# Superconductivity how it works based on the BCS and other more recent theories

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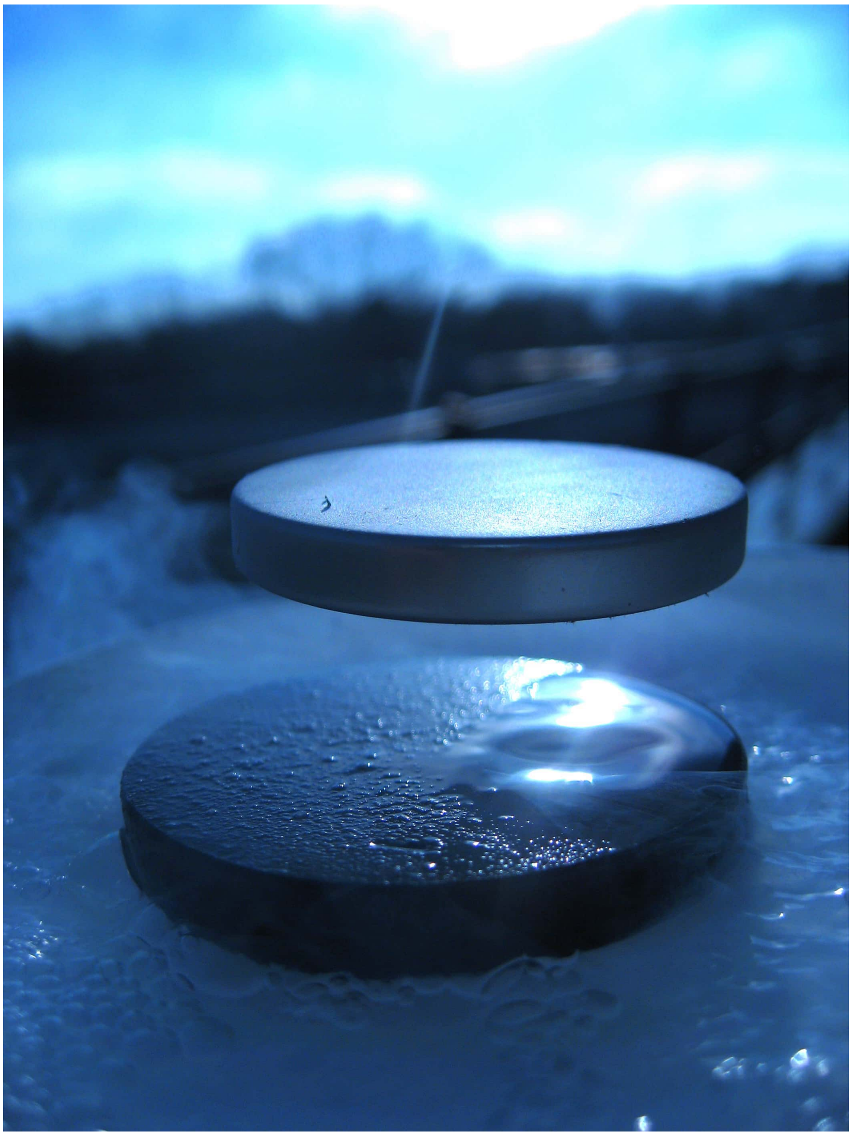
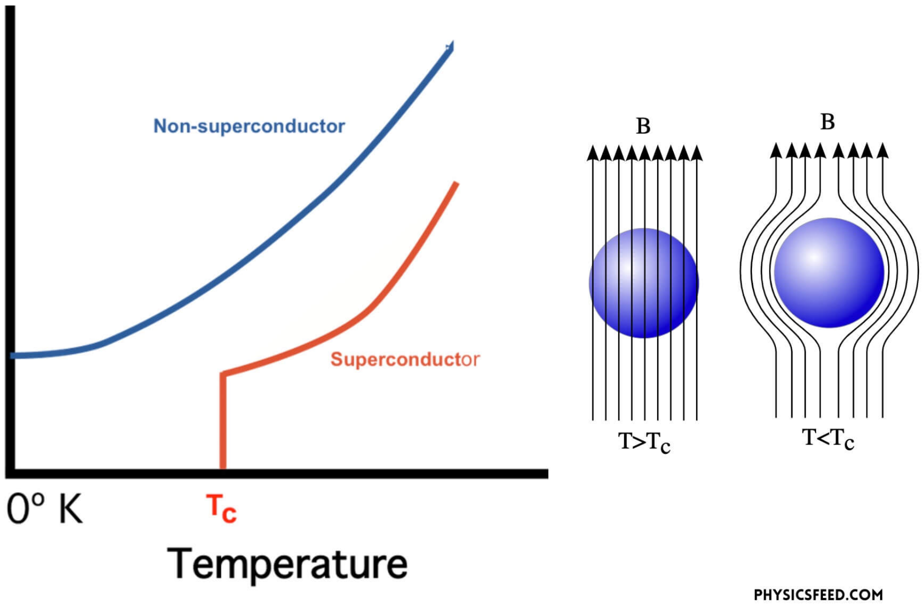


