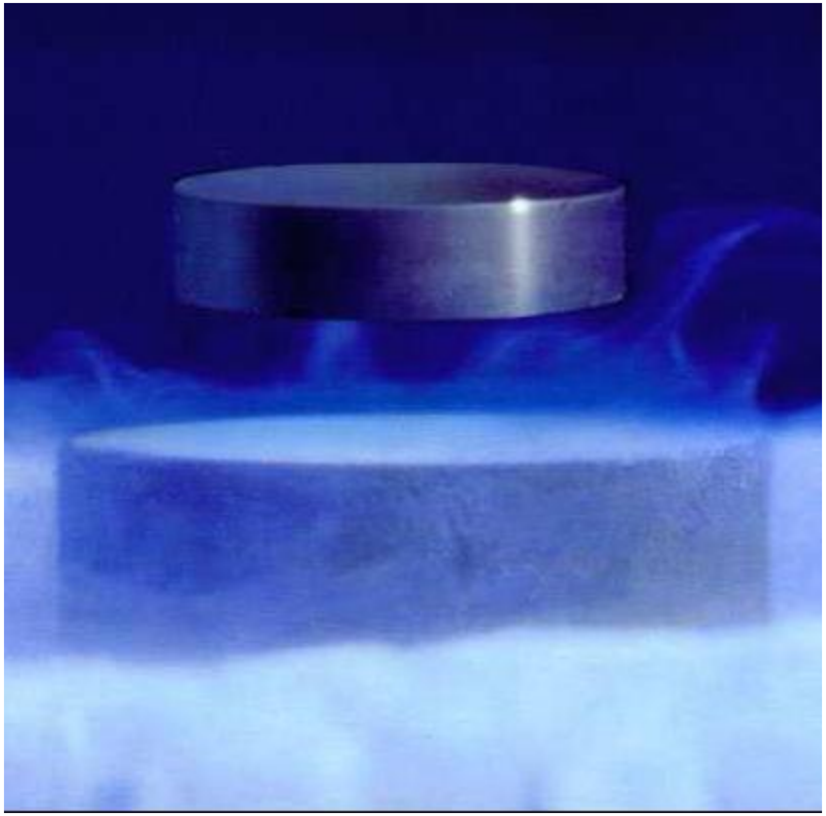
So, inside the SC body **B=0**

This is known as Meissner Effect, which is the characteristic property of a superconductor

Meissner Effect



The Meissner Effect



"A superconductor excludes all magnetic flux from its interior"

Superconductors are perfect diamagnetic

- as, $B = \mu_0 (H+M)$
- when $B = 0$ or, $M / H = \chi = -1$
- **Susceptibility is negative shows that the material behaves as <u>diamagnetic material</u>**

<u>B=0 ,does not follow from zero resistivity(ρ=0)</u>

As from Ohm's law $J = \sigma E$

Or, $E = \rho J$, if $\rho \rightarrow 0$, J is finite $\Longrightarrow$ $E = 0$

From Maxwell's em field equation : $\nabla \times E = -\frac{\partial B}{\partial t} \Rightarrow \frac{\partial B}{\partial t} = 0$

Or, B is constant, so $B \neq 0$ always

- **For a zero resistivity material magnetic induction is not necessarily zero also**
- **Hence B=0 is a special property of superconductors only**
- **Difference between a perfect conductor and superconductor!!!**

- Critical temperatures of elemental superconductors are lower than SC compounds

element	Tc(K)	alloys	Tc(K)
V	5.38	Nb_3Sn	18.1
Nb	9.5	Nb_3Ge	23.2
In	3.4	Nb_3Al	17.5
Sn	3.72	V_3Si	17.1
Hg	4.15	NbTi	10.0
Pb	7.19		

