Analyzing Critical Temperatures Qualitatively and Quantitatively for High-Temperature Superconductors

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Superconductivity is a unique quantum mechanical effect where certain materials exhibit zero resistance below a critical temperature (T_c). This experiment observes these properties by manipulating two high-temperature superconductors (HTSC), YBCO and BSCCO, analyzing their behavior through the Meissner effect, resistance versus temperature comparison, and critical temperature measurements at differing currents. Using liquid nitrogen (LN) as our coolant, conditions were created to simulate the Meissner effect. Furthermore, the critical temperatures of the HTSC materials were observed using both magnetic field expulsion and four-probe measurements, experimentally $104 \pm 2K$ for YBCO and $128 \pm 6K$ for BSCCO. The dependence of T_c on current was analyzed, highlighting the impact of increased current on damping the effect of superconductivity. Using T_c at four different amp levels, extrapolation was used for $T_c = 77K$ to find $I_c = 1.74 \pm 0.08A$.

Introduction

The discovery of superconductivity was first observed by Heike Kamerlingh Onnes in 1911, marking a milestone in condensed matter physics by revealing that certain materials exhibit zero electrical resistance below a critical temperature (T_c). This observation remained unexplained until 1957, when Bardeen, Cooper, and Schrieffer (BCS) developed a quantum mechanical theory describing superconductivity, known as Cooper pairs, which allow electrons to move through the lattice without resistance.

A fundamental characteristic of superconductors is the Meissner effect, discovered by Meissner and Ochsenfeld in 1933, which explains the outward expulsion of magnetic fields, allowing for magnetic levitation. This effect is utilized in modern technology, including MagLev trains, MRI machines, ultrasensitive magnetometers, and high-efficiency power transmissions.

High-temperature superconductors (HTSC) were discovered in the 1980s, making real-world applications more practical, as these materials exhibit superconductivity above the boiling temperature of liquid nitrogen (77 K). In this experiment, YBCO and BSCCO, two HTSC materials, are studied by observing magnetic levitation due to the Meissner effect, critical temperature and resistance-temperature analysis, and current fluctuation observations of superconducting behavior.

Theory

Superconductors exhibit zero electrical resistance and expulsion of magnetic fields below a critical temperature (T_c). BSCCO ($Bi_2Sr_2Ca_2Cu_3O_{10}$) and YBCO ($YBa_2Cu_3O_7$) belong to a class of superconductors called high-temperature superconductors (HTSC). Unlike conventional superconductors that require cooling to 4.2 K with liquid helium, HTSC transition to a superconducting state can be achieved using liquid nitrogen, which can efficiently cool materials to 77 K.

A defining property of superconductors is the Meissner effect: when cooled below their critical temperature, they expel all magnetic fields. This effect is correlated with the formation of a super current on the surface, which generates a counteracting magnetic field. The result is a state of perfect diamagnetism, meaning the superconductor does not allow magnetic field penetration.

The superconducting current density (J_s) is described by the London equations, formulated by Fritz and Heinz London in 1935.

$$\frac{dJ_s}{dt} = \frac{n_s e^2}{m_e} E \tag{1}$$

Relationship between superconducting current and magnetic field (B).

$$\nabla J_s = -\frac{n_s e^2}{m_e} B \tag{2}$$

Combined with Ampere's Law, this leads to the concept of penetration depth (λ), which describes the depth to which an external magnetic field can penetrate a superconductor before being expelled.

$$\lambda = \sqrt{\frac{m_e}{\mu_0 n_s e^2}} \tag{3}$$

One of superconductors fundamental features is the share drop of residence at (Tc). For any temperature above this point, the material exhibits normal metallic resistance due to electron scattering from lattice vibrations. Below (Tc) electrons form Cooper pairs which move without resistance where (Ro) is the normal state resistance.

$$R(T) = \begin{cases} R_0, & T > T_c \\ 0, & T < T_c \end{cases} \tag{4}$$

The four-point probe method measured resistance as a function of temperature. The sharp transition from finite residence to zero resistance is used to determine the (Tc) values for YBCO and BSCCO.

