Determining the critical temperature of $YBa_2Cu_3O_7$ superconductor by using a four-point probe and type-T thermocouple

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This paper investigates the critical temperature of type-II, $YBa_2Cu_3O_7$ superconductor. The superconductor was submerged in liquid nitrogen until thermal equilibrium was achieved at 77 K. At this temperature, the material has zero resistance. By using a four-point electric probe and a type-T thermocouple, and by passing a current through the superconductor, the resistance and temperature was recorded as the superconductor was warming up. The resistance along with the derivative of the resistance as a function of temperature was analyzed to determine the critical temperature of the material. The critical temperature of $YBa_2Cu_3O_7$ superconductor was measured to be $T_c = 108.1 \pm 0.8$ K , which is 14% from the accepted value of $T_c = 93$ K.

I. INTRODUCTION

Superconductivity is a phenomenon of zero resistivity and the expulsion of the magnetic fields in materials that are cooled below a certain temperature known as critical temperature. This phenomenon was first discovered in 1911 by Heike Kamerlingh Onnes while investigating the electrical proprieties of metals at low temperatures. Using liquid helium as a coolant, he found that mercury had zero resistance at temperatures below 4.2 K. In 1986, researchers discovered that ceramics from class of perovskites are superconductors at 32 K [1]. Further research resulted in materials with superconductive proprieties at temperatures bellow 100 K. This allowed to change the coolant from liquid helium to liquid nitrogen. This was an important change, since nitrogen is abundant in nature and is easy to collect and condense, making it more cost effective.

This paper focuses on the superconductive proprieties of $YBa_2Cu_3O_7$ (YBCO), by finding the critical temperature of the ceramic material. The critical temperature is considered to be the temperature at which materials transform from normal conductors to superconductors. Ideally, this change occurs instantaneously in superconductors, but in imperfect superconductors, the transition is more gradual. This experiment uses liquid nitrogen (boiling point at $T_B = 77$ K) as a coolant for the YBCO ceramic material.

II. THEORY

Superconductivity cannot be considered an extension of the normal electrical conductivity for a couple of reasons. The theory of electrical resistance suggest that all conductors should experience finite resistivity at absolute zero due to the impurities and imperfections in their structure. The discontinuous change in resistance at the critical temperature cannot be explain with conventional theory, and the expulsion of the magnetic field below the critical temperature, known as the Meissner effect, is not a direct result of zero resistivity. This suggests that electrons in a superconductor do not behave the same as in a normal conductor. A theory explaining superconductivity was proposed by Bardeen, Cooper and Schrieffer in 1957[2][4]. The BCS theory rests on the assumption that electrons form Cooper pairs. At absolute zero, the ions in the material are stationary. As an electron moves through the lattice consisting of positive ions, the attractive forces between opposite charges results in a slight distortion of the lattice. A higher concentration of positive charges is achieved, thus making it possible for a second electron to be attracted to this region. A pair of electrons moving at a same speed in opposite directions is created. The pair possesses less energy then compared with a pair of normal conduction electrons. The formation of Cooper pairs allows free movement of electrons, therefore making superconductivity possible [4]. There are two types of superconductors, Type-I and Type-II. Type-II differ from Type-I superconductors by possessing a higher critical temperature [3]. Although the BCS theory explains many phenomenon related to superconductivity, it fails to predict the critical temperature at which the material transitions to a superconductive state.

III. PROCEDURE

A. The Four-Point Probe

The resistance as a function of temperature was measured across the YBCO superconductor using a four-point probe. A graphical representation of the four-point probe along with the superconductor is shown in Fig. 1. The four-point probe measures the potential difference across the resistor in between probes 2 and 3 by using a Keithley 2000 digital multimeter when a constant current is supplied from a Kepco Current regulator across probes 1 and 4.

A close examination of the circuit diagram of the four-point probe shown in Fig. 2, indicates that the contact resistance, as the probes pass through the superconductor, can be neglected.

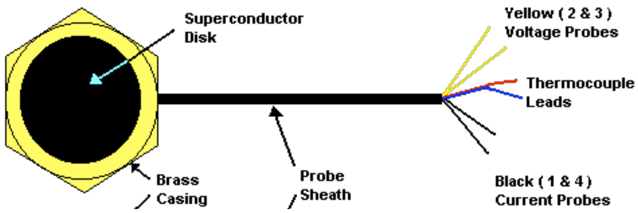

FIG. 1: Schematic representation of the four-point probe along with the YBCO superconductor in the brass casing.