- Highest Tc found is 138K in case of Hg-Ba-Ca-Cu-O

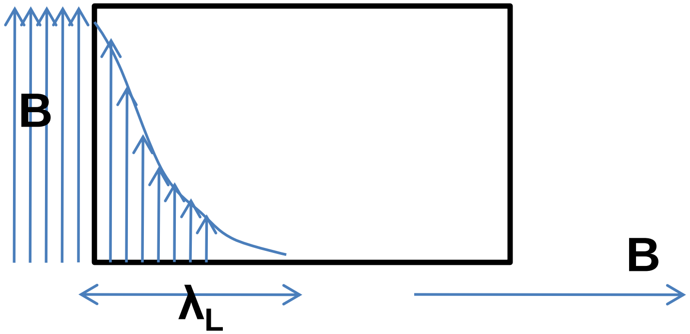
Coherence length and penetration depth:

Penetration depth:

- From London's equation

  $B(x) = B(0)\ e^{-x/\lambda L}$

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



λ_L is the penetration depth = $(m/ nq^2\mu_0)^{1/2}$

Coherence length:

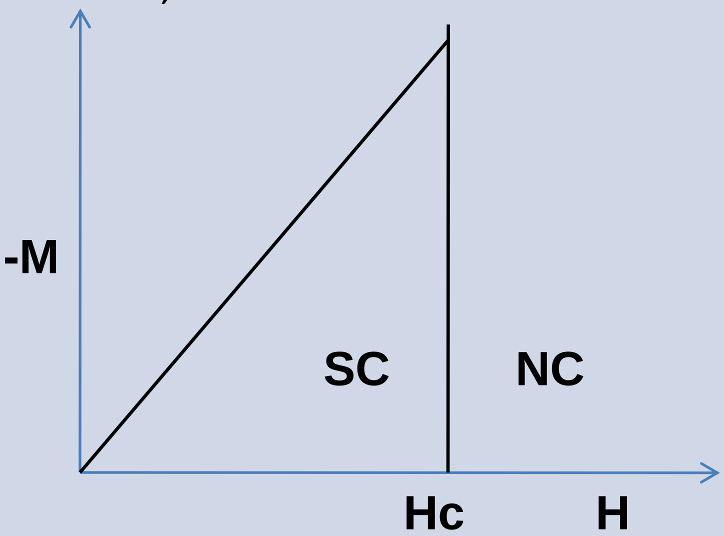
Where, coherence length is the range in a superconductor in which superconducting electrons remain in the same state in a spatially varying magnetic field.

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

Classification of superconductors:

Type-I or Soft superconductor

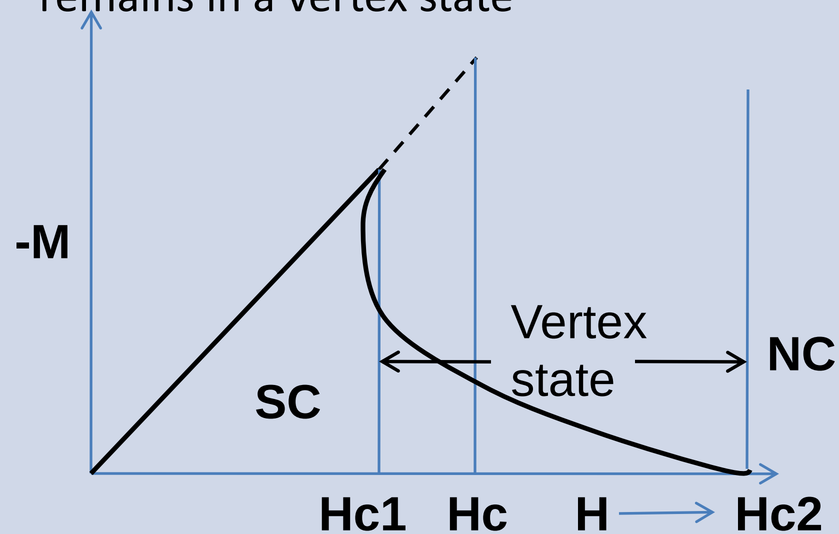
1. Meissner effect is complete.
2. At a sharp value of critical magnetic field, transition from SC to NC occur



3. Low value of Critical magnetic field, hence can be destroyed easily
4. Not fit for practical application
5. Coherence length large, penetration depth less
6. Pb, Sn, Hg, Cr, Al

