Measuring the Critical Temperature of a High Temperature Superconductor

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The critical temperature (T_c) for both a cooling and heating process of a $YBa_2Cu_3O_7$ ceramic superconductor were investigated. The results of this experiment yield a range of T_c= 86 to 100K for the cooling process, and a range of T_c= 89 to 98K for the heating process. Both ranges are very close to the accepted T_c value, with the published value (93K) located near the center of the determined ranges. This experiment does a very good job in illustrating the basic properties of a SC. However the drop in resistance to a negative value when the SC is warming, but slightly below T_c, should be further investigated, as this drop in resistance is not completely understood at the current time.

INTRODUCTION

Most ordinary materials are normal conductors, which means whenever electrical current flows through these materials, there is some resistance to the motions of the electrons[1]. This effect is barely noticeable with ordinary every day applications of current conduction. However, when trying to push a large amount of current through power lines for instance, the resistances are so high a large voltage must be applied across the lines in order for the proper current to flow. This can be quite problematic.

Imagine now a material that has no electrical resistance, and that could carry current indefinitely without requiring voltage expenditure for electricity[1]. In recent years, there has been a dramatic increase in the research for such a material, called a superconductor (SC).

Superconductivity has been a uniquely fascinating branch of physics for nearly a century. However, practical applications of these zero resistance conductors have been practically non-existent. This is mainly due to the fact that superconductors (SC) must be kept at extremely cold temperatures in order to function, 30K or less initially.

In recent years an exciting new type of SC has been developed: the high temperature superconductor (HTSC). These HTSC's are refrigerated in liquid nitrogen and can operate in higher temperatures, upwards of 130K. The relatively high operating temperatures in combination with the inexpensive cost of liquid N_2 makes HTSC's exciting to study. The development of the HTSC has made superconductivity practical.

The new HTSC's are oxides that contain the crucial transition element copper, such as the ceramic SC that will be studied in this experiment: $YBa_2Cu_3O_7$. The key to better understanding the copper-oxide SC is the Bardeen-Cooper-Schrieffer (BCS) theory of conventional superconductivity. The BCS theory is based upon the existence of an attractive interaction between electrons that will form a two-electron bound state, called a Cooper pair[2]. The BCS theory assumes the formation of Cooper pairs via an electron-electron attractive potential[2]. When electrons form these Cooper pairs and move through solids such as a copper-oxide, they are immune to energy loss[3]. The important idea from the BCS theory is the understanding that the copper-oxide solid must reach a critical temperature (T_c) in order to form Cooper pairs[3]. When this critical temperature is met, the solid will begin to superconduct.

The critical temperature is defined as the highest temperature at which the solid remains superconducting[1]. Through a process that slowly cools and warms the ceramic from room temperature to thermal equilibrium with liquid N_2 (and back), T_c can be indirectly measured by identifying the point at which the resistance goes to zero, and hence the ceramic superconducts.

EXPERIMENT

The procedure used in this experiment was fairly straightforward. Using a liquid Nitrogen bath, a $YBa_2Cu_3O_7$ ceramic was slowly cooled until it reached a superconducting state. The ceramic was gradually heated by slowly raising it up out of the bath, and warming back above T_c. The rate at which the SC was cooled and heated was controlled manually using string wrapped around a rod, which was connected to the SC apparatus.

A circuit, as shown in figure below, was constructed in order to take specific measurements. Using a four point electrical probe, the current through the SC as well as the resistance could be accurately measured without the two measurements interfering with one another. The SC was from Colorado Superconductors Incorporated (CSI), and was specially designed to be used with a four-point probe set-up.

