Finding the critical temperature of a YBCO superconductor using a voltage probe.

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This experiment was conducted to determine the critical temperature at which a $YBa_2Cu_3O_7$ superconductor's resistance goes to zero. The experiment was performed by submerging a sample of the superconductor in liquid nitrogen while passing a current through the superconductor and monitoring temperature using LabVIEW. The resistance as a function of temperature was then plotted in Igor Pro to determine the critical temperature. The experiment found the critical temperature of a YBCO superconductor to be 86.6 ± 1.1 K, off from the accepted value of 93 K by 7%.

I. INTRODUCTION

Superconductivity is one of the least understood phenomena in modern physics and one with astounding potential. Economical materials that superconduct have only been discovered fairly recently but already superconductors are used to create extremely powerful permanent magnets without a constant supply of current, like those use in Magnetic Resonance Imaging, and being tested for use in the national power grid. Because of the myriad opportunities presented by superconduction it is a very active field of research.

II. HISTORY

The idea that the electrical resistance of a material would go to zero as temperature decreased was first proposed by James Dewar and John Ambrose Fleming, who conjectured that metals would become perfect electrical conductors at absolute zero. The first experimental discovery happened in 1911 when Kammerlingh Onnes found that mercury had zero resistance below 4.2 K, using liquid helium as a coolant. Soon after several other materials were found to superconduct, but none at temperatures above approximately 15 K. While theoretical work on superconductors continued the next experimental breakthrough in superconductivity came in 1986 when Bednorz and Mueller found a lanthanum-based ceramic that superconducted at temperatures just below 35 K, a temperature believed before to be forbidden for superconduction. This was quickly followed with Paul Chu and M. K. Wu's replacement of the lanthanum with yttrium, which creates a superconductor called YBCO with a critical temperature of around 93 K[1]. This was economically important because this is above the boiling point of liquid nitrogen, 77 K, meaning the cheap and easily available nitrogen could be used as coolant for a superconductor instead of the more expensive helium. Since then more exotic superconductors have been found, such as $(TMTSF)_2ClO_4$, di-(tetramethyltetraselenafulvalenium)-perchlorate, an organic superconductor that still superconducts in high magnetic fields[2].

The latter property of TMTSF is novel because most superconductors have a unique behavior in magnetic fields, called the Meissner effect. Normal materials let magnetic fields pass right through them, superconductors do not. On average magnetic fields can only penetrate 100 nm into a superconductor; this distance is called the depth called the London penetration depth. For a known magnetic field H this can be found with the formula $\nabla^2 H = \lambda^{-2} H$ when λ is the penetration depth. One of the most stunning ramifications of the Meissner effect is that this rejection causes a repulsive force on a magnet near a superconductor, and this can result in levitation as shown in figure 1.

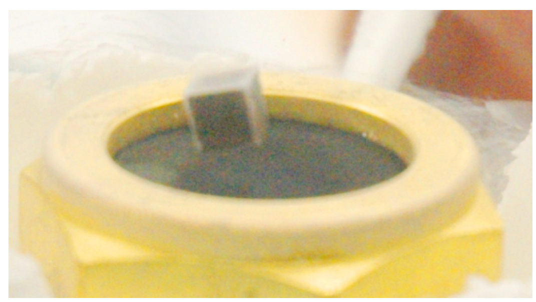

FIG. 1: A neodymium magnet levitating above a YBCO type superconductor.

III. THEORY

The theory of superconductivity is what is known as the BCS theory, proposed by John Bardeen, Leon Cooper and John Schreiffer in 1957, for which they won the Nobel Prize in Physics in 1972. The basis of this theory are the Cooper Pairs, pairs of electrons bound together that form a superfluid in the material according to the BCS theory, able to move freely throughout the material without restriction. This freedom of electron movement is what makes superconductivity possible. In normal superconductors this has agreed well with experiment; most notably it has been found that the fundamental quantity of charge in superconductors is twice that of normal electrons[3]. However, BCS theory can not explain high-temperature superconductivity and there are other things affecting the BCS theory at low temperatures which are not fully understood.

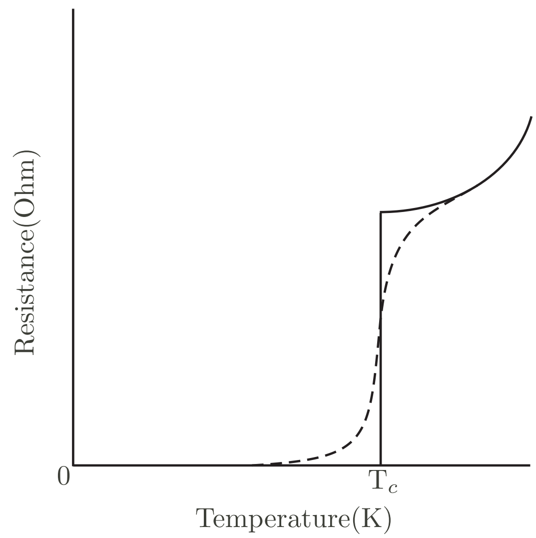

FIG. 2: The solid line shows the resistance versus temperature for a perfect superconductor crystal while the dotted line shows the expected curve of a imperfect superconductor. Based off of a figure from reference [4].