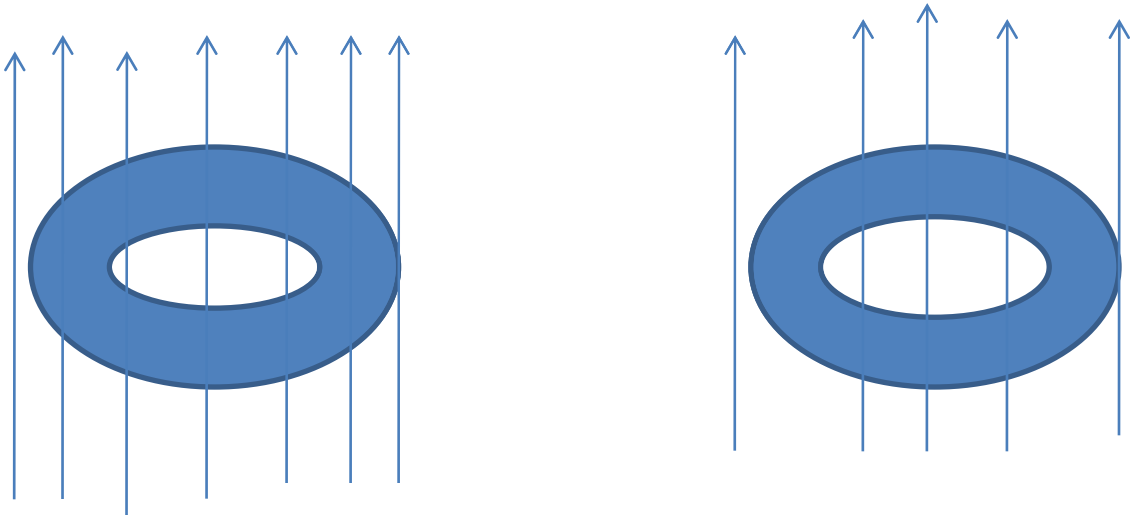
Type-II or Hard superconductor

1. Meissner effect is incomplete.
2. Two values of critical magnetic field, at Hc1 penetration of magnetic lines start and at Hc2 penetration is completed. In between these two values the SC remains in a vertex state



3. SC property stays for a longer time large value of critical field , Hc2=100 Hc1
4. Useful for practical application
5. Coherence length small, penetration depth large
6. Nb-Zr, Nb-Sn

FLUX QUANTISATION



T>Tc

T<Tc

Flux through a SC ring is quantised
$\Phi = nh / 2e$

BCS THEORY:

- **Bardeen, Cooper, Schrieffer** attributed the cause of superconductivity to pair of electrons formed by the interaction between two electrons 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 "**COOPER PAIR".**
- One electron interact with