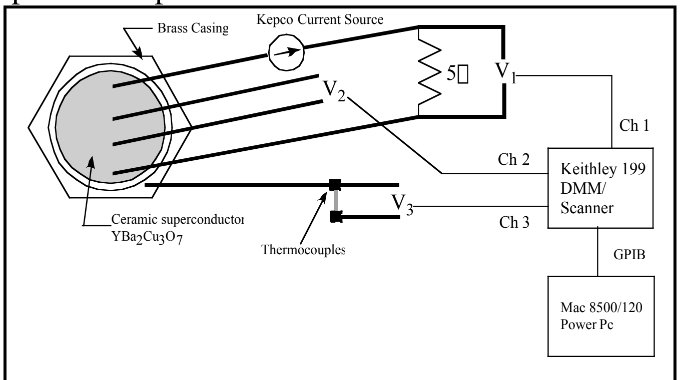

Figure 1 shows the complete set-up as was used in this experiment. Here V_1 measures the current through the circuit, V_2 measures the resistance across the ceramic SC, and V_3 measures the temperatures via a thermocouple.

Measurements of the circuit's total current (V_1), the SC's resistance (V_2), and the SC's temperature (V_3: thermocouple of copper and constantan) were recorded as the SC was cooled and heated. All of the measurements were taken with a Keithley 199 DMM/Scanner via its different channels. A LabVIEW program was used to collect the data and make the appropriate calculations.

The collected data was then plotted and analyzed. The analysis produced a calculated critical temperature (T_c) at which the ceramic started to superconduct. The measured T_c was then compared to both theoretical conjecture and other experimental determinations.

DATA

Figures 2 and 3 show the plotted data acquired from this experiment. Figure 2 shows the relation of SC resistance versus time, and figure 3 demonstrates the relation of SC resistance versus temperature. The temperature was calculated using a thermocouple, with one end connected to the SC apparatus and the other at room temperature. Using a linear extrapolation, the analysis of the collected data yielded a result of T_c=86±13K for the SC cooling, and a determined range between 89 and 98K (94±4K) for the heating of the SC.

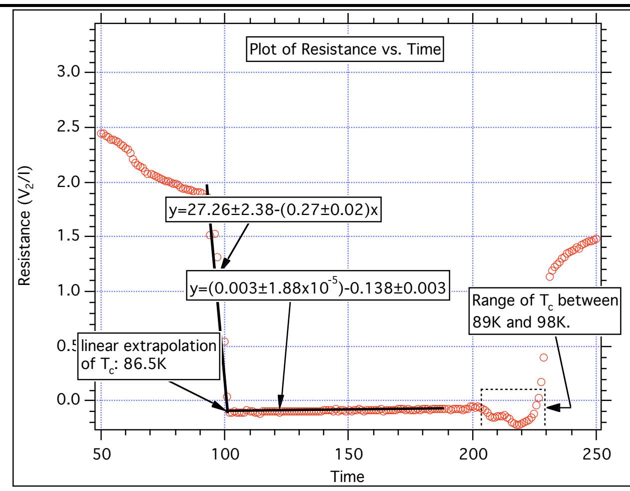

Figure 2, shows the plot of SC resistance versus time. Using a linear extrapolation, the analysis of the collected data yielded a result of T_c=86±13K for the SC cooling, and a determined range between 89 and 98K (94±4K) when heating the SC. The cooling process is the left side, and the heating process is to the right side.

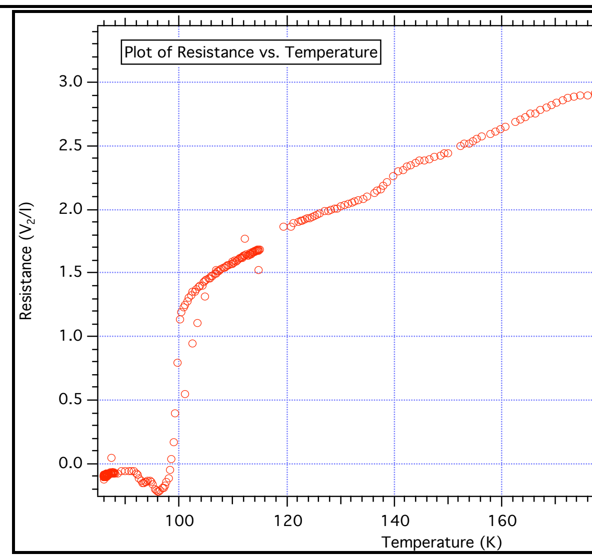

Figure 3 is a plot of SC resistance versus temperature. This plot demonstrates the small hysteresis of the system, as the data points for the heating and cooling process lie upon one another.

