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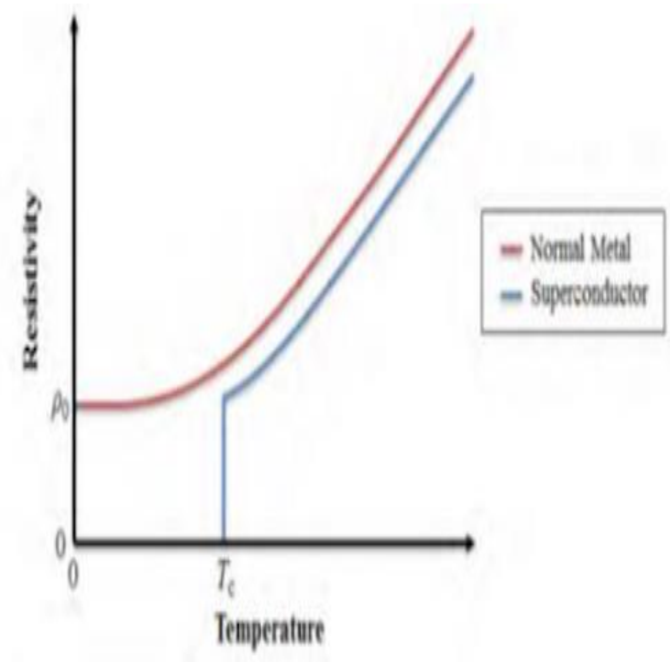
Superconductivity

(Core Course : 14)

Introduction

In 1911, H. Kamerlingh Onnes, a dutch physicist observed that the electrical resistivity of many metals and alloys drops suddenly to zero when they are cooled to a sufficiently low temperature. This phenomenon is called *superconductivity* and the material is known as *superconductor*.

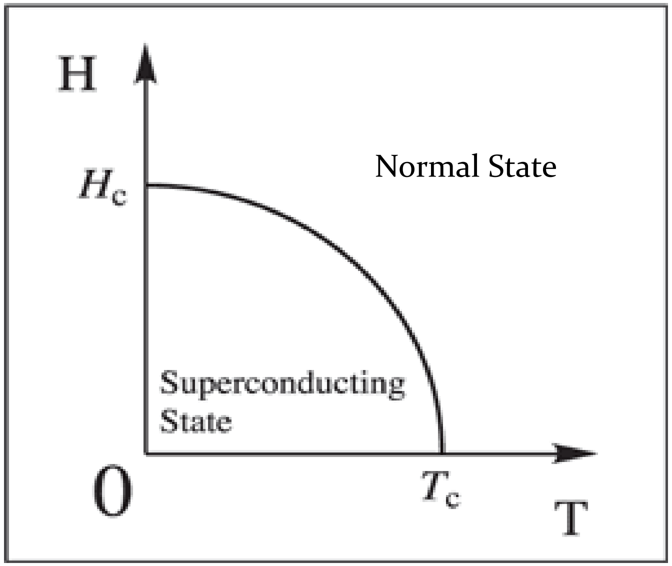
- The temperature at which a material suddenly shows zero resistivity is known as the transition temperature.
- The requirement of very low temp., makes the process of manufacturing of devices using superconducting materials very difficult as well as very expensive.



Effect of magnetic field

Factors governing the SC state of metal:

- the temperature at which the specimen is kept.
- the magnetic field in which the specimen is placed.



A sufficiently strong magnetic field will destroy superconductivity.

