ENTRI

HSST PHYSICS

MODULE 7 : PART 6

SUPERCONDUCTIVITY

- Superconductivity is one of nature's most intriguing quantum phenomena. It was discovered more than 100 years ago in mercury cooled to the temperature of liquid helium (about -452°F, only a few degrees above absolute zero). Early on, scientists could explain what occurred in superconductivity, but the why and how of superconductivity were a mystery for nearly 50 years.
- At what most people think of as "normal" temperatures, all materials have some amount of electrical resistance. This means they resist the flow of electricity in the same way a narrow pipe resists the flow of water. Because of resistance, some energy is lost as heat when electrons move through the electronics in our devices, like computers or cell phones. For most materials, this resistance remains even if the material is cooled to very low temperatures. The exceptions are superconducting materials. **Superconductivity is the property of certain materials to conduct direct current (DC) electricity without energy loss when they are cooled below a critical temperature (referred to as T_c). These materials also expel magnetic fields as they transition to the superconducting state.**
- In 1957, three physicists at the University of Illinois used quantum mechanics to explain the microscopic mechanism of superconductivity. They proposed a radically new theory of how negatively charged electrons, which normally repel each other, form into pairs below T_c. These paired electrons are held together by atomic-level vibrations known as phonons, and collectively the pairs can move through the material without resistance. For their discovery, these scientists received the **Nobel Prize in Physics in 1972.**

- ❖ Following the discovery of superconductivity in mercury, the phenomenon was also observed in other materials at very low temperatures. The materials included several metals and an alloy of niobium and titanium that could easily be made into wire. Wires led to a new challenge for superconductor research. The lack of electrical resistance in superconducting wires means that they can support very high electrical currents, but above a "critical current" the electron pairs break up and superconductivity is destroyed. Technologically, wires opened whole new uses for superconductors, including wound coils to create powerful magnets. In the 1970s, scientists used superconducting magnets to generate the high magnetic fields needed for the development of magnetic resonance imaging (MRI) machines. More recently, scientists introduced superconducting magnets to guide electron beams in synchrotrons and accelerators at scientific user facilities.
- ❖ Since then, many new high-temperature superconducting materials have been discovered using educated guesses combined with trial-and-error experiments, including a class of iron-based materials. However, it also became clear that the microscopic theory that describes superconductivity in metals and metal alloys does not apply to most of these new materials, so once again the mystery of superconductivity is challenging the scientific community. Recently experiments on hydrogen-based materials under extremely high pressure confirmed a theoretical prediction of superconductivity at temperatures approaching room temperature.

Superconductivity Facts

- Superconductivity was discovered in 1911 **by Heike Kamerlingh-Onnes**. For this discovery, the liquefaction of helium, and other achievements, he won the **1913 Nobel Prize in Physics**.
- Five Nobel Prizes in Physics have been awarded for research in superconductivity (1913, 1972, 1973, 1987, and 2003).
- Approximately half of the elements in the periodic table display low temperature superconductivity, but applications of superconductivity often

employ easier to use or less expensive alloys. For example, MRI machines use an alloy of niobium and titanium.

