SUPERCONDUCTIVITY

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COOPER PAIRS

- As mentioned earlier, the superconductors offer zero resistance. So, when an electron in a solid passes by adjacent ions in the lattice, it imparts a momentum to these ions due to Coulomb interaction.
- It means the ion starts vibrating and hence phonon gets excited. Now consider a second electron which is subsequently passing through the moving region of increased positive charge density.
- It will experience an attractive Coulomb interaction and can absorb all momentum of vibrating region. Under this situation, the vibrations of ions are stopped and hence the phonon is absorbed by this second electron.
- So in this interaction, the momentum which was imparted by the first electron is taken up by the second electron and hence these electrons undergo an interaction.
- This interaction would be an attractive interaction because exchange of momentum takes place via Coulomb attraction interaction; of course through phonon.
- According to BCS theory, under certain conditions this attractive interaction overcomes the force of repulsion between the two electrons. Therefore, the electrons are loosely bound together.
- This pair of electrons is called Cooper pair.

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2. BOSE EINSTEIN CONDENSATION

Based on the fact that bosons are governed by Bose Einstein statistics and they are not constrained by the Pauli exclusion principle, *Einstein* in 1924 had pointed out that bosons could condense in unlimited numbers into a single ground state. Then very late anomalous behaviour of liquid helium was noticed at low temperatures. Actually a remarkable discontinuity in heat capacity of helium was observed when it was cooled to critical temperature of 2.17K. Under this condition, the liquid density drops and a fraction of the liquid attains a zero viscosity, i.e. it becomes a superfluid. This superfluidity takes place due to the fraction of helium atoms which condenses to the lowest possible energy. This is called *Bose Einstein Condensation*, which can be achieved when the participating particles are identical. This condition of indistinguishability requires that the deBroglie wavelengths of the particles overlap significantly. This is possible only at extremely low temperature as the deBroglie wavelengths become longer. This also requires a high density of particles to narrow the gap between the particles. *Cornell* and *Wieman* together with *Ketterle* received the 2001 Nobel Prize for achieving Bose Einstein Condensation in dilute gases of alkali atoms.

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BCS THEORY: QUALITATIVE EXPLANATION

- The basis of a quantum theory of superconductivity was led by the classic 1957 paper of Bardeen, Cooper and Schrieffer.
- This is now called the BCS theory. It was widely applicable, for example, from He3 atoms in their condensed phase to type I and type II metallic superconductors.
- This theory involves the electron interaction through phonons as mediators.
- The formulation of BCS theory is bases on two experimental facts viz. the isotope effect and the variation of specific heat of superconductors.
- The isotope effect indicated that the lattice vibrations play an important role in achieving the superconducting state.
- Further, Tc attains a value zero when atomic mass M approaches infinity. This implies that non-zero transition temperature Tc is a consequence of finite mass of ions.

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- According to second observation, the jump in the value of specific heat at transition temperature indicates the presence of an energy gap in the energy specturm of the electron in the superconducting state. We discuss below the quantum theory of superconductors due to BCS.
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- We discuss below the quantum theory of superconductors due to BCS.
- When an electron approaches a positive ion core then it suffers attractive Coulomb interaction. So, the ion core sets in motion due to this attraction. Consequently the lattice gets distorted. It is obvious that this distortion will be greater if the mass of the positive ion core is small. Now suppose that another electron interacts with the distorted lattice. Due to this interaction, the energy of the second electron gets lowered. Thus we can say that the two electrons interact via the lattice distortion or the phonon field.

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The superconductivity occurs when an attractive interaction (as mentioned above) between two electrons due to phonon exchange dominates the usual repulsive interaction. This is the fundamental postulate of the BCS theory. As discussed earlier also, the two electrons, which interact attractively, are called a Cooper pair. The energy of the pair of electrons in bound state is less than the energy of the pair in free state. This difference of energy is called binding of Cooper pairs. It means by applying this amount of energy we can break this pair. The pairing is complete at $T = 0K$ and completely broken at $T = T_c$. It was observed that the binding energy of the Cooper pair is maximum when electrons forming the pair have opposite momenta and spins.

In addition, there is a BCS wavefunction composed of particle pairs. When treated by BCS theory, it gives the familiar electronic superconductivity observed in metals and exhibits the energy gap. For the accomplishment of BCS wavefunction, we need that

(i) An interaction (attraction) between electrons can lead to a ground state separated from excited states by an energy gap. The thermal properties and most of the electromagnetic properties are consequences of this energy gap.

(ii) The magnetic flux through a superconducting ring is quantized and effective unit of charge is 2e rather than e.

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APPLICATION OF SUPERCONDUCTIVITY

The attractive property of zero resistance (absence of Joule heating) and Meissner effect make superconductors very useful for many applications. Some of the applications are listed below.

(i) Superconducting cables can be used to transmit electric power over long distances without power losses.

(ii) Superconductors can be used to check unwanted magnetic flux by using their diamagnetic property.

(iii) By using superconductor, very fast and accurate computers can be developed.

(iv) Superconductors are used to detect brain wave activities.

(v) Superconductors are also used in harnessing the various forms of nuclear energies.

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(vi) Most successful application is to use superconducting wire to carry the large currents in high field electromagnets. Such superconducting magnets are widely used in modern particle accelerators. Superconducting magnets are also used in magnetic resonance imaging (MRI) in medicine.

(vii) The superconducting quantum interference device (SQUID) may be configured as a magnetometer to detect incredibly small magnetic fields, i.e. small enough to measure the magnetic fields in living organisms.

(viii) Highly powerful strong field superconductor electromagnets are fabricated using liquid helium superconductors. These electromagnets are used in NMR spectrometers and NMR imaging that are employed in medical diagnosis. Electromagnets are also used to produce Josephson's devices, electromagnetic shields and magnetically levitating world's fastest trains.

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(ix) Low temperature superconductors have been used to construct fractional wavelength antennas, leading to a significant improvement in radiation efficiency. However, the use of liquid helium as a cryogen limits the application of such antennas.

(x) It is seen that conventional metal guides at mm wavelength have attenuations of the order of 10 dB/m due the high value of surface resistance of the metal walls at ~200GHz. Therefore, potential application for superconductors is also in the construction of electromagnetic waveguides. The advantage over conventional metal waveguides would be at the higher frequencies.

(xi) Now it has been possible to design ceramic superconductors which can act at temperature > 77 K, i.e. it can act as hi-T_c superconductors. These superconductors have advantage over low T_c superconductors because liquid nitrogen can be used as coolant, which is cheaper and has better cooling due to its high thermal capacity.

(xii) Other industrial applications of superconductors are through magnets, sensors, transducers and magnetic shielding.

(xiii) Superconductors also have applications in power generation, energy storage, fusion, transformers and transducers.