Brief Exploration of Superconductivity's Temperature-dependence

Mattaeus Klonowski
Department of Physics, The College of Wooster, Wooster, Ohio 44691, USA
(Dated: December 12, 2019)

A superconducting material was induced into its superconducting state by lowering its temperature to that of liquid nitrogen. The superconductor was studied by plotting resistance versus temperature, measured using a four-point probe and a thermocouple, respectively. The critical temperature of the yttrium-barium-copper-oxide (YBCO) superconductor studied was measured to be 108 K, a 14% error from the accepted value of 95 K.

I. INTRODUCTION

Superconductivity was first discovered by Heike Kamerlingh Onnes (1853-1926) in 1911. When experimenting with the conductivity of metals at near-zero temperatures, he discovered that after passing below a certain temperature, which would become known as the critical temperature, of a given metal, its resistance would drop to zero. This fascinating observation founded what is today known as the study of superconductivity. For his experimental work Kamerlingh Onnes was awarded the Nobel prize in physics in 1913.

The first microscopic theory to explain superconductivity was proposed jointly by John Bardeen, Leon Cooper, and John Robert in 1957. This theory, which would become known as BCS theory, proposed that superconductivity was a result of electrons forming Cooper pairs, and thus negating the resistive effects electrons normally encounter within a conducting material. For their theoretical work John Bardeen, Leon Cooper, and John Robert were awarded the Nobel prize in physics in 1972.

The most prominent effects that arise from superconductors are the creation of persistent currents and permanent electromagnets, allowing for a variety of useful applications. In addition to powerful electromagnets being used in particle accelerators, superconducting materials have found applications in many different commercial sectors. Magnetic levitation (maglev) trains allow for significantly faster transportation, magnetic resonance imaging (MRI) scans allows for more in depth medical analyses, and electric generator facilities that use superconducting wire allow for much more efficient energy generation and distribution.

Similarly, BCS theory has been applied to other areas of physics. In nuclear physics, nucleon pairing can be explained by BCS theory, and in condensed matter physics, the Fermi level shares some overlap with BCS theory.

However, many questions still remain to be answered regarding the phenomenon of superconductivity. BCS theory has an upper temperature limit of about 30 K, but superconductors with critical temperatures of up to 250 K have recently been discovered [1], meaning BCS theory cannot fully explain superconductivity. The effects that allow certain materials to become superconductors at relatively high temperatures remain unknown. Ultimately, superconductivity is a relevant topic of study, with many potential applications and unanswered questions worthy of inquiry.

II. THEORY

A. Persistent Current

A superconducting material that falls below its specified critical temperature T_c will become superconductive, meaning that the resistance R of the material will become zero. The electrical implications of this can be understood through Ohm's law,

$$V = R \cdot I, \tag{1}$$

where V is voltage, R is resistance, and I is current. If there is no resistance R, then virtually any current I can flow through the superconductor without the typically necessary voltage V. This effect is commonly referred to as persistent current. However, each superconductor also has a critical current density J_c, which cannot be exceeded without losing superconductive properties. Another electrical perspective on the persistent current effect can be shown through the power equation,

$$P = R \cdot I^2, \tag{2}$$

where P is power. Thinking about relative change of power P with respect to current I and knowing that resistance R is zero, virtually any change in current I will result in no change in power P. This indicates that there is virtually no power loss for currents travelling through superconductors.

B. BCS Theory

Now a microscopic theory will be described that explains the macroscopic effects observed regarding superconductors. From a microscopic perspective, resistance is simply travelling electrons interfering with the electron clouds of the atoms in the structural lattice of the conducting material. However, at low temperatures this microscopic

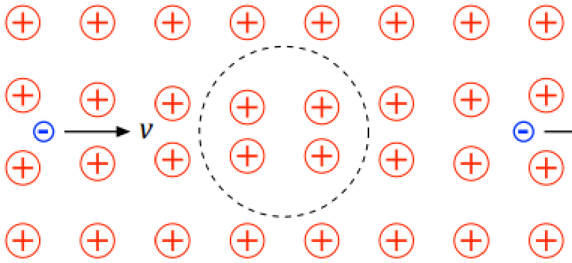


FIG. 1: Positive red points represent atomic nuclei and the smaller negative blue points represent electrons within an atomic lattice of a given superconducting material. The dashed line circle in the center of the diagram represents a relatively positively charged space in the lattice, which can attract pairs of electrons. These pairs of electrons can then become weakly bound to one another through phonon interactions, which are referred to as Cooper pairs and take on a boson state. This leads to the negation of microscopic resistance within a superconductor. This image is adapted from the junior physics independent study lab manual [2].