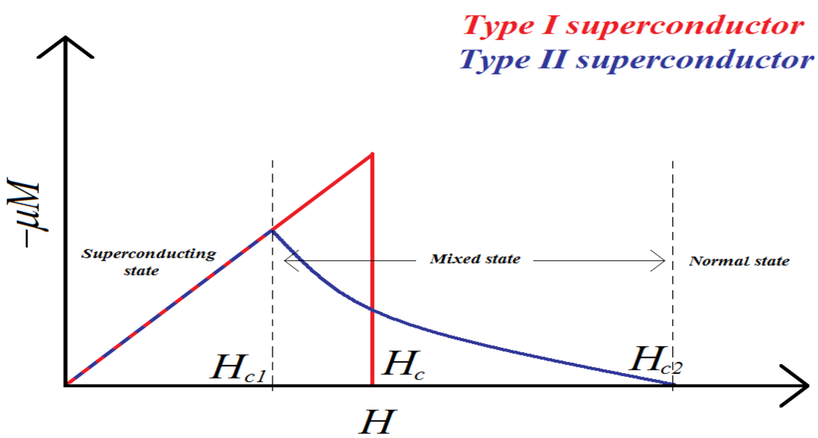
- One of the important physical properties exhibited by a conducting material exhibiting superconductivity is that there is no magnetic flux field present in the material as the presence of magnetic flux fields leads to a loss in energy and an indication of the presence of resistance in the material.
- The use of superconductors in magnets is limited to one fact. When magnetic fields are super strong and above a certain critical value, it causes the superconductor to revert to its normal non-superconducting state, even when the material is kept well below the transition temperature. This varies from material to material used in superconductors.
- In superconductivity, the conductivity of material becomes such that when an electric current is passed through a loop of such a superconductor the electric current will keep flowing through it indefinitely without any need of a power supply.

This can lead to the creation of self-sustaining energy sources solving innumerable problems such as power surges and costly electricity. And because there is no loss of energy due to the resistance of the material the electricity available will be much cheaper when such superconducting material sources are used as power sources.

Type I and Type II superconductors

There are two types of superconductors. They are called Type I and Type II superconductors.

Type I superconductors transform abruptly from their normal state to superconducting state and vice versa at the transition temperature. These superconductors show complete Meissner’s effect below their transition temperatures.However, type II does not show any abrupt change. Instead, they first show partial Meissner’s effect in between two critical values of applied magnetic field and later on show complete Meissner's effect. There are wide applications of Meissner's effect especially in designing levitation trains.



Type 1 superconductors	Type – II Superconductors
Low critical temperature (typically in the range of 0K to 10K)	High critical temperature (typically greater than 10K)
Low Critical magnetic field (Typically in the range of 0.0000049 T to 1T)	High Critical magnetic field (Typically greater than 1T)
Perfectly obey the Meissner effect: Magnetic field cannot penetrate inside the material.	Partly obey the Meissner effect but not completely: Magnetic field can penetrate inside the material.
Exhibits single critical magnetic field.	Exhibits two critical magnetic field
Easily lose the superconducting state by low-intensity magnetic field. Therefore, type-I superconductors are also known as soft superconductors.	Does not easily lose the superconducting state by external magnetic field. Therefore, type-II superconductors are also known as hard superconductors.

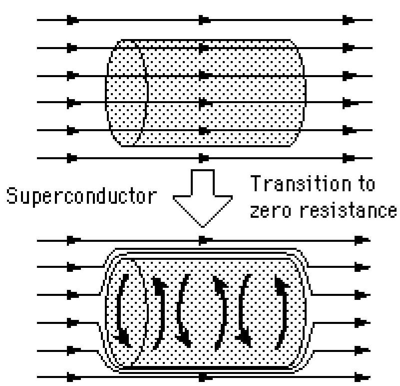
The transition from a superconducting state to a normal state due to the external magnetic field is sharp and abrupt for type-I superconductors.	The transition from a superconducting state to a normal state due to the external magnetic field is gradually but not shape and abrupt. At lower critical magnetic field (H_{C1}), type-II superconductor starts losing its superconductivity. At upper critical magnetic field (H_{C2}), type-II superconductor completely loses its superconductivity. The state between lower critical magnetic field and upper magnetic field is known as an **intermediate state or mixed state**.
Due to the low critical magnetic field, type-I superconductors cannot be used for manufacturing electromagnets used for producing strong magnetic field.	Due to the high critical magnetic field, type-II superconductors can be used for manufacturing electromagnets used for producing strong magnetic field.
Type-I superconductors are generally pure metals.	Type-II superconductors are generally alloys and complex oxides of ceramics.
BCS theory can be used to explain the superconductivity of type-I superconductors.	BCS theory cannot be used to explain the superconductivity of type-II superconductors.
These are completely diamagnetic.	These are not completely diamagnetic
These are also called as Soft Superconductors.	These are also called as Hard Superconductors.
No mixed state exists in type-I Superconductors.	A mixed state exists in type-II Superconductors.

