Superconductivity: Properties and Applications

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Abstract

Superconductivity is a phenomenon in low-temperature materials which exhibit zero electric resistance and repel magnetic fields. The two types of superconductors are Type I and Type II. Type I superconductors need much lower temperatures, are generally pure metals, and only exist in the Meissner state. Type II superconductors have much higher critical temperatures and critical magnetic fields, and can exist in the pure Meissner state or the mixed state. The BCS (Bardeen-Cooper-Schrieffer) theory explains why Type I superconductors are formed; however, Type II superconductors can be formed several different ways. Superconductors have various applications, but they are mostly used for strong magnets. These strong magnets are useful for MRIs, MagLev trains, and more. Another main application of superconductors is quantum computers, which utilize Josephson junctions to measure small changes in magnetic flux.

Introduction

Superconductivity was discovered in 1911 by Dutch physicist Heike Kermerlingh Onnes, who discovered that there was no electrical resistivity of a mercury wire when it was cooled below 4 K.[1] This discovery was preceded by James Dewar's work in liquefying hydrogen in 1898. He worked on liquefying other gasses later, providing the necessary tools to achieve the extremely low temperatures required for superconductivity.[2]

For many years, scientists believed the only property of superconductors was zero electrical resistance. However, in 1933, German physicists W. Meissner and R. Ochsenfeld discovered that superconductors expel a magnetic field.[2] In 1934, brothers Fritz and Heinz London were able to describe various properties of superconductors mathematically. They proposed superconductors could be described by a macroscopic quantum wave function.[2]

However, at this time, research was still focused on low-critical-temperature superconductors, which were both expensive and complex. In 1986, IBM researchers Georg Bednorz and K. Alex Müller discovered the first high-temperature superconductor, with a critical temperature of 35.1 K.[3] This was soon modified by Ching-Wu Chu, who made a superconductor with a critical temperature of 93 K.[4] High-temperature superconductors were extremely useful, because researchers no longer had to cool liquid helium to reach the temperatures low enough to create the superconducting state.[5] Instead, they could use liquid nitrogen, which was less expensive and more practical. However, the superconductors' complex structures and precise doping levels made the handling and creation of the material much more difficult.

Superconductors are used often throughout our lives, with applications from medical imaging to quantum information. Not only are they useful, they have also taught us a lot about quantum mechanics, opened up new fields of research, and created many advancements in materials science. There are many possibilities for superconductors to be applied in energy systems, medical technology, and computing in the future.

This paper discusses Type I and Type II superconductors, Bardeen-Cooper-Schrieffer (BCS) theory, applications of superconductors, and the future of superconductivity. Type I superconductors exhibit various properties such as no electrical resistance and the expulsion of a magnetic field. The creation of Type I superconductors can be explained through the behavior of the Cooper pairs (electrons that pair up in the superconducting state) from the BCS theory. Type II superconductors exhibit similar properties as Type I superconductors, but they also have sections in which the material is normal, where the material is essentially a normal metal with no superconductive properties. There are many applications of superconductors – they are mainly used for strong magnets, but they also are used for various machines. This paper is intended for a high school audience with basic physics knowledge.

Basic properties of Type I superconductors

Type I superconductors, usually pure metals, need extremely low temperatures to exist. For example, Niobium has a critical temperature of 9.3 K to stay in the superconducting state.[6] When in the superconducting state, they expel a magnetic field. Any external magnetic field passing through will go around the superconductor, meaning the magnetic susceptibility would be -1.[7] The penetration depth (λ) refers to the distance the magnetic field penetrates into the superconductor before being expelled.[8] For Type I superconductors, this depth is very small since it expels the magnetic field completely. However, if the magnetic field is too strong, the material will no longer be in its superconducting state. For Type I superconductors, the critical magnetic field is very low, and as the temperature increases, the critical magnetic field must decrease, as shown in Figure 1. The critical magnetic field and critical temperature are related through the equation

$$B_c(T) = B_c(0)[1 - (\frac{T}{T_c})^2],$$

where $B_c(T)$ is the critical magnetic field at temperature T, $B_c(0)$ is the critical magnetic field at a temperature of 0 K, T is the temperature in Kelvins, and T_c is the critical temperature. This phenomenon is known as the Meissner effect. [9]