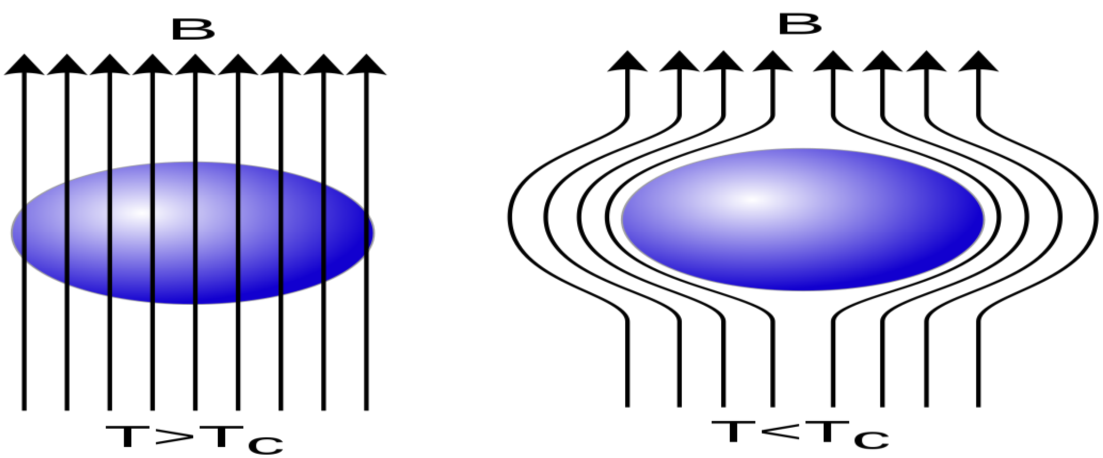
If the temperature T of the specimen is raised above T_c (i.e, $T > T_c$) the superconductivity disappears. It also disappears if the magnetic field H is raised above the critical magnetic field H_c , H_c is a function of T.

$$H_c(T) = H_c(0) [1 - (T/T_c)^2]$$

Where, $H_c(0)$ is the critical magnetic field at 0 K and T_c is characteristic temperature of the material.

The Meissner Effect

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.



- as, $B = \mu_0 (H + M)$
- when $B = 0$ or, $M / H = \chi = -1$

Susceptibility is negative shows that the material behaves as **diamagnetic material**

London Equations

London brothers, Fritz and Heinz London in 1935 proposed a phenomenological theory of Superconductivity.

Their theory was originally motivated by the two-fluid model of super-fluid Helium. They assumed that there are two-types of conduction electrons in a superconductor, viz., *super-electrons* and *normal-electrons* at $T < T_C$.

A superconductor contains only super-electrons at T=0 K. But, at $0 < T < T_C$ as the temperature rises the ratio of normal electrons to super-electrons increases and when $T = T_C$, all electrons are normal. Hence, at value of T between 0 and T_C the conduction electron density is ,

$$N = n_n + n_s \quad \text{------(1)}$$

where , n_n and n_s refer to the density of normal and super-electrons respectively.

Derivation :-

➢ *All parameters imply their usual meaning.*

- Equation of motion of Super electrons under electric field is $m\frac{du_s}{dt} = -eE$
- Now current & drift velocity are related as