The Meissner Effect

When a material makes the transition from the normal to superconducting state, it actively excludes magnetic fields from its interior; this is called the **Meissner** effect. This constraint to zero magnetic field inside a superconductor is distinct from the perfect diamagnetism which would arise from its zero electrical resistance.

Zero resistance would imply that if you tried to magnetize a superconductor, current loops would be generated to exactly cancel the imposed field (**Lenz's law**). But if the material already had a steady magnetic field through it when it was cooled trough the superconducting transition, the magnetic field would be expected to remain. If there were no change in the applied magnetic field, there would be no generated voltage (**Faraday's law**) to drive currents, even in a perfect conductor. Hence the active exclusion of magnetic field must be considered to be an effect distinct from just zero resistance. A mixed state Meissner effect occurs with Type II materials.

This Meissner state breaks when the magnetic field (either external or produced by current flowing superconductor itself) increases beyond a certain value and sample starts behaving like an ordinary conductor.This certain value of magnetic field beyond which superconductor returns to ordinary state is called Critical Magnetic Field. The value of the critical magnetic field depends on temperature. The value of the critical magnetic field increases when the temperature below the critical temperature reduces.



One of the theoretical explanations of the Meissner effect comes from the **London equation**. It shows that the magnetic field decays exponentially inside the superconductor over a distance of 20-40 nm. It is described in terms of a parameter called the **London penetration depth**.

The London Equations

As discussed in the Meissner effect that one of the conditions of the superconducting state is that Magnetic flux density (B) = 0 inside the superconductors that is the magnetic flux cannot penetrate inside the superconductor. But experimentally it is not so. The magnetic flux does not suddenly drop to zero inside the surface. The phenomenon of flux penetration inside the superconductors was explained by H. London and F. London.

They started with the simple equations;

m$\frac{dv}{dt}$ = eE or $\frac{dv}{dt} = \frac{eE}{m}$

Also J = nev

Or $\frac{dJ}{dt}$ = ne $\frac{dv}{dt}$ = ne$\frac{eE}{m}$ = $\frac{ne^2}{m}$E

Or $\frac{m}{ne^2}\frac{dJ}{dt}$ = E

Then $\frac{m}{ne^2}$ was equated to $\frac{\lambda^2}{c^2}4\pi$, This was done to introduce a new quantity λ into the equation.

Thus, $\frac{\lambda^2}{c^2}4\pi\frac{dJ}{dt}$ = E

Taking curl on both side of the equation, $\frac{\lambda^2}{c^2}4\pi$ curl $(\frac{dJ}{dt})$ = curl E

In Maxwell's equations curl E = $-\frac{1}{c}\frac{dH}{dt}$ hence,

$\frac{\lambda^2}{c^2}4\pi$ curl $\left(\frac{dJ}{dt}\right)$ = $-\frac{1}{c}\frac{dH}{dt}$ or

$\frac{\lambda^2}{c}4\pi$ curl $\left(\frac{dJ}{dt}\right)$ + $\frac{dH}{dt}$ = 0

Integrating the above equation, we get

$\frac{\lambda^2}{c}4\pi$ curl J + H = 0

In the above integration, the constants of integration have been taken to be zero, which is justified both in the case of the perfect conductor or superconductor. Thus, we get

H = - $\frac{\lambda^2}{c}4\pi$ curl J

Now taking curl on both sides of equation, we have

Curl H = $\frac{-\lambda^2}{c}4\pi$ curl (curl J) = $\frac{\lambda^2}{c}4\pi\ \Delta^2 J$

As curl H = $\frac{4\pi}{c}$ J

So we have $\frac{4\pi}{J}$ = $\frac{\lambda^2}{c}4\pi\ \Delta^2 J$

J = $\lambda^2\ \Delta^2 J$……………..(1)