While a full treatment of superconductivity is beyond the scope of this paper there is one fundamental property of superconductors that is very important, the critical temperature. The nature of superconductors is such that the transition from a state where they do not superconduct to one where superconduction takes place is very rapid, as in figure 2. For an ideal superconductor where the structure of the material is a perfect crystal this will happen at one temperature, the critical temperature. This critical temperature is what defines normal and high-temperature superconductors. High-temperature superconductors are defined as superconductors with critical temperatures above 30 K. For an imperfect superconductor the transition to superconduction is still rapid but is not nearly as abrupt and still allows for reasonable estimation of the critical temperature of the superconductor.

IV. EXPERIMENTAL SET UP AND PROCEDURE[5]

For this experiment the entire data collection was run using a LabVIEW 7.1 program on a Apple Mac G4. This was connected to constant current source, a Kepco Current Regulator, and voltage meter, a Keithley 2000 Multimeter, using a GPIB connection, as shown in figure 3. In order to determine the temperature of the superconductor when it was in the liquid nitrogen a type T thermocouple was used with one junction in the superconductor's case and one outside in a reference bath of

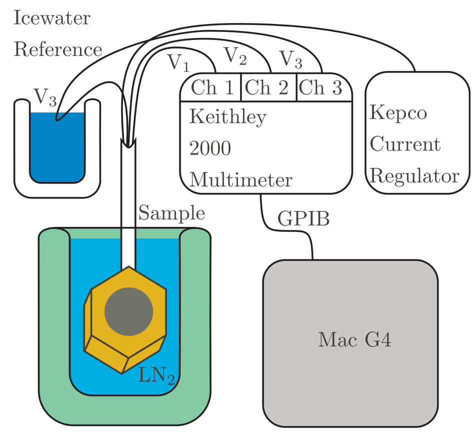

FIG. 3: Schematic of the experiment set up with the sample suspended in the liquid nitrogen bath. Diagram after reference [6].

ice and water at 273 K. A thermocouple works by the thermoelectric effect, whereby two dissimilar metals in contact produce a voltage across their contact point, dependent on their temperature. Since all metals produce different amounts of voltage for changes in temperature thermocouples can be designed specifically for different temperature ranges based on the other properties of the metal. Thermocouples work best for comparison though, so a known reference temperature is used to find the temperature of the second junction of the thermocouple. The superconductor was suspended in the liquid nitrogen from a stand, which allowed the sample to be submerged to cool and placed just above the liquid nitrogen for slow warming. The superconductor itself was purchased from Colorado Superconductor, Inc in its brass case with a four-point probe system already integrated into it as well as a type T thermocouple. As in figure 4 the six leads of the superconductor system are divided into three sets of two. The first set is on far sides of of the superconductor disk and is used to measure the voltage across a precision resistor with a resistance of 5.0003 Ohms, from which the current in the superconductor can be found. The second pair measures the voltage across a smaller section of the superconductor disk. With the values from the first two pairs the resistance of the superconductor can be found using Ohm's law, $V = IR$. The final set of leads is for the thermocouple, leading in to the sample probe junction, out to the reference junction, and back to the voltmeter. These three voltages were then sent onto the LabVIEW program running on the G4 which converted the information into the resistance of the superconductor and the temperature of the thermocouple.

The actual experiment itself was very simple to do. First the constant current source was set to 75 mA for the first two runs and at 250 mA for the latter four runs. After preparing the LabVIEW program to take data the sample was submerged in liquid nitrogen until the liquid ceased boiling, which was when the sample reached the temperature of the liquid nitrogen, 77 K. Then the Lab-

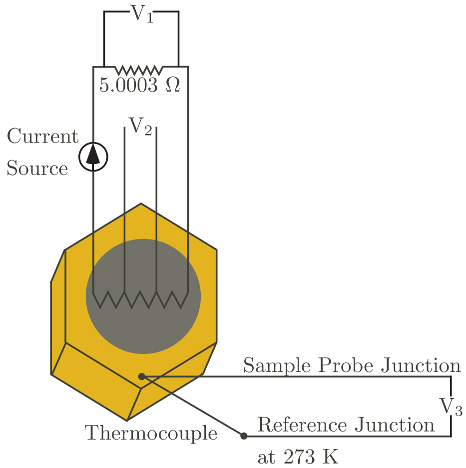

FIG. 4: Diagram of the four-point probe and thermocouple of the superconducting sample.

VIEW program was started taking data and the initial reading of the thermocouple for submersion temperature was recorded. Then the sample was gently removed and suspended just above the surface of the liquid nitrogen to warm slowly. When the graphical output of the LabVIEW program indicated that the sample was no longer superconducting the program was shut off and the data saved. The process could then be repeated to collect more data.