$$I_s = n_s e A u_s$$

$$\therefore J_s = n_s e u_s$$

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

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

$$\boxed{\therefore \frac{d\vec{J}_s}{dt} = \frac{n_s e^2 \vec{E}}{m}}$$

→ London's first equation

$$\therefore \frac{d\vec{J}_s}{dt} = \frac{n_s e^2 \vec{E}}{m}$$

$$\vec{E} = \frac{d\vec{J}_s}{dt}\frac{m}{n_s e^2}$$

$$\therefore \frac{d\vec{J}_s}{dt}\frac{m}{n_s e^2} = -\frac{d\vec{A}}{dt}$$

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

$$\therefore \left(\frac{m}{n_s e^2}\vec{J}_s\right) = -\vec{A}$$

$$\boxed{\therefore \vec{J}_s = -\frac{n_s e^2}{m}\vec{A}}$$

→ London's second equation

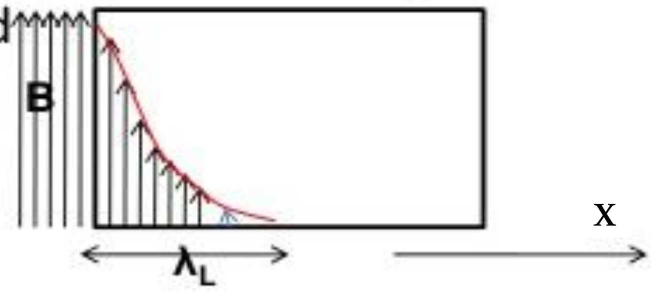
Penetration depth and Coherence length

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

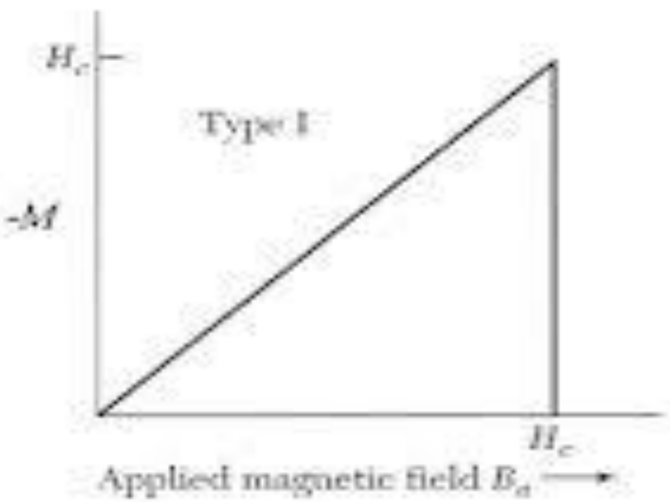
Coherence length:

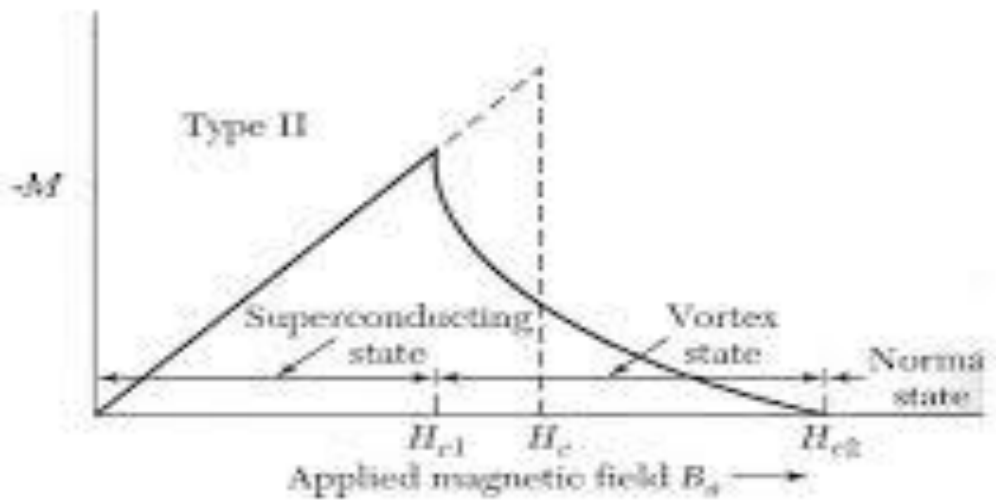
Where, coherence length is the range in a superconductor in which superconducting electrons remain in the same state in a spatially varying magnetic field.

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

Type-I & Type-II Superconductors

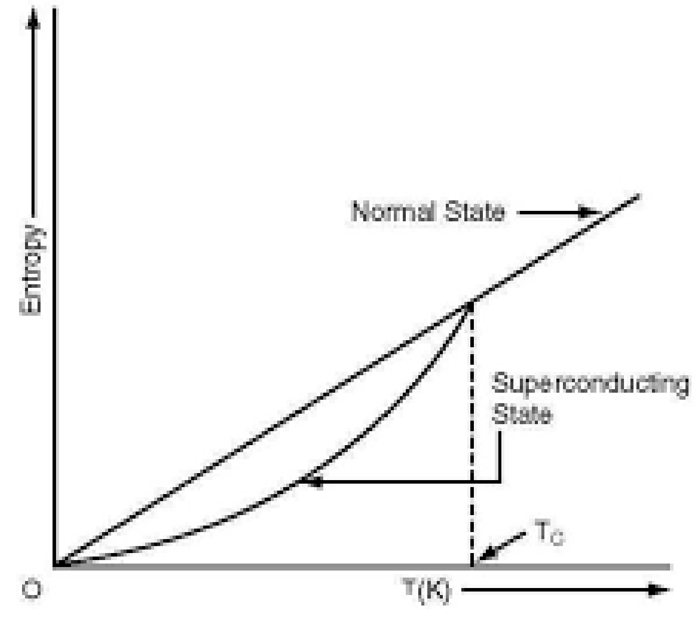
Type I superconductor	Type II Superconductor
1. These superconductor are called as soft superconductor.	These superconductor are called as hard superconductor.
2. They exhibit complete **Meissner** effect.	They do not exhibit complete **Meissner** effect.
3. They have only one critical magnetic field, H_c	They have two critical magnetic field, lower critical magnetic field HC_1 and upper magnetic field HC_2
4. The material loses magnetization abruptly.	The material loses magnetization gradually.
5. Example :Pb,Sn,Hg	Example: Nb-Sn, Nb – Zr, Nb_3Ge, Nb3si