Again starting from the Maxwell equation that curl H = $\frac{4\pi}{c}J$ and taking curl of both the sides. We have,

Curl(curl H) = $\frac{4\pi}{c}\, curl\ J$

Or

H = $\lambda^2\ \Delta^2 H$ …………(2)

The solution of equation (2) is $H = H_0 \exp(-x/\lambda)$, which means that the field will not be completely expelled from the bulk but will penetrate it to a certain depth on the surface. The field will exponentially fall from the maximum value H_0 with a characteristic length λ, which is called the **London penetration depth**.

Definition of London penetration depth: The London penetration depth is the distance inside the surface of a superconductor at which the magnetic field reduces to 1/e times its value at the surface.

The London penetration depth depends strongly on the temperature and becomes much larger as T approaches critical temperature Tc.

Energy gap

In the experiments on the specific heat of superconductors, the idea of the energy gap Δ emerged. It was found that when a superconductor is raised from the ground state to the nearest exited state, energy at least equal to 2Δ must be supplied. Where 2Δ is the energy required to break a bound pair of electrons. This energy gap decreases slowly as the temperature is increased.

This energy gap encountered in superconductors is totally different from that observed in the semiconductors or insulators. In the former, the energy gap due to the electron-electron interaction at the Fermi surface, but in the latter, it is due to the interaction between the electron and the lattice.

However, it may be noticed that there are examples of gapless superconductors also, materials with sufficient amount of magnetic ions are liable to become gapless superconductors.

Isotope Effect

Maxwell and Reynolds found that the transition temperature Tc, depends on the isotopic mass. It was puzzling fact as to how the superconductivity which is an electronic phenomenon, can be affected by the mass of a substance or the number of neutrons that vary from isotope to isotope. The relationship was fond to be $m_i^{\alpha}T_c$ **= a constant** where the exponent α was found to be = 0.5

M is the mass of the superconducting isotope

For a diatomic molecule, the vibration frequency is given by,

$$V = \frac{1}{2\pi}\sqrt{\left(\frac{k}{\mu}\right)}$$

Where k is the force constant between two atoms and μ is the reduced mass given by

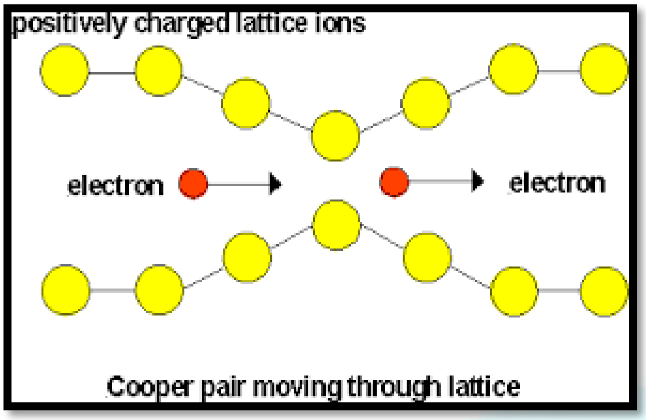
$$\frac{1}{\mu} = \frac{1}{m_1} + \frac{1}{m_2}$$

The value of k will not change by changing isotopes and the only thing that can change is μ which depends on the mass of the atoms or the isotopes.

Cooper Pairs

Cooper pair or BCS pair (Bardeen–Cooper–Schrieffer pair) is a pair of electrons (or other fermions) bound together at low temperatures in a certain manner first described in 1956 by American physicist **Leon Cooper**.

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 superfluid 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 behavior of such electron pairs was further investigated by Cooper and they are called "***Cooper pairs***". The condensation of Cooper pairs is the foundation of the BCS theory of superconductivity.