a positive ion in the lattice

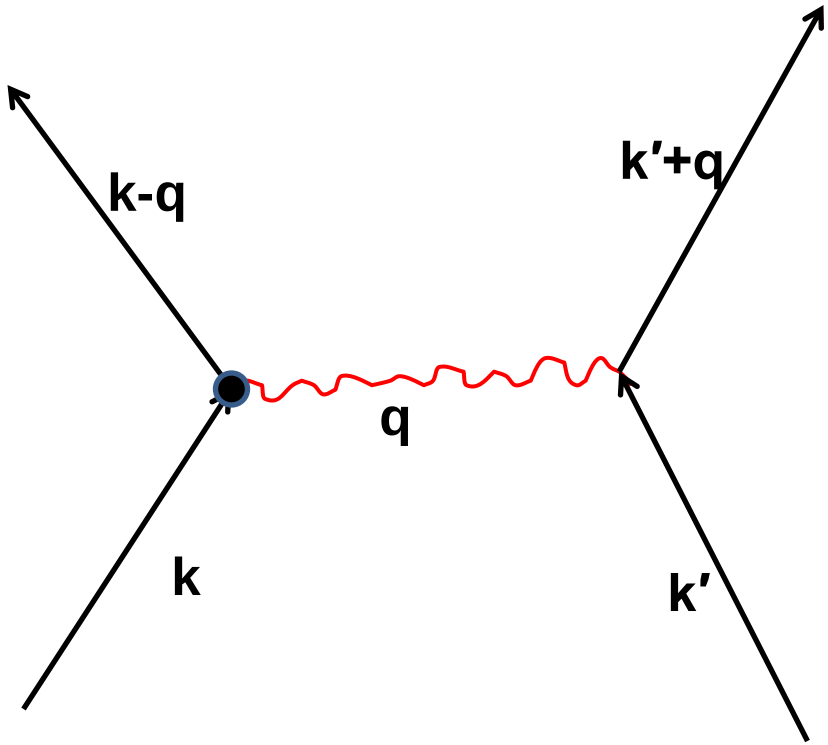
and deforms the lattice,

a second electron with compatible

momentum, passing nearby interacts

With the same ion in the distorted

Lattice so as to minimize its energy.

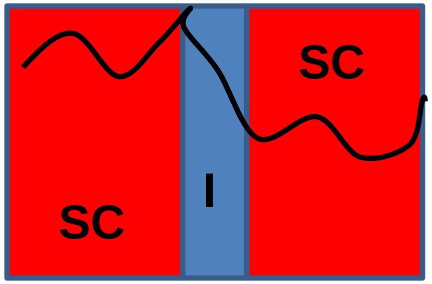


Cooper pairs:

- The electrons forming cooper pair have equal and opposite momentum
- One in spin up and the other in spin down state, total spin is zero
- 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, $\Delta \approx 1.4\ k_\beta T_c$
- At T = 0K energy gap is maximum as pairing is maxm. (SC)and at T = Tc energy gap disappears as all pairings are broken (NC)
- **Single electrons are scattered by the vibrating ions and experience opposition , hence ρ≠0, but cooper pairs are not scattered, so ρ=0**

Josephson Tunneling

- When two SC are separated by a thin layer of an insulator, cooper pairs from the first can tunnel through the insulator to the 2^{nd} SC, which is a quantum mechanical effect.



- <u>High Tc Superconductors</u>

High Tc Superconductors	Critical Temperature
$La_{1.85}Ba_{0.15}CuO_4$	36
$YBa_2Cu_3O_{6.9}$	90
$Tl_2Ba_2Ca_2Cu_3O_{10}$	125
$HgBa_2CaCu_2O_{6+}$	138