Entropy

Entropy is a measure of disorder of a thermodynamic system. Entropy of metals in normal state decreases linearly with the decrease in temperature, but in superconductors the entropy decreases remarkably on cooling below the critical temperature as shown in figure.



Behavior of the curve shows that the superconducting state is more ordered than the normal state. Some or all of the thermal electrons in the normal state are ordered in the superconducting state.

The isotope effect

The critical temperature T_C of a superconductor varies with the isotopic mass.

The experimental results within each series of isotopes may be a relation of the form :

$$M^{\alpha} T_C = const.$$

Original BCS model : $\alpha = 0.5$

Material	α	Material	α
Zn	~0.45	Hg	~0.5
Cd	~0.32	Mo	~0.33
Pb	~0.49	Sn	~0.47

From the relation we conclude that the lattice vibration and hence the electron-photon interaction must be the basis of the phenomenon of superconductivity through the Debye theory.

Theoretical aspects of Superconductivity

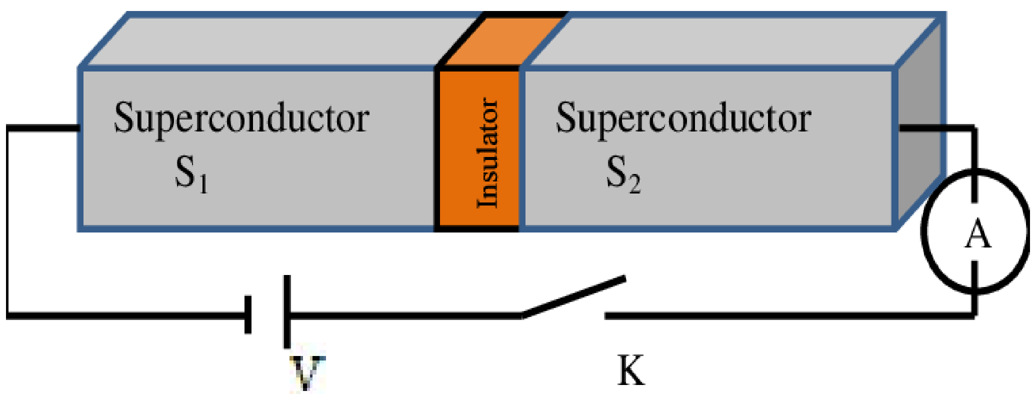
A lot of different approaches have been taken to explain the theory of superconductors. For example, the phenomenological theory proposed by London brothers (1935), the so-called Ginzburg –Landau theory (1950) and the microscopic theory given by Bardeen, Cooper and Schrieffer popularly known as "The BCS theory"(1957) are regarded as the most successful approaches to explain the basic properties of superconductors.

However, it is essential to skip the brief explanation of these theories here, as those are beyond our scope .

But, if interested, students are advised to knock the references which may lead them to the glorious as well as the rigorous theories of superconductivity and their consequences.

Josephson effect

In 1962, the British physicist Brian David Josephson, a PG student of Cambridge observed that under suitable conditions a super-current consisting of correlated pairs of electrons can be made to flow across a layer of insulator between two superconductors provided the gap is small enough. This macroscopic quantum phenomenon is known as ***Josephson effect*** and the junction is called the *weak link*.



According to this effect the ***Cooper pairs****** can tunnel through the Josephson junction or weak link even when there is no potential difference between the two superconductors.

Continuing ...