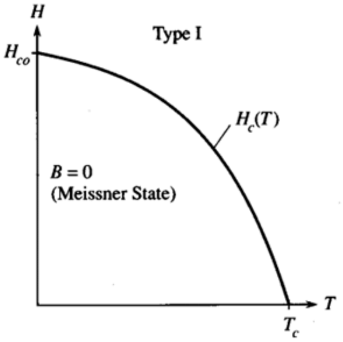

Figure 1: Phase diagram of a Type I superconductor. The x-axis represents temperature and the y-axis represents magnetic flux. H_{co} *represents the critical magnetic field, which is the maximum magnetic field that the superconductor can stay superconducting.* T_c *represents the critical temperature, which is the maximum temperature that the superconductor can stay superconducting. Underneath the* $H_c(T)$ *curve is where the material is in the superconducting state. Reproduced from [10].*

Another property of Type I superconductors is that there is no electrical resistance. In regular materials, there is electrical resistance due to collisions of electrons. These electrons can collide with impurities or phonons (vibrational modes of a solid) in the metal, which causes resistance.[11] When the temperature rises, the lattice vibrations increase, meaning there are more phonons available to collide with the electrons, thus increasing the resistance. This means in normal metals, the resistance will decrease steadily as the temperature lowers. However, in superconductors, when the material cools to the critical temperature, the electrical resistance suddenly drops to zero.[12] This property puzzled scientists until the Bardeen-Cooper-Schrieffer Theory was developed.

BCS theory

The Bardeen-Cooper-Schrieffer (BCS) Theory was first developed in 1957 to explain superconducting behavior.[13] According to the BCS Theory, electrons are able to pair up through attractive forces between two electrons some distance from each other.[13] This distance, ξ, is known as the coherence length.[8] These pairs, named Cooper pairs, are created from the lattice vibrations.[8,14]

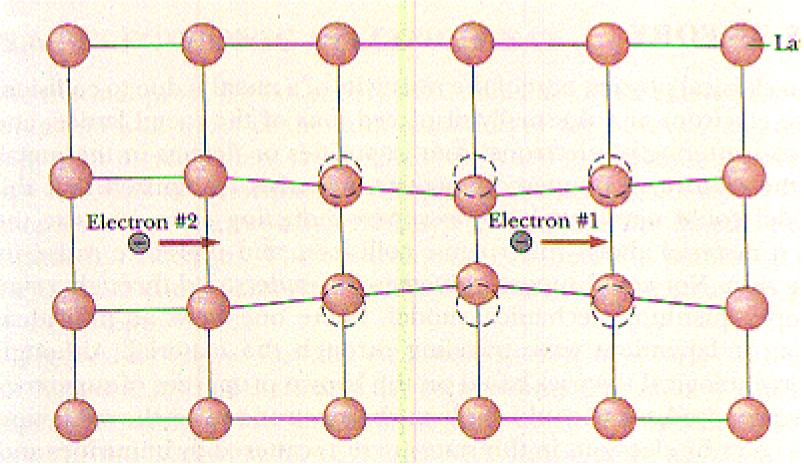

Figure 2: Diagram of Cooper pairs. The figure shows two electrons (a Cooper pair) moving through the lattice. The surrounding nuclei are attracted to the first electron, permitting the second electron to follow the first with no resistance. The dashed circles represent the original position of the nuclei. Reproduced from [15].

Normally, electrons would have too much energy to pair together, and the repulsive Coulomb forces would prevent an attraction between them.[13] However, once the temperature is lowered enough in superconducting materials, the attractive force from the phonons can overcome the repulsive Coulomb forces, which allows the electrons to form pairs.[16] When a voltage is applied, the Cooper pairs move, creating a current. As the electron moves through the lattice, the surrounding nuclei are attracted to it due to its positive charge, as shown in Figure 2.[14] This creates an area of positive charge that pulls, or attracts, the other electron in the direction of the first. After the second electron moves through, the nuclei return to its original place. This means they can move through the material with no electrical resistance.[13] If the temperature rises too high, then the lattice vibrations increase continuously until the electrons cannot avoid bumping into other objects in the lattice such as impurities, creating electrical resistance and losing superconductivity.

Also, complying with the Pauli Exclusion Principle, the electrons in the Cooper pairs pair up at zero net spin as represented by Figure 3.[17] Below the critical temperature and critical magnetic field, the Cooper pairs can stay together at the lowest energy state. However, when the magnetic field becomes too strong, this breaks the electron pairs into separate energy levels, and the material exits the superconductivity state.[18] However, not all superconductors have electrons pairing like this – some unconventional superconductors are spin triplets.[19] This means instead of having only one way to organize (i.e. spin up and spin down), there are three ways to organize the electrons. This is uncommon, but is an emerging research field within superconductivity.