Characteristics

High T_C

1-2-3 Compound

Perovskite crystal structure

Direction dependent

Reactive, brittle

Oxides of Cu + other elements

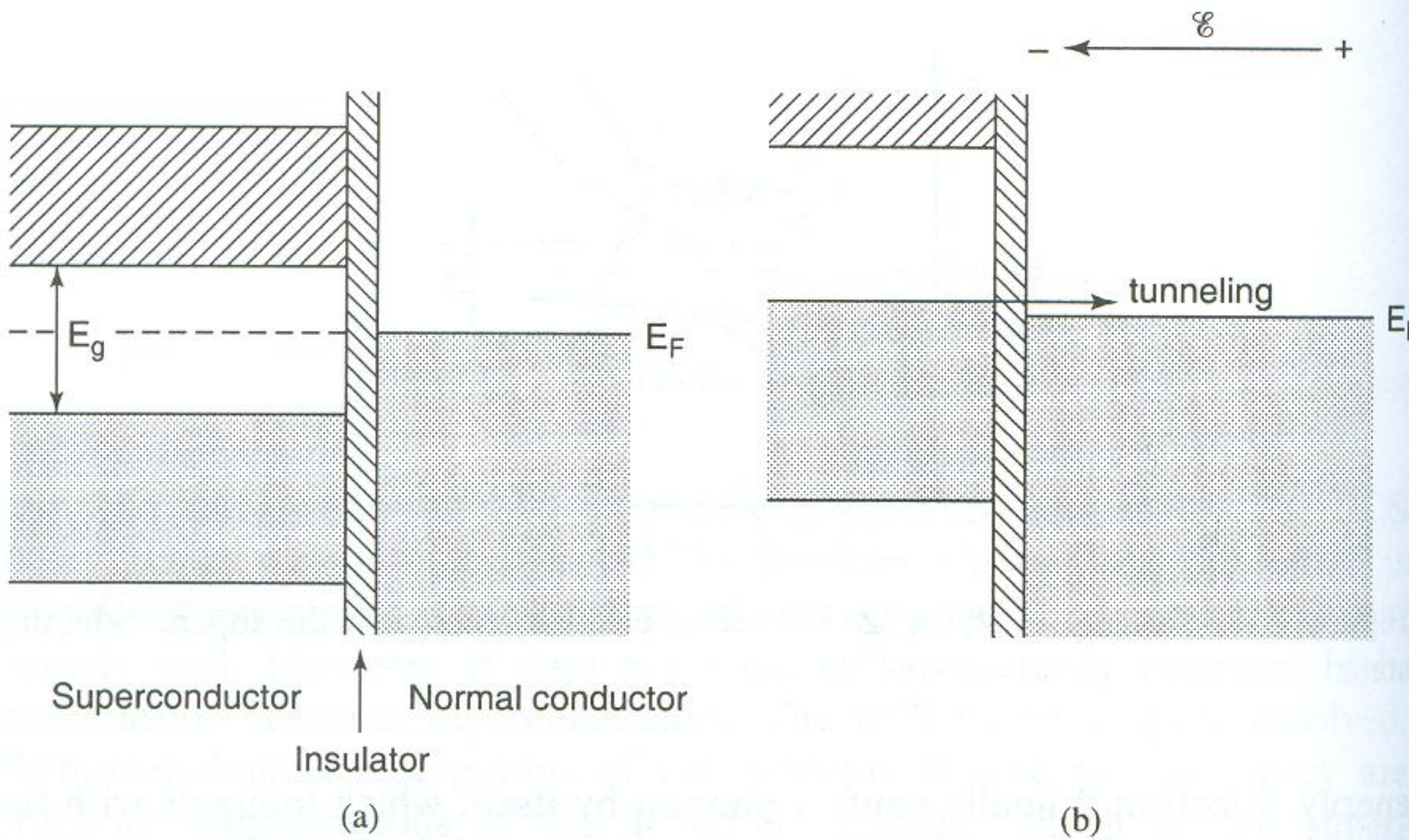


Figure 7.18. Josephson junction (a) in the unbiased state (b) with applied voltage across the junction which facilitates tunneling in the indicated direction.