resistance ceases to exist. The initial step of this process is visually represented in Fig. 1. When electrons flow through a conducting material, they carry current by slowly drifting towards the positive electric potential caused by an applied voltage. As the electrons drift, spaces devoid of negative charge and therefore relatively positively charged may appear in the lattice. When positive charge is localized in this way, two electrons can become paired by their mutual attraction to this positive space. This attraction is relayed through phonons, which are particle representations of lattice vibrations, over a distance of approximately 100 nm. At room temperature, where there is a lot of thermal noise, these interactions do not occur on a large scale. However, at low enough temperatures these interactions occur on a large enough scale where their effects are observable. This can be understood by using the Boltzmann factor to represent energy,

$$E = k \cdot T, \tag{3}$$

where E is energy, k is the Boltzmann constant, and T is temperature. Plugging in the approximate electron binding energy E value of 10^{-3} eV, and the approximate Boltzmann constant k value of 10^{-4} eV/K, a quick calculation yields that temperature must be about 10 K, closely matching experimental observations for the first discovered superconductors.

A pair of electrons that has bound at a low temperature is known as a Cooper pair. The most significant change that occurs during Cooper pairing is that electrons change from their typical fermion state to a boson state. Fermions are subatomic particles that have half-integer spin ($-\frac{1}{2}$, $\frac{1}{2}$,...), while bosons are subatomic particles that have integer spin (-1, 1,...). Electrons are fermions with spin $\pm\frac{1}{2}$, and Cooper pairs are bosons with spin 0 or 1. Spin is more formally referred to as intrinsic angular momentum, with its quantum mechanical origin being more clearly discernible in this way. The main difference between fermions and bosons are the way they interact energetically. Fermions follow what is known as the Pauli exclusion principle, which is due to the fact that fermions cannot occupy the same quantum state. This means that their energy distribution follows what is known as Fermi-Dirac statistics. Bosons on the other hand do not follow the Pauli exclusion principle, and can occupy the same quantum state. This means that their energy distribution follows what is known as Bose-Einstein statistics.

So when a bunch of fermions transform into a bunch of bosons, in this case forming a Bose-Einstein condensate, the electrons which are now in the form of Cooper pairs can all condense down to their lowest energy, and negate the interactions they have with the other electrons in the material. Therefore at this state, current is able to travel with no resistance.

C. Meissner Effect

Another effect of superconductors is that they can become permanent electromagnets, allowing other magnets to hover above them indefinitely. Understanding this begins with applying Ampere's circuital law to the superconductor,

$$\oint B \cdot dl = \mu_0 \cdot I_{enc}, \tag{4}$$

where B is the magnetic field, l is the path length, μ_0 is the permeability of free space, and I_{enc} is the enclosed current. The current running through the superconductor will this induce a magnetic field, in accordance with the right hand rule, visually represented in Fig. 2. In this way the induced magnetic field will oppose the intrinsic magnetic field of a magnet, and the superconductor and magnet will repel each other, just like two magnets repel each other. In typical conducting materials this effect is not observed because the electrons are all randomly arranged, and therefore do not coherently resist the penetrating magnetic field lines. However in a superconductor, due to the relatively ordered arrangement of the electrons, they are able to coherently resist the penetrating magnetic field with magnetic field lines of their own, seen in Fig. 3.

III. PROCEDURE

The superconducting material tested was yttrium-barium-copper-oxide (YBCO), from the Colorado Superconductor Inc. "Complete Exploration Kit". This material has a molecular formula of $YBa_2Cu_3O_7$ (Y_{123}). Interestingly YBCO is not fully saturated with nine oxygens,

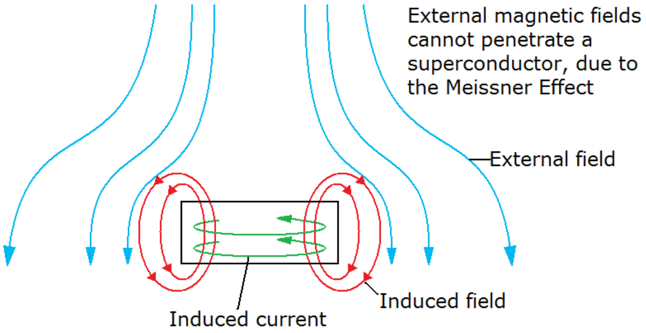
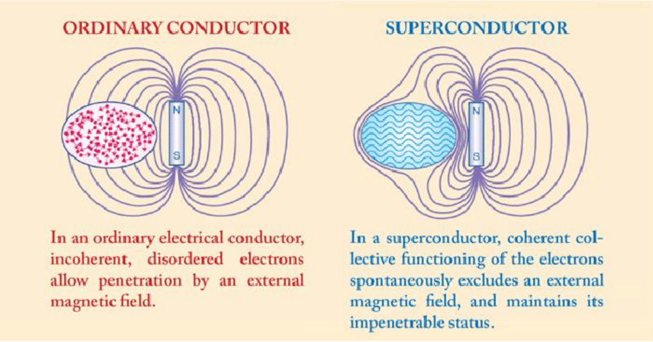