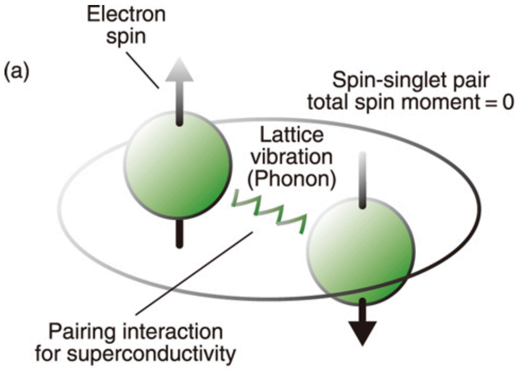

Figure 3: Representation of the spin of electrons when s=0. Through the Pauli Exclusion Principle, the electrons pair up with opposite spins in order to use the least energy possible. Reproduced from [20].

Type II superconductors

Some superconductors, called unconventional superconductors, do not follow the BCS Theory.[21] These are the superconductors with high critical temperatures. These superconductors commonly consist of metal alloys and complex oxide ceramics, like Yttrium Barium Copper Oxide (YBCO). They can reach temperatures as high as 138 K and magnetic fields much stronger than Type I superconductors.[22] They have two critical fields consisting of the vortex state and the Meissner state, as shown in Figure 4.[23] According to the Ginzburg-Landau Theory, in Type II superconductors, the coherence length (distance between the Cooper pairs) is much shorter than Type I superconductors.[23] This theory relates the coherence length to the upper critical magnetic field through the equation $H_{c2} = 2.07\times10^{-15}\ \mathrm{T\cdot m^2}/(2\pi\xi^2)$, which shows that the critical magnetic field and the coherence length have an inverse relationship.[24] This leads to a negative interface energy, permitting two critical fields. Negative interface energy allows a normal and superconducting region to exist in the same material because it is energetically favorable in that way. In Type I superconductors, the energy for having a boundary is higher than not having a boundary, meaning that it has positive interface energy.[25]

The Meissner state exhibits the same properties as the Type I superconductors, but the vortex state permits partial penetration of the magnetic field, meaning the penetration depth of Type II superconductors is much longer than Type I superconductors.[26] The critical magnetic field of some Type II superconductors is so high that we do not have measurements for them. In YBCO, the H_{c2} is 22 T, which is much higher than the the critical magnetic field of 0.19 T in a Type I superconductor made of Nb.[6,22]

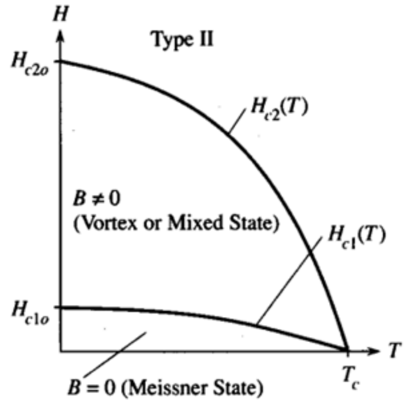

Figure 4: Phase diagram of Type II superconductor. The x-axis is represented by temperature and the y-axis is represented by magnetic flux. H_{c1} represents the first critical magnetic field, which is the maximum magnetic field that the superconductor can stay fully superconducting, essentially like a Type I superconductor. H_{c2} represents the second critical magnetic field, which is the maximum magnetic field that the superconductor can stay superconducting and is in the vortex state. T_c represents the critical temperature, which is the maximum temperature that the superconductor can stay superconducting. Underneath the $H_{c1}(T)$ curve is where the material is in the Meissner state, similar to how a Type I superconductor is. Underneath the $H_{c2}(T)$ curve is where the material is in the vortex state, where the superconductor exhibits properties of Type II superconductors. Reproduced from [10].

The partial penetration of the magnetic field in a superconductor creates vortices. This permits a phenomenon known as flux pinning, where these vortices get trapped by impurities in the material, which eliminates the movement of vortices throughout the material.[27] This increases the critical magnetic field of the superconductor and increases the critical current density.[28] The vortex state essentially allows the magnetic field to go through some areas of the material (the normal cores) while maintaining the superconducting state in other areas of it, as shown in Figure 5. As long as these vortices are stationary, or pinned, the magnetic fields can penetrate while maintaining zero electric resistivity.[27] As the temperature or external magnetic field is increased, the normal regions are forced closer together, which eventually breaks the superconducting state.