ABO3--PEROVSKITES

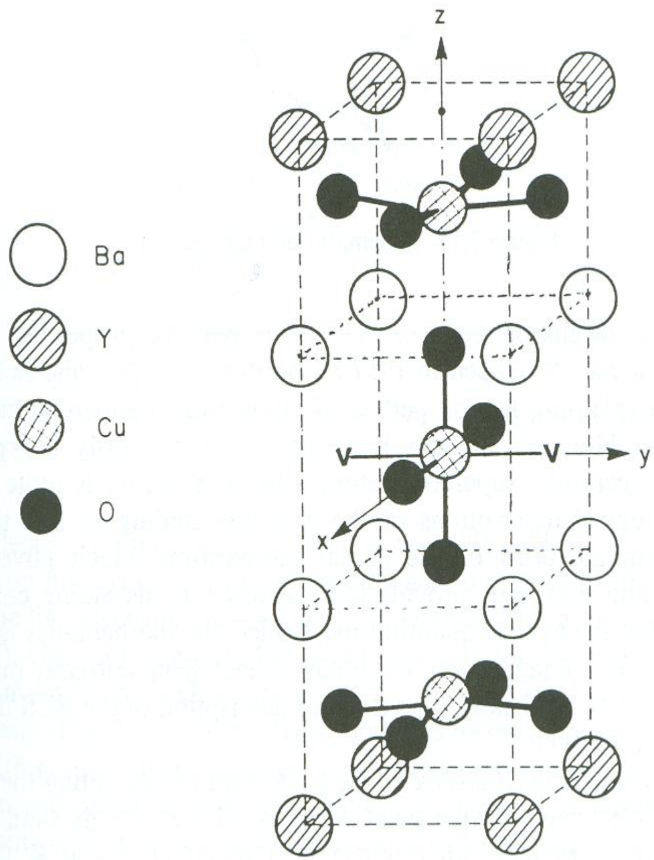
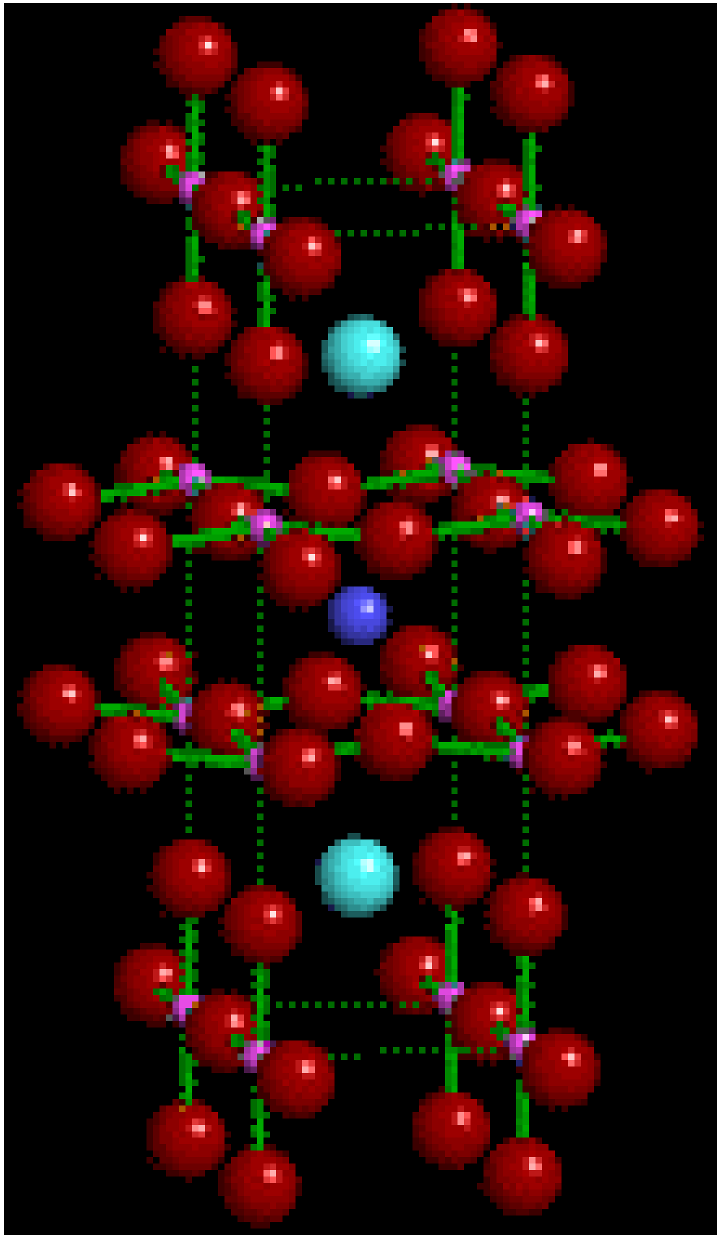


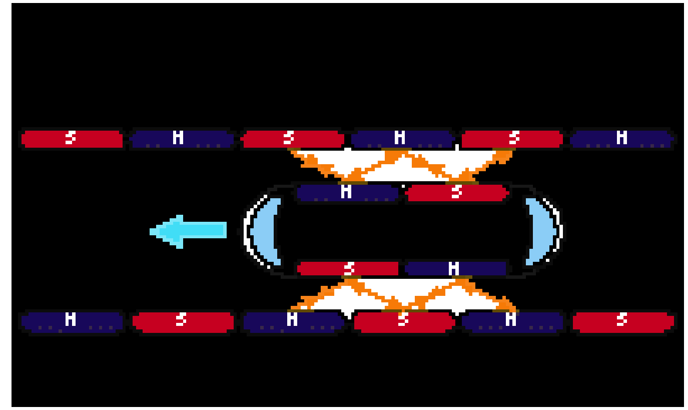
Figure 7.14. Room-temperature unit cell of $YBa_2Cu_3O_{7-x}$. The structure is an orthorhombic layered perovskite ($BaTiO_3$) containing periodic oxygen vacancies. Two examples for oxygen vacancies are indicated by a "V." Adapted from M. Stavola, *Phys. Rev. B*, **36**, 850 (1987).