B. Cooling and Data Collection Process

Liquid nitrogen ($T_B = 77$ K) was used to cool the superconductor. The coolant was poured into a dewar and the superconductor was fully submerged until thermal equilibrium was reached. The YBCO superconductor was then raised just above the surface of liquid nitrogen and allowed to warm up. The temperature and the resistance of the superconductor were monitored. Data were collected at current values ranging form 10 mA to 500 mA. The data from the multimeter were recorded in LabVIEW and then exported in IgorPro for further analysis.

C. Measuring the Temperature of the Superconductor

During data collection, the temperature of the superconductor was recorded by a type-T thermocouple. One junction of the thermocouple was introduced in ice-water

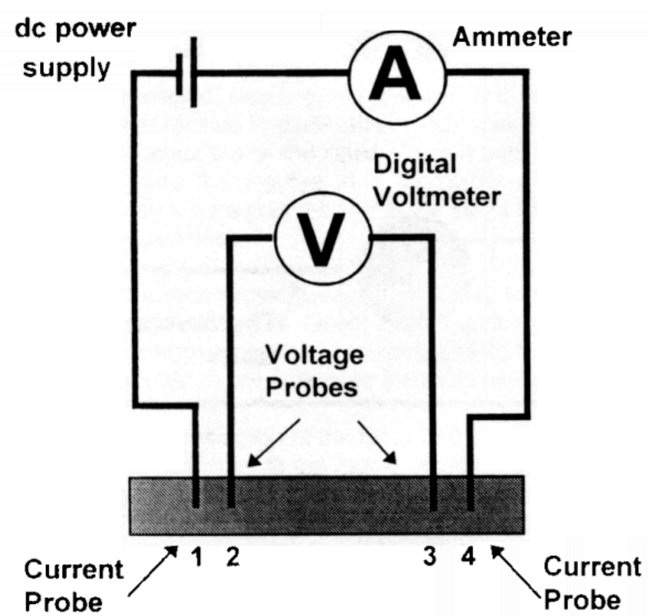

FIG. 2: Circuit diagram of the four-point probe. A digital multimeter was used to measure the current and the voltage.

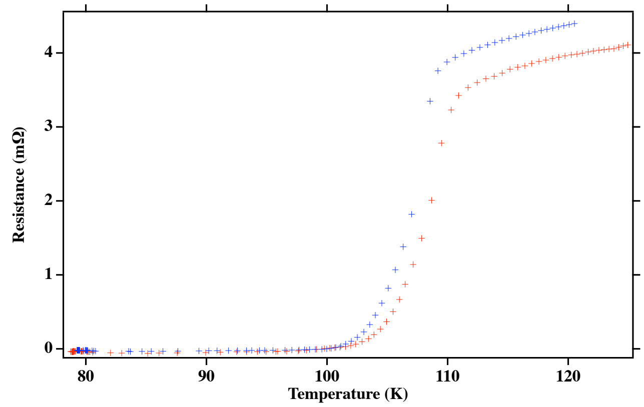

FIG. 3: Graph describing the resistance as a function of temperature. The red data were taken using a current of 200 mA, while the blue data were collected using a current of 400 mA.

and the other one was located in the brass casing of the superconductor. The thermocouple measures the potential difference across two different metals and since metals possess different potential differences across the contact point, the thermocouple is designed for specific temperature ranges. For this experiment a thermocouple consisting of a copper-constantan junction was used. By maintaining the ice-water at a constant temperature of 273 K, LabVIEW was able to record the temperature difference between the superconductor and the ice-water.

IV. RESULTS AND ANALYSIS

LabVIEW outputted a table with the resistance values of the superconductor at different temperatures in a text file, which was imported in IgorPro for analysis. A plot of resistance as a function of temperature is shown in Fig. 3. In order to calculate the critical temperature of the YBCO superconductor, a line can be fitted to the data points where the rapid change in resistance occurs. The x intercept of the line fit can be considered the critical temperature of the superconductor.