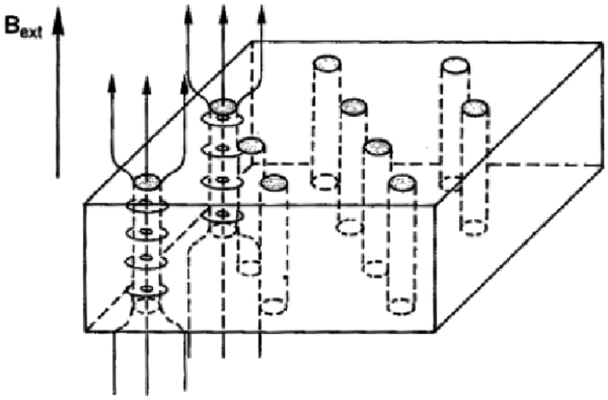

Figure 5: Type II superconductor vortex state. In the vortex state, there are areas of non-superconducting material where magnetic fields can go through. The small cylinders in the block represent pinned vortices within the Type II superconductor. B_{ext} represents the magnetic field going through the pinned vortices. Reproduced from [29].

Type II superconductors can be created through several ways including solid-state synthesis and doping.[21,30] To create a cuprate superconductor, a superconductor made with layers of copper oxides and other metal oxides, we dope it by adding impurities or charge carriers to materials. Normally, the electrons are antiferromagnetically aligned (spin is pointing in opposite directions); however, doping a material with oxygen destroys the magnetic order.[21] This turns the material into a Type II superconductor.

Applications

Most superconductors used in everyday life are Type II, due to the cheaper and easier creation. Due to the high critical field, Type II superconductors have a wide range of applications; whereas Type I superconductors are used for more sensitive applications, or devices before the discovery of Type II superconductors.

There are many applications of superconductors, the most common being strong magnets.[31] Whenever a large magnetic field is needed, we can use superconductors to create these. Since superconductors can conduct currents with zero electrical resistance, large amounts of current can go through superconducting coils, creating a strong magnetic field. A common example of this is Magnetic Resonance Imaging (MRI).[32] MRIs need large magnets to produce a magnetic field around the body of the machine.

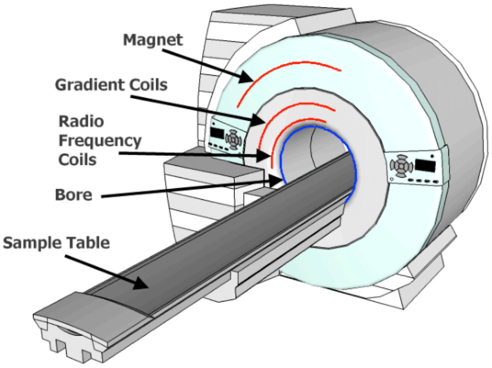

Figure 6: Diagram of an MRI. The MRI consists of a large magnet, which is often actually a superconductor, gradient coils, radio frequency coils, a bore, and a sample table. Reproduced from [33].

The human body is made up of water, which is magnetic. The hydrogen atoms in water act like small magnets, meaning they have positive and negative poles, which makes them sensitive to magnetic fields.[34] The MRI uses a big magnet, or a superconductor, to produce a magnetic field around the body. Because superconductors have zero electric resistance, they can carry large currents without heating up, which produces a large magnetic field; therefore, it is necessary to use superconductors for MRIs.[32] Then, the gradient (thin conductive sheets or loops of wire) separates the magnetic field into smaller sections, isolating certain body parts.

Inside the body, some water molecules (called low-energy water molecules) move at a different frequency as the magnetic field produced by the superconductor.[32,34] Radio waves are sent to move the low-energy molecules, and when these waves stop, the low-energy water molecules release the energy absorbed from the radio waves, and go back to their original position.[34] The MRI software then collects this information and uses it to image the body.