$YBa_2Cu_3O_7$



APPLICATIONS:

Transportation: Superconducting Magnetic Levitation

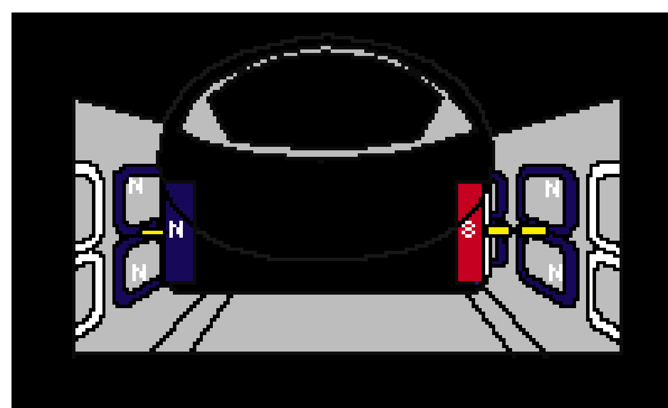


The Yamanashi MLX01MagLev Train

The track are walls with a continuous series of vertical coils of wire mounted inside. The wire in these coils is not a superconductor.

As the train passes each coil, the motion of the superconducting magnet on the train induces a current in these coils, making them electromagnets.

The electromagnets on the train and outside produce forces that levitate the train and keep it centered above the track. In addition, a wave of electric current sweeps down these outside coils and propels the train forward.




Japan’s
Maglev

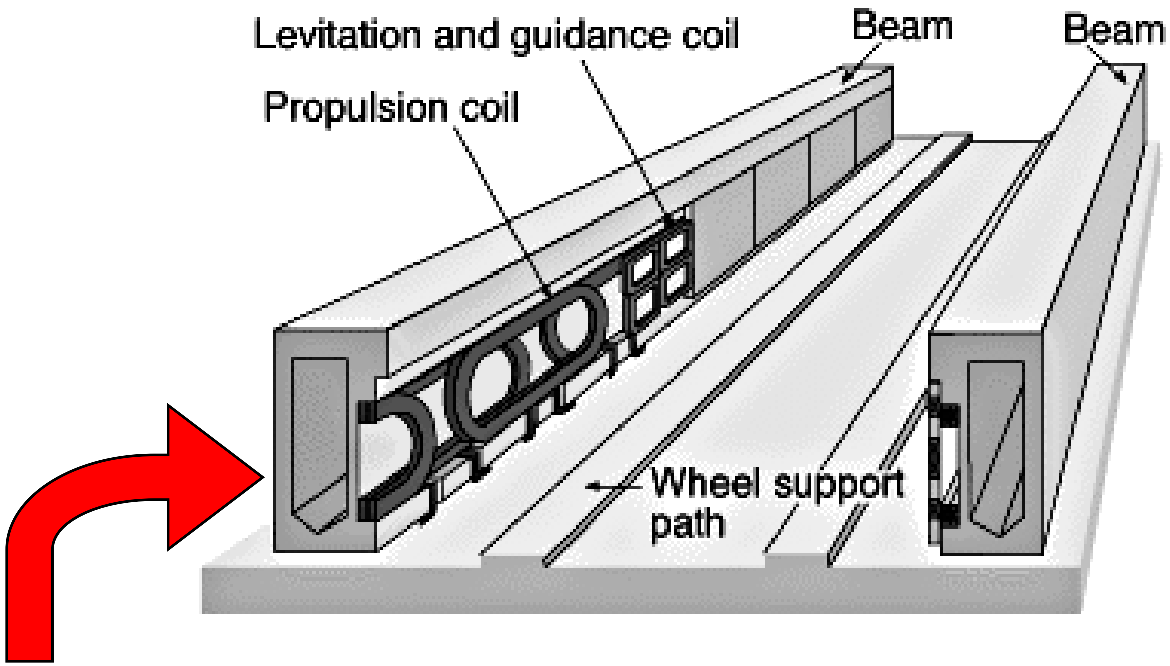
Germany's Maglev:

The "Transrapid"

Shanghai's Maglev

Click here to take a ride on the Shanghai Maglev!