FIG. 2: A diagram demonstrating the Meissner effect. A superconductor with a current travelling through it, represented by the green arrows, induces a magnetic field according to Ampere's (circuital) law, represented by the red arrows. This induced field then repels the magnetic field intrinsic to any magnet. The repulsive force between these two magnetic fields is what causes a magnet placed over a superconductor to levitate. This image is adapted from Dux College's Crimson Academies website [3].



In an ordinary electrical conductor, incoherent, disordered electrons allow penetration by an external magnetic field.

In a superconductor, coherent collective functioning of the electrons spontaneously excludes an external magnetic field, and maintains its impenetrable status.

FIG. 3: Schematic comparing the interactions of the electrons within an ordinary conductor to electron interactions within a superconductor, in the presence of a magnet. Whereas for a typical conductor the electrons are randomly ordered, the electrons within a superconductor are well ordered. This ordering allows the electrons within a superconductor to resist potential magnetic fields. This image is adapted from Meissner's original article on what came to be known as the Meissner effect [4].

instead containing only seven oxygens, two less than expected for a typical molecular structure.

The experimental setup used can be seen in Fig. 4. A Kepco current regulator was used as the power source, and provided current to the superconductor across one set of wires. Voltage across the superconductor was measured across a second set of wires. The first two sets of wires are commonly known as a four-point probe. Four-point probes are used because if current is passed through the same set of wires that measure voltage, the resistance between the wire and the sample can skew the measured voltage. A third set of wires measured a voltage which was subsequently converted to temperature, known as a thermocouple. A thermocouple measures the voltage across two different metals as a result of a temperature gradient between them and a reference, which is then converted to temperature based on the metals used. All three pairs of wires were connected to a relay within a Keithley 2000 multimeter. Voltages measured from each pair of wires were then analyzed using the Labview computer program. Resistance of the superconductor was found through a simple manipulation of Ohm's law (Eq. 1), dividing the voltage measured from the second set of wires by the current measured from the first set of wires. Temperature was calculated using a quartic fit function dependent on the voltage measured by the third set of wires. In this way a graph of resistance versus temperature could be collected.

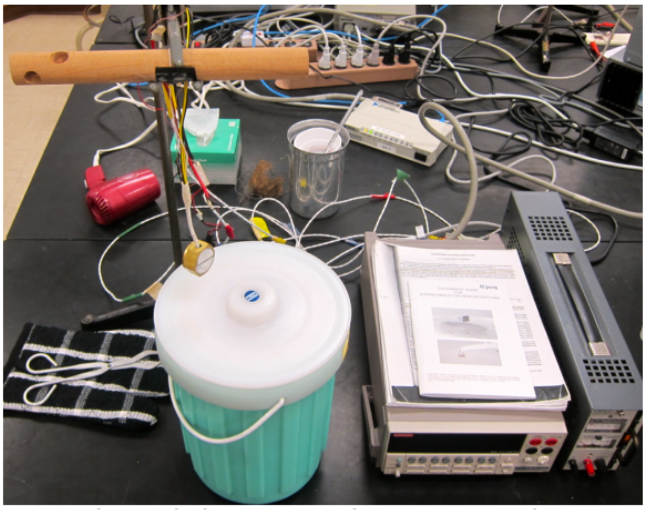


FIG. 4: An image depicting the experimental setup. The green dewar is meant to contain liquid nitrogen, with the superconductor dangling above it, ready to be dipped and tested. A multimeter and power source are located directly to the left of the dewar. This image is adapted from the official junior physics independent study lab manual [2].

Superconductivity was tested by placing a superconductor in a container of liquid nitrogen and taking the described measurements. The Meissner effect is able to be tested by simply placing a magnet above a superconducting material submerged in liquid nitrogen.