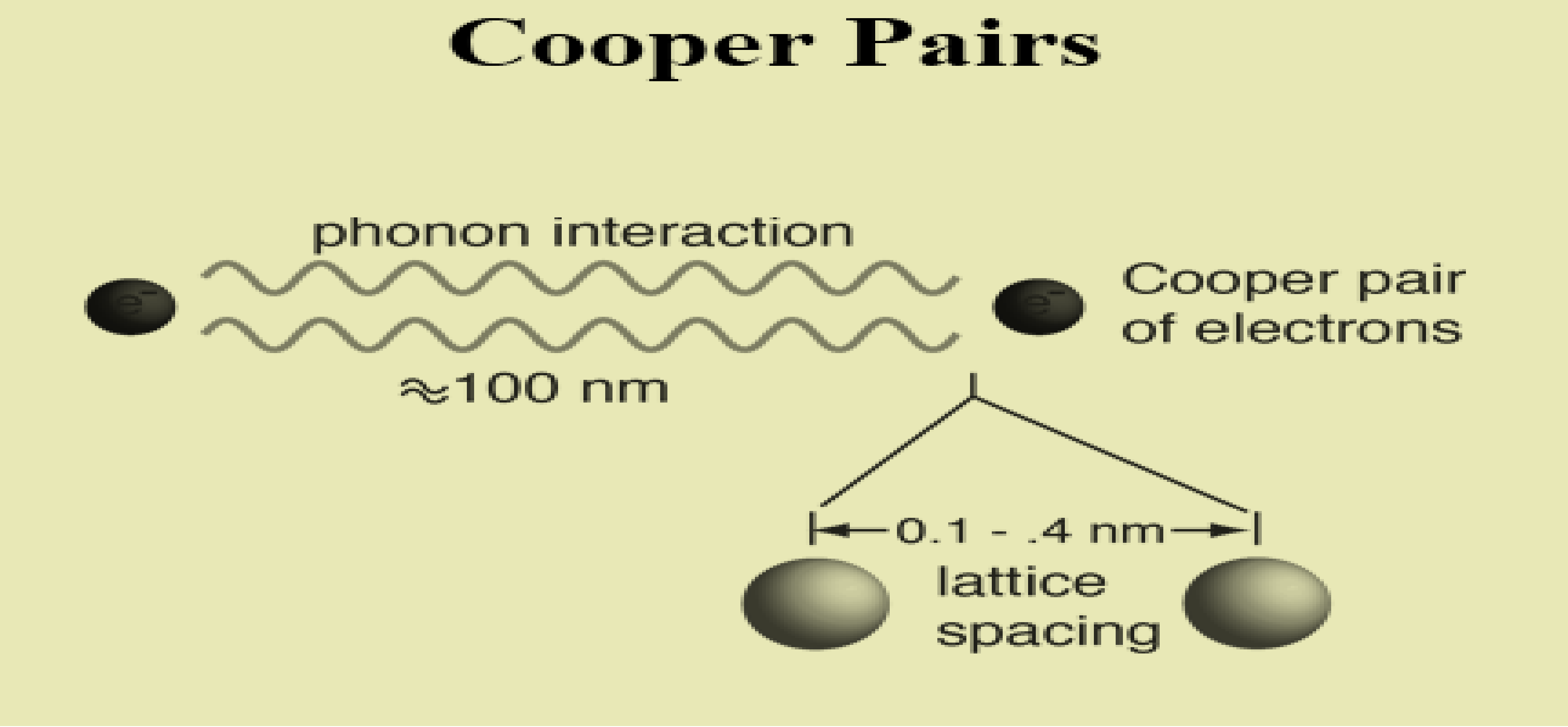
Josephson effect

The tunneling of Cooper pair through the weak link includes the following effects-