In order to explain the zero resistivity exhibited by superconductors, consider one of the electrons of the cooper pair propagating through the lattice as shown in figure. The coulomb attraction between the electron and ions deforms the lattice which is propagated along with the electron. This propagating wave is associated with phonon transmission, and the electron-phonon resonance allows the electron along with its pair elsewhere in the lattice to move without resistance.

Bardeen-Cooper-Schrieffer (BCS) Theory of Superconductivity

- BCS theory, in physics, a comprehensive theory developed in 1957 by the American physicists **John Bardeen, Leon N. Cooper, and John R. Schrieffer** (their surname initials providing the designation BCS) to explain the behavior of superconducting materials. Superconductors abruptly lose all resistance to the flow of an electric current when they are cooled to temperatures near absolute zero.

- Cooper had discovered that electrons in a superconductor are grouped in pairs, now called Cooper pairs, and that the motions of all of the Cooper pairs within a single superconductor are correlated; they constitute a system that functions as a single entity. Application of an electrical voltage to the superconductor causes all Cooper pairs to move, constituting a current. When the voltage is removed, current continues to flow indefinitely because the pairs encounter no opposition. For the current to stop, all of the Cooper pairs would have to be halted at the same time, a very unlikely occurrence. As a superconductor is warmed, its Cooper pairs separate into individual electrons, and the material becomes normal, or nonsuperconducting.

- Many other aspects of the behavior of superconductors are explained by the BCS theory. The theory supplies a means by which the energy required to separate the Cooper pairs into their individual electrons can be measured experimentally. The BCS theory also explains the isotope effect, in which the temperature at which superconductivity appears is reduced if heavier atoms of the elements making up the material are introduced.

High-temperature superconductors

High-temperature superconductors (abbreviated high-Tc or HTS) are operatively defined as materials that behave as superconductors at temperatures above 77 K (−196.2 °C; −321.1 °F), the boiling point of liquid nitrogen, one of the simplest coolants in cryogenics.

The major advantage of high-temperature ceramic superconductors is that they can be cooled by using liquid nitrogen.On the other hand, metallic superconductors usually require more difficult coolants - mostly liquid helium. Unfortunately, none of high-temperature superconductors are coolable using only dry ice, and none of them work at room temperature and pressure (they work well below the lowest temperature recorded on Earth). All high-temperature superconductors require some type of cooling system.

The main class of high-temperature superconductors is in the class of copper oxides (only some particular copper oxides). The second class of high-temperature superconductors in the practical classification is the class of iron-based compounds. Magnesium diboride is sometimes included in high-temperature superconductors: It is relatively simple to manufacture, but it superconducts only below −230 °C, which makes it unsuitable for liquid nitrogen cooling (approximately 30 °C below nitrogen triple point temperature). For example, it can be cooled with liquid helium, which works at much lower temperatures.

The first high-temperature superconductor was discovered in 1986, by IBM researchers Bednorz and Müller, who were awarded the Nobel Prize in Physics in 1987 "for their important break-through in the discovery of superconductivity in ceramic materials".

Cuprates

Discovered in 1986, the cuprate superconductors to date hold the record for superconducting transition temperature (Tc) under ambient pressure. The high Tc and critical magnetic field of these materials have been crucial for many technological applications. Moreover, the intriguing superconducting and normal state properties of the cuprates have continuously challenged the conventional understanding of solids, galvanizing the exciting research field known as the strongly correlated electron systems.

The cuprate superconductors have a layered crystal structure consisting of copper oxygen planes and charge reservoir layers. In a simplified picture, a copper oxide plane can be viewed as a square lattice where every site contains one hole with dx2-y2 orbital character. The hole concentration can be altered by hole doping (p) or electron doping (n) from the charge reservoir layers. With no doping, the system is a Mott insulator, where holes cannot move around because of the large energy penalty (U) associated with two of them occupying the same site. At very high doping, correlation effects weaken, and the system approaches a normal metal described by band theory. While these two limits are relatively well understood, superconductivity and many other fascinating phenomena emerge in between, where a subtle balance of different interactions presents significant challenges for theory.