Another example of superconductors as large magnets is Maglev trains.[35,32] Superconducting magnets on the train induce currents in conductive coils on the track, creating repulsive magnetic forces that allow the train to levitate.[35,36] Because the train never actually touches the track, the lack of friction creates a smoother ride and allows the train to reach high speeds. Also, particle accelerators use superconductors to generate strong magnetic fields which are used to accelerate charged particles.[37]

Superconductors also exhibit the Josephson Effect.[38] The Cooper pairs from one superconductor flow to the other through a thin insulating layer.[38] When we have two Josephson junctions (a junction which exhibits the Josephson Effect), this creates a loop with a switch, as shown in Figure 7.[39] This loop is extremely sensitive to outside magnetic fields. A special property of these loops is that they only allow integer quantum flux through. When there is little outside magnetic field, the current through the loop proceeds in the normal direction to cancel out the outside magnetic flux.[39,40] However, once the outside magnetic field becomes too strong, the current switches direction. Instead of canceling the outside magnetic flux, this current (or the magnetic field caused by the current) now adds to the outside magnetic flux in order to do the least work.[40] The amount of flux allowed through is the integral amount of flux, which is given by the equation $\Phi = \Phi_0 (n + ½ + \delta/2\pi)$, where Φ_0 is the magnetic flux quantum, approximately 2.067×10^{-15} Wb, n represents the number of flux quanta, and δ is the phase difference across the Josephson junctions.[40,41]

This loop creates a superconducting quantum interface device (SQUID), which is used to measure small magnetic fields.[39] They can also be used in quantum computers, where the current in the SQUID determines the state of qubits.[42] These qubits, or quantum bits, are similar to bits in classical computers, but are a lot more powerful. In classical computers, there are switches that allow current to flow through the circuit – the bit is either a 0 (off), or a 1 (on). In quantum computers, the Josephson junctions create the switch for the qubits, which can be 0, 1, or a combination.[43] This allows the quantum computer to do work much faster than a classical computer, and consume less power.

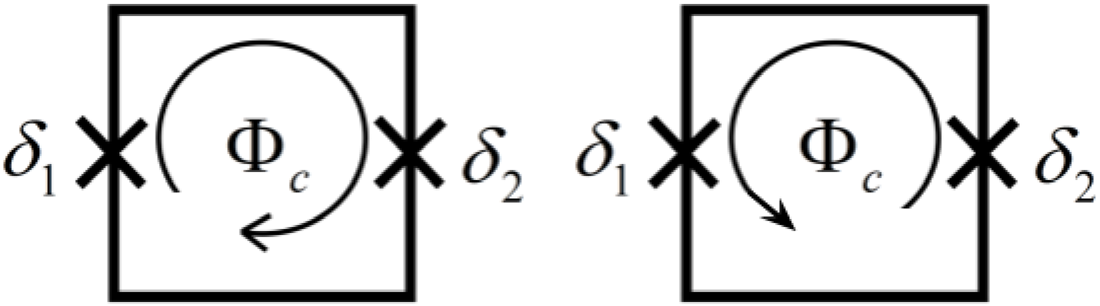

Figure 7: Diagram of a SQUID loop. The crosses next to the δ symbol represent Josephson junctions. The circular arrow represents the direction of the current. The diagram to the left represents when the outside magnetic flux is canceled out by the current, and the diagram to the right represents when the current adds to the outside magnetic flux. Reproduced from [44].

Conclusion

Research on superconductivity is still popular today. Researchers are hoping to discover higher temperature superconductors, so eventually we could have room-temperature superconductors. While we have not achieved that yet, this discovery would increase the accessibility to superconductors, revolutionizing infrastructure and electronic devices. Additionally, finding more common, cheap materials that exhibit superconducting behavior could reduce the costs greatly. One of the largest challenges for superconducting research is the high costs of producing the materials and keeping the temperature low.

Current research includes finding new ways to create superconductors, especially Type II superconductors. An MIT team recently found that iron selenide shifts to the superconducting state in a new way – instead of undergoing a shift through spin, the atoms undergo a shift in their orbital energy.[45] Additionally, there have been several controversies regarding room-temperature superconductors. Some researchers have claimed that they have discovered a hydrogen-based superconductor that can exist at room temperature; however, their results could not be replicated and the work was later retracted.[46] Additionally, there are superconductors that are a mix of Type I and Type II superconductors called Type 1.5 superconductors. These multicomponent superconductors have two or more coherence lengths, one which is shorter than the penetration depth and one which is longer than the penetration depth.[47] These often are van der Waals heterostructures.[48]

Overall, superconductivity is a fascinating phenomenon that has potential to be applied in many different areas. There are many different types of superconductors, but the current focus is to find the highest possible temperature superconductor that can exist under an attainable magnetic field and pressure. Superconductivity could revolutionize our infrastructure and technology, increasing the efficiency of our world.

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