Since it is unclear which data points should be included in the line fit, this method was not used in this experiment. Instead, the resistance was differentiated with respect to the temperature and then plotted against the temperature as shown in Fig. 4. A Gaussian fit function was used to model the data and the inflection point was taken to be critical temperature. The values for the critical temperature of the YBCO superconductor for different current values are shown in Table. I.

The data do not show a dependency between the critical temperature and the value of the current. The critical temperature of the YBCO superconductor was calculated to be $T_c = 108.1 \pm 0.8$ K, which is in 14% from the accepted value of $T = 93$ K. The uncertainty was calculated as the standard deviation of the data.

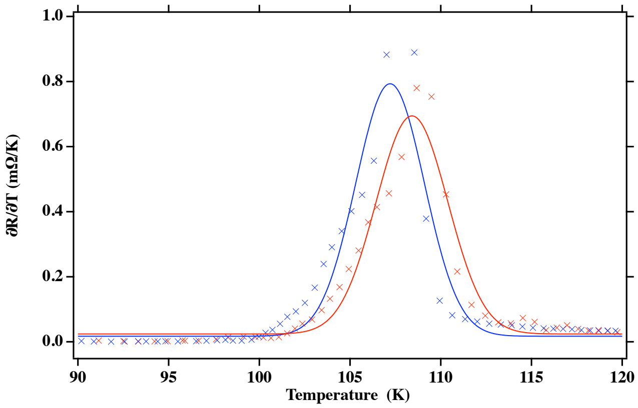

FIG. 4: Graph describing the derivative of resistance as a function of temperature, $\partial R/\partial T$ vs T along with a Gaussian fit. The red data were taken using a current of 200 mA, while the blue data were collected using a current of 400 mA.

TABLE I: Value of the critical temperature of the YBCO superconductor for varying current.

Current (mA)	Temperature (K)
10	108.5 ± 1.0
50	108.2 ± 0.2
200	108.5 ± 0.1
400	107.7 ± 0.5
500	107.3 ± 0.3

V. RESISTANCE BEHAVIOR FOR LOW CURRENT VALUES

An interesting behavior of the resistance was noticed at low value current. As soon as the superconductor starts to warm up, without reaching its critical temperature, the resistance slightly increases above 0 Ω and then drops to a negative value. Such a behavior is shown in Fig. 5. This phenomenon is not currently understood and needs to be investigated. The "dip" was noticed fade away when the current reached values above 50 mA. Due to limited time, this phenomenon was not covered in this experiment, but further investigation is encouraged.

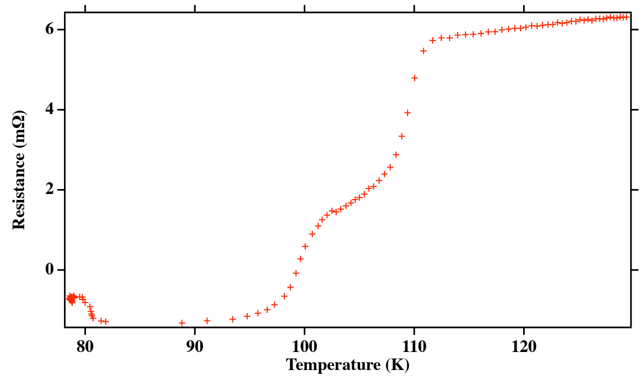

FIG. 5: Graph showing the unusual behavior of the resistance as a function of temperature at low current. For this run the current had a value of 10 mA.

VI. CONCLUSION

This experiment yielded a value of $T_c = 108.1 \pm 0.8$ K for the critical temperature of the YBCO superconductor which is in 14% from the accepted value. There are a couple sources of error. The inflection point of the Gaussian fit used in the $\partial R/\partial T$ vs T data is not the exact critical temperature, it is rather a point where the superconductive proprieties are already lost. Another source of error can be due to the thermocouple. A systematic shift in the value of the critical temperature might be present since the temperature of the ice-water was not exactly 273 K at all time, due to the melting of the ice. Lastly, another source of error can be considered the age of the superconductor. The YBCO superconductor might have lost some of its original proprieties. An improvement to this experiment can be achieved by thermally isolating the experimental setup and by finding a better method for determining the critical temperature of the superconductor. An extension to this experiment is studying the behavior of resistance at low current values, smaller than $I = 50$ mA.

VII. ACKNOWLEDGMENTS

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