CHAPTER I

# Introduction

Superconductivity is a remarkable phenomenon that has captivated scientists for over a century. In simple terms, superconductivity is the ability of certain materials to conduct electricity with zero resistance when cooled below a critical temperature.




This phenomenon was discovered in 1911 by Heike Kamerlingh Onnes, who observed that the electrical resistance of mercury disappeared completely when cooled to 4.2 K (-269°C). The discovery of superconductivity marked a turning point in the history of physics and led to the development of many revolutionary technologies. Superconducting materials are now used in a wide range of applications, such as magnetic levitation trains, MRI machines and particle gas pedals. The development of new high temperature superconductors has opened up new possibilities for practical applications.

The understanding of superconductivity is based on the BCS theory, which was proposed by Bardeen, Cooper and Schrieffer in 1957. According to this theory, superconductivity is caused by the formation of Cooper pairs, consisting of two electrons that interact with each other through lattice vibrations. The BCS theory is still considered to be the most successful and complete explanation of superconductivity to date.

On the other hand, new theories of superconductivity have emerged that shed additional light on the phenomenon. These theories include high-temperature superconductivity, which was discovered in the 1980s, and the idea of topological superconductivity, which has gained attention in the past decade. These new theories have opened up exciting areas of research and have the potential to lead to even more advanced technologies.

CHAPTER II

# The BCS Theory

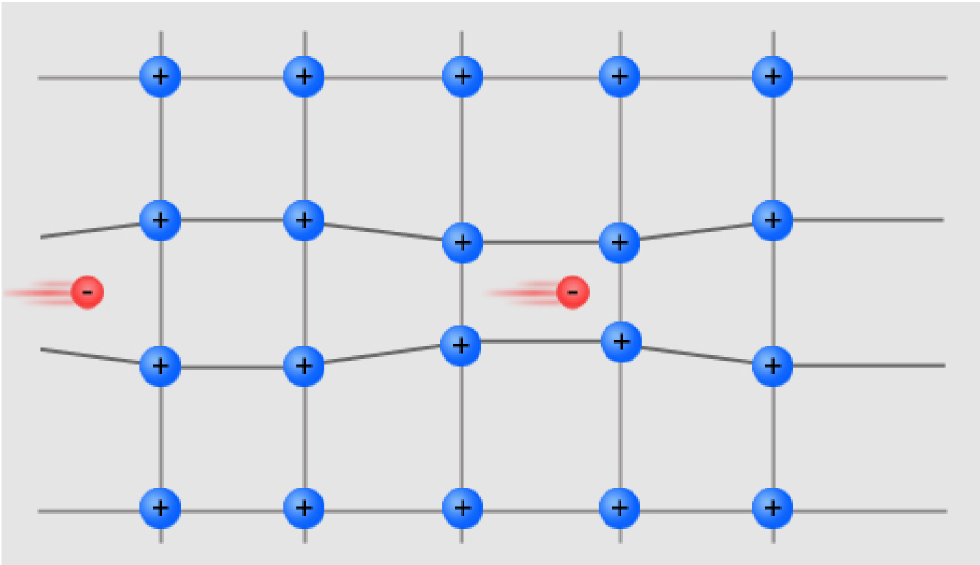
The BCS theory, proposed by John Bardeen, Leon Cooper and Robert Schrieffer in 1957, is the most complete explanation of superconductivity to date. According to this theory, superconductivity results from the formation of Cooper pairs, composed of two electrons that interact with each other through lattice vibrations.