IV. DATA ANALYSIS

Overall, the experimental data matched closely with theoretical predictions for superconductors (regarding both persistent current and permanent electromagnetism).
A graph of resistance versus temperature was plotted when the superconductor was submerged in liquid nitrogen and taken out to gradually let warm, as seen in Fig. 5. Because the temperature of liquid nitrogen, 77 K, is below the critical temperature of YBCO, 95 K, the YBCO matched the predicted superconductor property of hav-

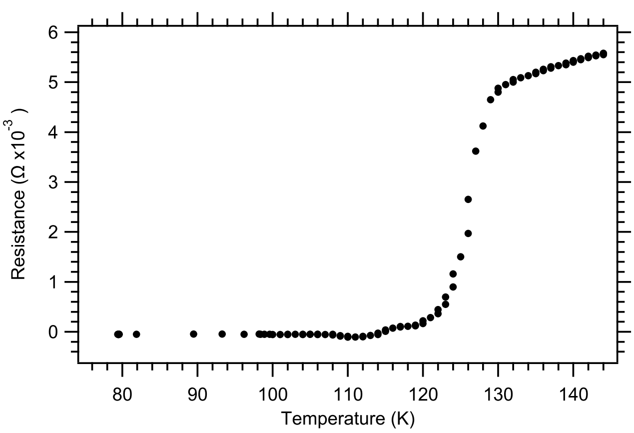


FIG. 5: A plot of resistance versus temperature as a YBCO superconductor rose from below to above its critical temperature, and thus changed from superconducting to non-superconducting properties. This transition can be observed by the rapid shift from a resistance of zero to a linearly increasing resistance, in accordance with Ohm's law.

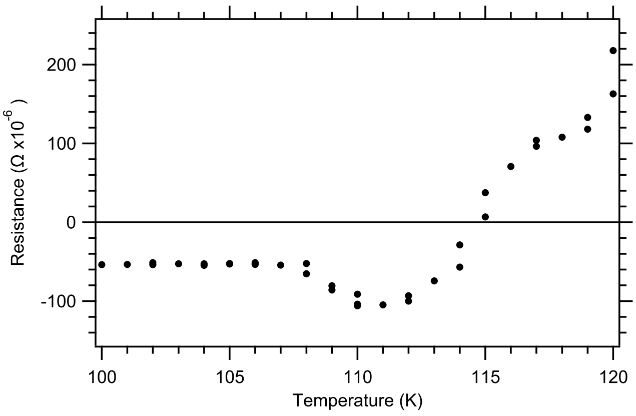


FIG. 6: An enlarged plot of resistance versus temperature focused on discerning the specific critical temperature of the superconductor, as resistance became non-zero. The initial dip, indicating a change in properties, is most likely where the superconductor began losing its superconducting property of zero resistance.

ing zero resistance below its critical temperature. As the temperature slowly increased, the resistance dramatically (almost instantaneously) rose above zero after the critical temperature was reached, and then leveled off again in a linear fashion, in accordance with Ohm's law. An enlarged version of Fig. 5, which focuses on the critical temperature, can be seen in Fig. 6. Although the first temperature measurement where resistance rises above zero is at approximately 115 K, the first deviation from what is zero resistance is at approximately, 108 K. Using this value gives an error of 14% from the accepted critical temperature of YBCO of 95 K [5]. This is likely partially due to the overall age of the experimental setup, but mostly due to the inaccuracy of the quartic fit function used to convert from voltage to temperature.

V. CONCLUSION

This experiment successfully determined the critical temperature of a YBCO superconductor to be 108 K, a 14% error from the accepted value of 95 K. With more time, the Meissner effect would be studied. A more satisfactory and in-depth quantitative analysis of the critical temperature could also be attempted. However, many mysteries remain to be solved in terms of the theory behind superconductivity at temperatures greater than approximately 30 K.

VI. ACKNOWLEDGEMENTS

Gratitude is owed to Dr. Lehman and Abigail Ambrose, the professor and teaching assistant of the physics junior independent study course, for assistance in lab.

VII. NOTES

A significant amount of time in lab was also spent preparing a new experimental setup with Dr. Lehman, using a new superconducting material whose critical temperature has not yet been measured. Before conducting this experiment with the new setup, it is suggested that some type of cover is applied to the exposed portions of wire.

VIII. REFERENCES

[1] High Temperature Superconductor (2019). https://arxiv.org/abs/1812.01561.

[2] Department of Physics, The College of Wooster, Wooster, OH. *Junior IS Lab Manual* (2019).

[3] Macro Meissner Effect (2019). https://dc.edu.au/hsc-physics-ideas-to-implementation/.

[4] Meissner, W. & R., O. "A New Effect of Superconductivity" (English translation). *Naturwissenschaften* **21**, 787–788 (1933).

[5] YBCO Critical Temperature (2019). https://link.springer.com/chapter/10.1007/978-1-4613-0639-9$_7$4.