How Maglevs work:



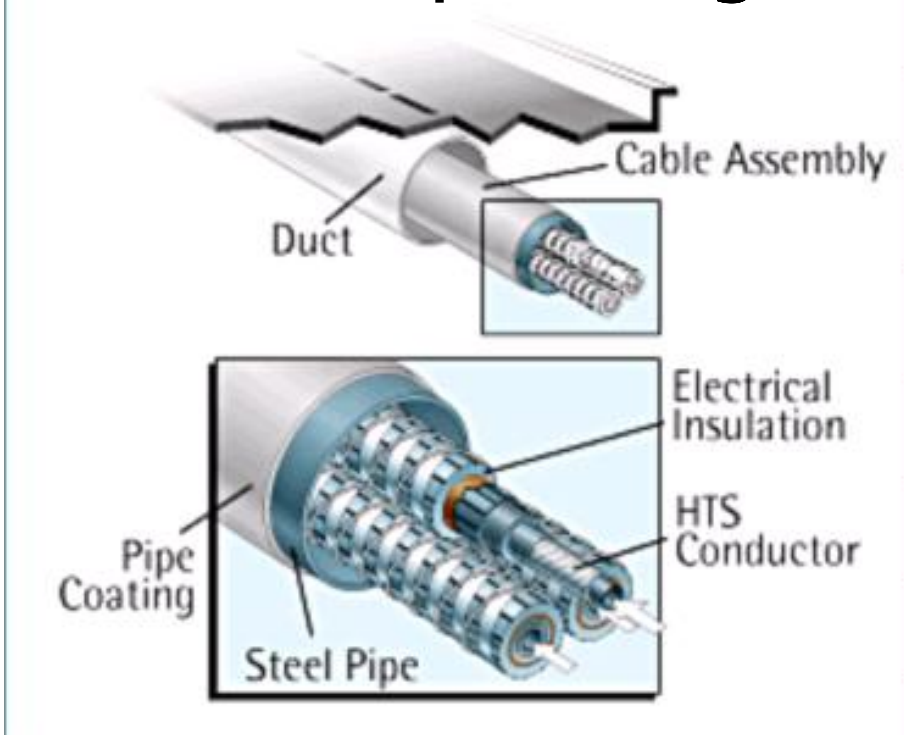
Electromagnets on track: they attract the train as it is coming, and repel it as it's going

APPLICATIONS: Medical (MRI, NMR)

MRI (Magnetic Resonance Imaging) scans produce detailed images of soft tissues.

The superconducting magnet coils produce a large and uniform magnetic field inside the patient's body.

APPLICATIONS: Power (HTS power generation)



The cable configuration features a conductor made from HTS wires wound around a flexible hollow core.
Liquid nitrogen flows through the core, cooling the HTS wire to the zero resistance state.

The conductor is surrounded by conventional dielectric insulation. The efficiency of this design reduces losses.

Superconducting Transmission Cable
From American Superconductor

Application:

- **Research**
- **Computers use Josephson junction for high speed operation**
- **Military: detection of submarines, in motors for naval ship, E-bombs (strong SC derived magnetic field to create fast, high intensity em pulse to disable enemy equipments)**
- **Space research**
- **Pollution control (to reduce greenhouse effect)**
- **Refrigeration: (cryogenic cooling)**
- **SQUID (<u>S</u>uperconducting <u>QU</u>antum <u>I</u>nterference <u>D</u>evices): to detect weak magnetic field**
- **To accelerate particles in nuclear accelerator**
- **Magnetic storage devices**

A SQUID (Superconducting QUantum Interference Device) is the most sensitive type of detector known to science. Consisting of a superconducting loop with two Josephson junctions, SQUIDs are used to measure magnetic fields.