V. ANALYSIS

A. Data Analysis

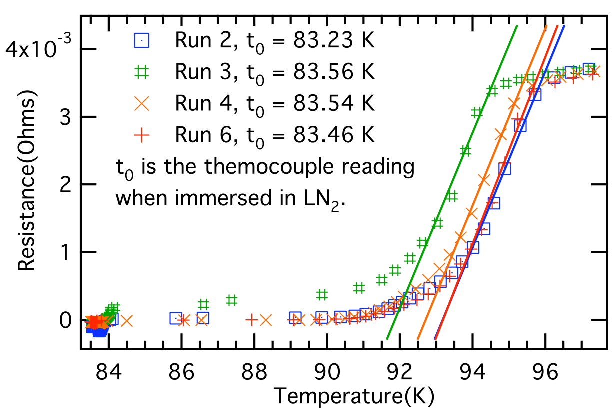

FIG. 5: Plot of resistance versus temperature of the superconductor for runs 2, 3, 4, and 6.

Due to the fact that the LabVIEW program outputted tables of temperature and resistance data the analysis was very easy to perform. The text files that were saved were imported into Igor Pro and plotted for all runs, shown in figure 5. On every run there was a distinct change in the resistance as the critical temperature was approached. However, it was noted that before each run the temperature t_0 measured by the thermocouple was not completely consistent. Instead of being the 77.35 K it should have been it was 80.38 K for the first run and just over 83 K for runs 2, 3, 4, and 6. Run 5 was eliminate from analysis as it was taken with the reference junction of the thermocouple at room temperature instead of 273 K.

With our data narrowed down the critical temperature for our four valid runs by fitting lines to the points of data where the rapid change in resistance occurred. The x-intercept values of these lines were then found and taken to be the critical temperature found for each run, table I, similar to the idea of figure 2. Then all of the intercept values were adjusted by the difference between boiling point of liquid nitrogen and the submerged temperature. The mean and standard deviation of these adjusted critical temperatures was then found to be 86.6 ± 0.6 K and taken as the best fit for our value of the critical temperature with an error of the standard deviation of the values.

TABLE I: Original and Adjusted Critical Temperature of Runs

Run #	Original (K)	t_0 (K)	Adjustment (K)	Adjusted Temp (K)
2	93.17	83.23	5.88	87.29
3	91.87	83.56	6.21	85.66
4	92.71	83.54	6.19	86.53
6	93.18	83.46	6.11	87.07
Mean	92.73			86.62
Std. Dev.	0.6			0.6

B. Error Analysis

The largest concern for this experiment is the offset of the thermocouple reading when the sample is submerged in liquid nitrogen, the consistent six degrees off is not reassuring. Above we assume that the difference is linear and simply lower the final temperature we found by approximately 6 K depending on the initial temperature of the run. This adjustment may not be completely correct as LabVIEW program used a higher order polynomial to change the thermocouple voltage into a temperature but the 0th and 1st orders of the polynomial dominate the equation so it is a good approximation. Also, the thermocouple in fact may be reading the right temperature, the sample may not be making it all the way down to 77.35 K. Only the brass case and some of the surface of the superconductor sample is in contact with the liquid nitrogen and though we wait for the boiling to subside as an indication of thermal equilibrium the center of the superconductor may not be 77 K because of imperfect heat transfer. Furthermore the boiling never fully goes away, it does reduce drastically but a low bubbling continues indefinitely. This low bubbling may be an artifact of the wire connecting the 77 K system to the room temperature sensor systems and therefore adding heat to the system.

Also of note is the fact that error has not been propagated through the calculations done by the LabVIEW program. Error propagation was not done because there is a spread in the final critical temperatures found for the different runs. The standard deviation of the critical temperature was taken to be sufficient for error purposes. This results in a precise value for the critical temperature of YBCO that may or may not be accurate. Therefore we consider the spread in the adjustments of the runs as another measure of error in the system, and add the standard deviation of 0.5 of the adjustments to the standard deviation of the adjusted temperatures to get our error.

Finally, the fact that this superconducting sample may not be perfect must be taken into account. It has been in use since spring of 2007 and may no longer be as good condition as it once was. Even then it is rare for a superconductor to be perfectly pure and exhibit the highest critical temperature. This would be 95 K for a YBCO superconductor. An imperfect superconductor would have a lower critical temperature, in addition to the curved resistance plot above. Therefore the 93 K was taken as the accepted value of the critical temperature of YBCO, from the *CRC Handbook of Chemistry and Physics*[1].

VI. CONCLUSION

While there are large concerns about the accuracy of the thermocouple used in this experiment there is no doubt that both superconductivity and the critical temperature cut off were observed. The critical temperature of a YBCO superconductor was found to be 86.6 ± 1.1 K, a 7% difference from the accepted value of 93 K for the critical temperature. Given the unknown condition of the superconducting sample and thermocouple issues this small divergence from the known value is completely believable.

VII. ACKNOWLEDGMENTS

I would like to thank Dr. Lehman, Kelly Patton, and Mark Wellons for their assistance in this lab. I would also like to thank the person or persons who wrote the LabVIEW program that I used, who names are not listed in the program.

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