BCS Theory of Superconductivity: A Qualitative Overview

The BCS theory, developed by John Bardeen, Leon Cooper and Robert Schrieffer in 1957, is a fundamental theory of modern condensed matter physics and provides a comprehensive explanation of superconductivity in conventional superconductors. This theory explains how certain materials can conduct electricity with zero resistance and expel magnetic fields (the Meissner effect) below a critical temperature.

The Key Concepts of BCS Theory

1. **Cooper Pairs**:

The foundation of BCS theory is the concept of Cooper pairs. In a normal conductor, electrons move independently and are subject to scattering by impurities or lattice vibrations (phonons), which causes resistance.

In a superconductor, below a critical temperature (T_c), electrons near the Fermi surface (the highest energy electrons in a material) can form pairs known as Cooper pairs. Despite the fact that electrons are fermions (which normally repel each other due to their like charges), they can attract each other indirectly through interactions with the crystal lattice.

2. **Phonon-Mediated Attraction**:

The attractive force between two electrons in a Cooper pair is mediated by phonons, which are quanta of lattice vibrations. When an electron moves through the lattice, it distorts the positive ions, creating a local region of increased positive charge. This distortion can attract another electron with opposite momentum and spin, leading to the formation of a Cooper pair.

This pairing occurs despite the overall repulsive Coulomb interaction between the electrons because the phonon-mediated attraction is stronger at certain conditions, particularly at low temperatures.

3. **Energy Gap:**

In the superconducting state, Cooper pairs form a collective ground state and an energy gap opens up at the Fermi surface. This gap represents the energy required to break a Cooper pair and excite an electron to a higher energy state.

Because of this energy gap, there are no available states for the electrons to scatter into within the gap, meaning that scattering (and therefore resistance) is suppressed. This results in zero electrical resistance.

4. **Long-Range Coherence:**

Cooper pairs are not localized but instead form a coherent quantum state that extends over large distances within the material. This coherence is what allows superconductors to carry current without resistance.

The wavefunctions of Cooper pairs overlap, leading to a macroscopic quantum state where the pairs move in unison. This collective behaviour is key to the zero-resistance property of superconductors.

5. **Meissner Effect:**

The BCS theory also explains the Meissner effect, where a superconductor expels an applied magnetic field from its interior when it transitions into the superconducting state.

The expulsion of the magnetic field is due to the superconductor's ability to generate surface currents that exactly cancel the applied magnetic field within the material. This phenomenon is directly related to the coherence of the Cooper pairs and the energy gap.

[Summary
The BCS theory of superconductivity explains how, at low temperatures, electrons in a superconductor form Cooper pairs through a phonon-mediated attraction, leading to a collective quantum state. This pairing and the resulting energy gap at the Fermi surface are key to understanding the zero electrical resistance and perfect diamagnetism (Meissner effect) observed in superconductors. The BCS theory successfully describes the behaviour of conventional (low-temperature) superconductors and laid the foundation for the modern understanding of superconductivity.]