The basic idea of the BCS theory is that the electrons in a superconducting material make up a condensate, much like the atoms in a Bose-Einstein condensate. At low temperatures, the electrons are “paired” by their interactions with the crystal lattice. These paired electrons are called Cooper pairs, named after Leon Cooper, who was the first to propose their existence in 1956.

The formation of Cooper pairs is facilitated by the presence of lattice vibrations, or phonons, which create a net attractive interaction between electrons. When two electrons come together, they distort the lattice, creating a region of high positive charge density. This positive charge attracts other electrons, which reduces the energy of the system. As a result, the two electrons bond together in a Cooper pair.

The s-wave symmetry refers to a type of wave function where the electron pairs have an isotropic distribution around the nucleus, meaning that they have the same probability of being found in any direction. This type of symmetry is found in conventional superconductors

Cooper pairs make super conductors



At extremely low temperatures, an electron can draw the positive ions in a superconducting material towards it. This movement of the ions creates a more positive region that attracts another electron to the area.

Cooper pairs have several interesting properties. First, they are bosons, which means that they follow Bose-Einstein statistics rather than the more familiar Fermi-Dirac statistics of individual electrons. This means that they can occupy the same energy state, which leads to the phenomenon of superconductivity.

The BCS theory also explains the existence of a critical temperature (Tc), above which superconductivity disappears. At temperatures above Tc, the thermal energy of the system becomes large enough to break the Cooper pairs apart, causing the material to become resistive.

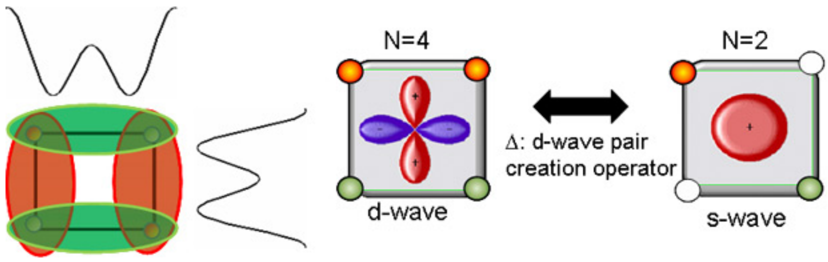
The BCS theory has been remarkably successful in explaining a wide range of experimental observations. It has also led to the development of many important technologies, such as superconducting magnets and particle accelerators. However, it has some limitations, such as its inability to explain high-temperature superconductivity. In the next chapter, we will discuss the more recent theories of superconductivity that have emerged in the last few decades.

CHAPTER III

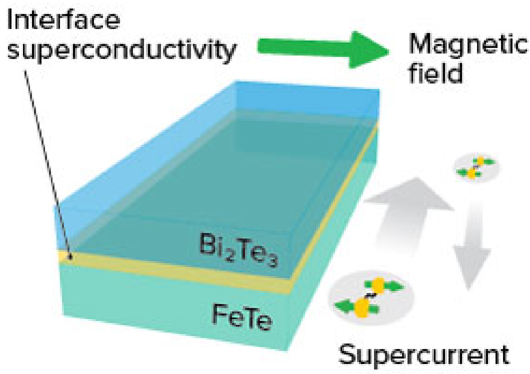
# Other Theories of Superconductivity

While BCS theory has been very successful in explaining many aspects of superconductivity, it is limited in its ability to explain high temperature superconductivity. In the 1980s, a new class of superconductors was discovered that exhibited much higher critical temperatures than predicted by BCS theory. These materials, known as high temperature superconductors (HTS), stimulated the development of new theories of superconductivity.

One of the most influential theories of high-temperature superconducting materials is the d-wave theory, which proposes that the superconducting state is characterized by a complex order parameter exhibiting wave symmetry. Unlike BCS theory, which predicts s-wave symmetry, d-wave theory explains the existence of nodes in the energy gap, which has been observed in many superconducting materials. The d-wave theory also provides a possible explanation for the mechanism of high temperature superconductivity. The d-wave theory refers to a wave function that has a directional dependence. This means that the probability of finding the electron pairs is not the same in all directions but instead depends on the angle. This type of symmetry is found in unconventional superconductors such as cuprate high-temperature superconductors. In d-wave superconductors, the pairing mechanism is more complex and may be related to the interaction between electrons themselves or with magnetic fluctuations.