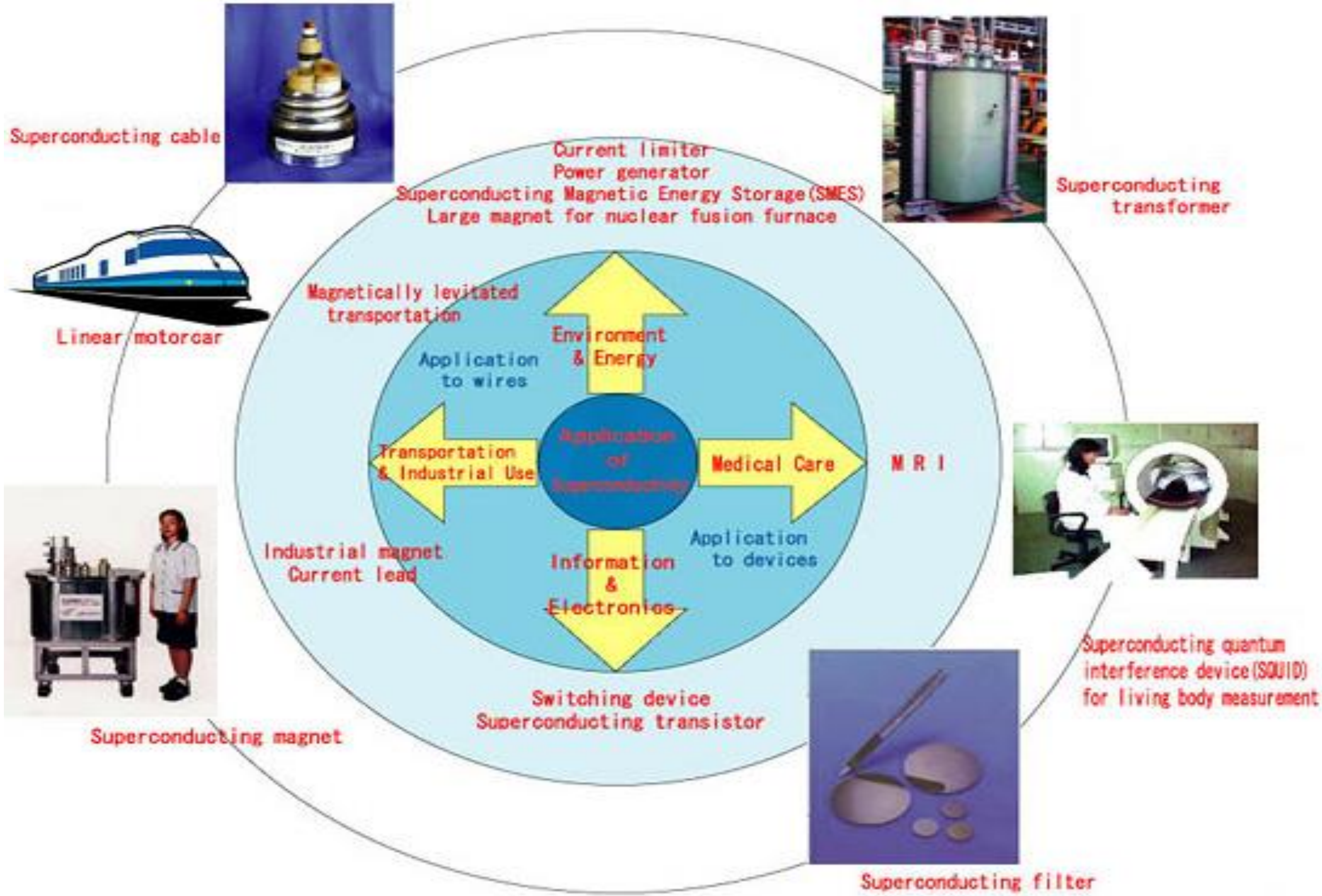
- **DC Josephson effect :-** In the absence of any electric or magnetic field, a DC current flows across the junction.
- **AC Josephson effect :-** When a DC voltage is applied across the junction a RF current oscillates across the junction. Further, an RF voltage applied with the DC voltage can cause a DC current across the weak link.
- **Macroscopic long-range quantum interference :-** If a DC magnetic field is applied across a superconducting circuit containing two Josephson junctions then it causes the maximum super-current to show interference effects as a function of magnetic field intensity. This is used in Superconducting Quantum Interference Devices ***(SQUIDS)*** which finds important application of Josephson junction in designing sensitive magnetometers.

* Cooper Pairs

A Cooper pair is formed due to lattice distortion or phonon mediated attractive interaction between two electrons dominates the usual Coulomb repulsion . Here, the electron pairs condense in a single quantum state. It is responsible for the flow of super-currents. It obeys Bose-Einstein statistics.



Applications



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Thank you