ANALYSIS AND INTERPRETATION

The investigation of the collected data from this experiment yielded a result of T_c=86±13K for the SC cooling, and a range between 89 and 98K (94±4K) for the heating of the SC. Both the T_c values for the heating and cooling are close to the accepted value, as the accepted value lies within the experimental uncertainty. The published value[1,2,3] for T_c for a $Yba_2Cu_3O_7$ ceramic SC is 93K, and the experimentally calculated values are within 7.5% of that accepted value.

The determination of the T_c for the cooling process was first done through a linear extrapolation of the slopes before and after the point at which the ceramic began (definitively) superconducting. This extrapolation method, shown above in figure 2, was first chosen because the slopes near the transition point (before and after) appear to be constant. Uncertainty in this calculation resulted from the temperature dropping faster than the experimental set up could take measurements, and hence the linear extrapolation method is not completely accurate. The large gaps between data points taken right before the transition point indicate that the temperature was dropping very rapidly. This resulted in fewer data points around the critical temperature. Therefore, a range was determined around the calculated T_c, in order to more accurately characterize the transition. The T_c is located in a range from 86 to 100K, as it is certain that at 86K the ceramic is superconducting and at 100K it is certain that the ceramic is not superconducting. This is evident because at 100K the resistance is still well above zero and therefore not superconducting. Conversely at 86K the resistance holds constant at zero, indication that superconducting is taking place. Due to the certainty of the boundaries of the range, it was decided that the range method for determining the T_c was better that a linear extrapolation.

The same range method used for the cooling process was again used to determine the T_c of the heating process. The range for the T_c for the heating process was determined to be between 89 and 98K. This range again shows nice agreement between the experimental results and the accepted value. However, an interesting phenomenon had occurred as the SC was heated. As the SC was slowly raised out of the liquid Nitrogen bath, a small drop in the SC resistance to negative values is observed around the T_c. Although it is not completely certain why this occurs in this experiment, a few thoughts have been entertained.

The main reason that is believed to cause this dip in resistance is a thermocouple interaction between the ceramic SC and the brass casing. This interaction will produce an unmeasured potential that will, however, affect the experimental measurements. It is estimated that the thermocoupling interaction between the copper-oxide and brass may be roughly about $1\mu V/K$[4]. With the maximum values of the measured potential across the V_2 being a few millivolts, the thermocoupling between the ceramic and brass might lead to quite a bit of uncertainty. If the thermocoupling interaction between the ceramic and brass is greater than $1\mu V/K$, the uncertainty will be even greater with respect to the measurement of V_2.

Another source of uncertainty in this experiment is the fact that that the thermocouple is essentially measuring the temperature of the brass casing instead of the ceramic SC. With this, it can never be completely certain that what the measured temperature reads is the actual temperature of the ceramic. By giving the ceramic and brass sufficient time to come to thermal equilibrium, the effects of this are thought to be minimized through cooling and heating the SC very slowly. However, this cannot be completely guaranteed.

CONCLUSION

In conclusion, the T_c for both a cooling and heating process for a $YBa_2Cu_3O_7$ ceramic SC were investigated. The results of this experiment yield a range of 86 to 100K for the cooling process, and a range of 89 to 98K for the heating process. Both ranges are very close to the accepted value, with the published value (93K) located near the center of the estimated ranges. This experiment does a very good job in illustrating the basic properties of a SC. However the drop in resistance when the SC is warming should be further investigated, as this drop is not completely understood at the present time.

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