Another theory that has gained attention in recent years is the idea of topological superconductivity. This theory suggests that the superconducting state can be characterized by a topological invariant, which is a property of the system that is protected from perturbations. In topological superconductors, the quasiparticles that emerge in the superconducting state have exotic properties, such as non-Abelian statistics and Majorana zero modes, which could have important implications for quantum computing and other technologies.




The discovery of high-temperature superconductivity has led to the development of new theories of superconductivity, which have expanded our understanding of this remarkable phenomenon. While the BCS theory remains the most successful and comprehensive explanation of superconductivity to date, the newer theories have opened up exciting research areas and have the potential to lead to even more advanced technologies in the future.

CHAPTER IV

# Quantum Mechanics in Superconductivity

Superconductivity is a phenomenon that occurs due to the quantum mechanical behavior of electrons in a material. It is important to understand the role of quantum mechanics in superconductivity to understand how it works.

## IV.1 Wave-Particle Duality

The wave-particle duality of electrons is one of the key concepts of quantum mechanics that plays an important role in superconductivity. According to wave-particle duality, electrons can exhibit both wave and particle behavior. In superconductivity, electrons behave as waves and form a macroscopic wave function that describes the behavior of all electrons in the material.

## IV.2 Electrons as Fermions

Electrons are fermions, which means that they obey the Fermi-Dirac statistics. According to these statistics, two fermions cannot occupy the same quantum state at the same time. This is called the Pauli exclusion principle. In a normal metal, the electrons scatter impurities, phonons and other electrons, resulting in resistance. In a superconductor, electrons form Cooper pairs and behave like bosons. This behavior allows them to occupy the same quantum state and move coherently in the material, resulting in zero resistance.

## IV.3 Quantum Tunneling

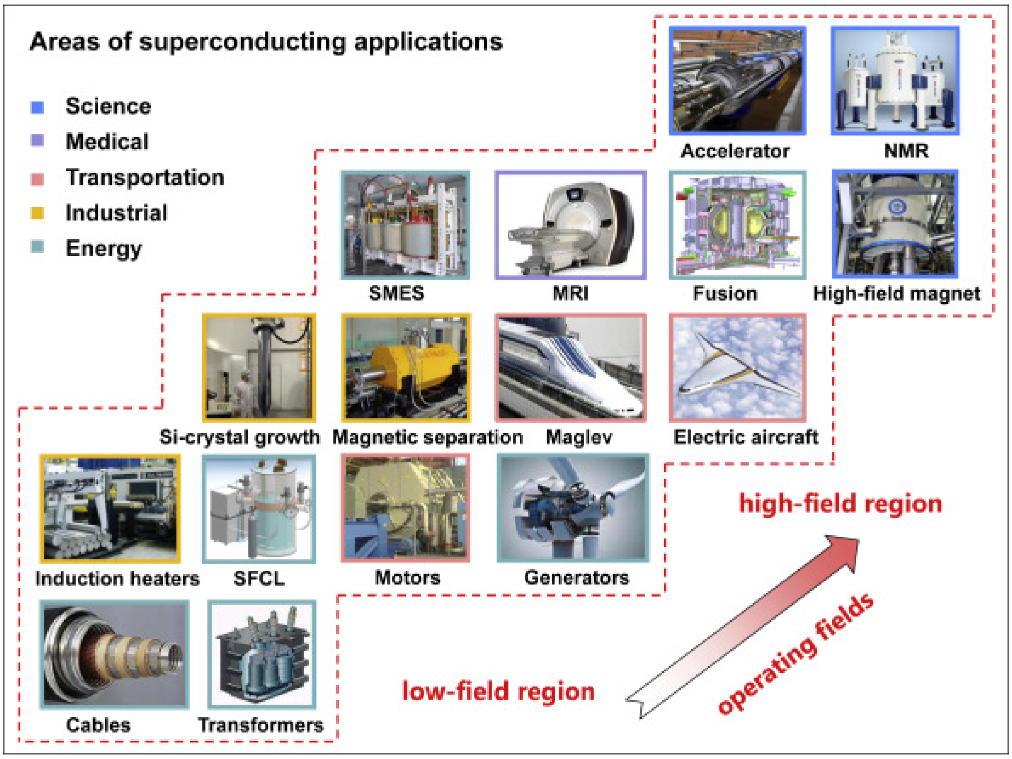
Quantum tunneling is a phenomenon that occurs when electrons are able to move through a potential barrier that they could not cross according to classical physics. This phenomenon is due to the wave nature of electrons, which allows them to tunnel through the barrier. In a superconductor, this results in a state of zero resistance where electrons can move through the material without any loss of energy.

## IV.4 Meissner Effect

The Meissner effect occurs when a superconductor is cooled below its critical temperature, it expels all magnetic fields from its interior. This is because the electrons in a superconductor form a macroscopic wave function that can interact with magnetic fields. When a magnetic field is applied to a superconductor, the electrons reorganize to cancel the magnetic field. This results in a complete expulsion of the magnetic field from the interior of the superconductor.

CHAPTER V

# Applications of Superconductivity




Superconductivity has many applications in a wide range of fields, from medicine and energy to transportation and computing. One of the most important applications of superconductivity is in the production of high-strength magnets, which are used in medical imaging devices such as magnetic resonance imaging (MRI) machines. These machines use strong magnetic fields to produce images of the body, and the use of superconducting magnets allows for higher field strengths and more detailed images.

Superconductivity is also used in particle accelerators, which are used in a variety of research fields such as high-energy physics, material science, and chemistry. The high magnetic fields needed to guide particles in the accelerator are provided by superconducting magnets, which allow for higher particle energies and better experimental accuracy.

Energy can be stored by an electric current in a coil of superconducting wire. Once the coil is closed on itself, the current remains indefinitely because there is no loss. With capacitors and batteries, this is the only way to store electricity directly. The losses are very low compared to other forms of energy storage. Unfortunately, the mass or volume density of the stored energy is not very high. A 20 Tesla coil stores about 45 kWh/m3 of energy.

D-SMES (Distributed Superconducting Magnetic Storage) coils are particularly designed for power grid stability. The superconducting coil is connected to the grid via a reversible AC-DC converter, which converts the alternating current of the grid into direct current for the coil. If there is a voltage drop in a grid, it immediately injects additional energy to stabilize the grid. It recharges in minutes and can withstand many charge/discharge sequences without degrading. Only 2 to 3% of the energy is lost in the transfers, which is very low. The first 8.4 kWh coils were installed on the Bonneville Power Administration grid in Tacoma (USA) in 1980. This was the first superconducting application to operate on a grid. The Wisconsin Public Service (WPS) purchased them for $4 million in 1999. Installed in July 2000, they protect the distribution in northern Wisconsin, which was prone to numerous outages. The system is 200 miles long and has a voltage of 115 kV.

Finally, superconductivity has potential applications in computing, such as in the development of quantum computers. Quantum computers use the properties of superconducting materials to perform calculations much faster than traditional computers, which could have important implications for fields such as cryptography and machine learning.

In conclusion, the applications of superconductivity are diverse and wide-ranging, with potential benefits for many areas of society. The development of new superconducting materials and technologies has the potential to revolutionize fields such as medicine, energy, transportation, and computing, and is an active area of research and innovation.

CHAPTER VI

# Conclusion

Superconductivity has many potential applications in fields such as medicine, energy, transportation and computing. From the development of high-strength magnets for medical imaging to the potential use of superconducting materials in quantum computing, the possibilities offered by superconductivity are vast and varied.

However, significant challenges must be overcome before these applications can be fully realized. These challenges include the need for low temperatures, the brittleness of some superconducting materials, and the need for more scalable devices.

Despite these challenges, ongoing research holds hope for the future of superconductivity. The development of new materials and technologies, as well as the discovery of new applications, offer the possibility of significant advances in many areas of society.

In conclusion, while there is still much to be discovered and developed in the field of superconductivity, the potential applications and benefits are vast and exciting. Continued research and innovation in this field offers hope for the future and the possibility of significant advances in many areas of society.

Superfluidity is another fascinating phenomenon from quantum mechanics, similar to superconductivity. In a superfluid, atoms or molecules have zero viscosity and can flow without any resistance, defying our everyday experience with fluids. The study of superfluids has led to many discoveries and applications, from understanding the behavior of neutron stars to developing new technologies in quantum computing.