Superconductors can carry a finite amount of limited current before they lose their superconducting state. The maximum current it can sustain before resistance rappers are known as the critical current (I_c) . This occurs as excessive current disrupts cooper pairs, breaking the superconducting state. The relationship between critical current and critical temperature is shown as.

$$T_c(I) = T_{c0} - mI \tag{5}$$

Experiment

A setup was designed to investigate high-temperature superconductors (HTSC) by observing the Meissner effect qualitatively, measuring the critical temperature based on two techniques, and determining the critical current. The Meissner effect is demonstrated by placing a BSCCO superconducting (SC) disc in a styrofoam recess and cooling it using liquid nitrogen (LN). A small cubic magnet is carefully placed on the SC disc, levitating due to the exclusion of the magnetic field. The magnet's behavior is examined by testing side-to-side motion to detect resistance and spinning to illustrate nearly frictionless motion. Trials were then conducted for a cylindrical magnet for comparison. A final test was conducted to quantitatively measure how long the magnet levitates before dropping as the SC warms past its critical temperature (T_c).

The subsequent step is to measure the critical temperature (T_c) using the Meissner effect more precisely. A YBCO four-point probe is utilized for this for accurate temperature monitoring. The probe wires are used to measure the temperature, current, and voltage. The SC probe is cooled to 85K using LN. A cubic magnet is then suspended above the SC, its behavior is observed while recording the SC voltage drops to pinpoint the temperature at which the critical temperature (T_c) of the superconductor is reached. This process is repeated three times for both the YBCO and BSCCO four-point probes to ensure accurate measurements.

To complement this method, a second technique is used to determine (T_c) based on resistance measurements. This secondary approach utilizes a cryostat system, consisting of an insulated mug, an aluminum can, and quartz sand to provide proper thermal insulation to isolate the reaction. For the secondary process, only the BSCCO four-point probe is tested. The wire of the probe is threaded through the lid of the insulated apparatus. LN is then poured into the apparatus until the SC reaches a temperature (85K) or 6.1mV on the thermocouple temperature reading. A constant current of 0.12A is applied, and voltage readings are taken incrementally as the system slowly warms up. These thermocouple and SC voltage readings are translated to track the given resistance variations as the temperature rises every (0.05mV) step change. The critical temperature is determined based on the point where the SC transitions out of the superconducting state at a temperature reading of (130K) or 4.4mV.

This setup is applied and redone for differing current levels applied progressively more during the different trials at 0.21A, 0.33A, and 0.42A. Higher currents lower the critical temperature (T_c) of the SC. The SC and thermocouple voltages are recorded for each trial and plotted against each corresponding trial. Continuous voltage and temperature readings allow for the characterization of the relationship between current load and loss of superconductivity. The probe is always kept below 0.5A so as not to damage the SC probe for future experimental testing.

Analysis

The Meissner effect was simulated by utilizing a BSCCO SC disc submerged in LN. The LN boiling subsided before the SC was tested for different qualitative observations. Plastic tweezers were used to place both a cubic and cylindrical magnet onto the separately cooled SC disc. The cubic magnet, when suspended, levitates in the center of the SC disc. The critical temperature is reached qualitatively by the expulsion of the agent from the locked magnetic field.

The cubic magnet, when placed, moves around the SC disc with ease as a result of its discrete edges and flat surfaces. When spun along its principal axis, the magnet moves as its magnetic dipole aligns relative to the SC disc. The shape's principal axis doesn't block the rotation of perpetual spinning due to instability in the locking of the SC disc's magnetic field, which exhibits superconductive properties. Spinning continues until thermal losses reduce the superconducting effects once the critical temperature of the SC disc is reached.

The cylindrical magnet doesn't have as well-defined a stable axis to rotate, causing the edges of the cylinder to be more easily locked within the SC disc's magnetic field. The cylindrical magnet also has a larger contact area with the SC disc, causing movement to require greater external force compared to the cubic magnet. The lack of defining edges creates an uneven distribution of forces when spinning, leading to a more halted movement pattern when externally spun or moved. The long axis of the cylinder prevents rotation around the stable axis, inhibiting the rotation of the cylindrical magnet.

Three separate time trials were run with the cubic magnet to test the length of the BSCCO SC disc that remained below the critical temperature when cooled to the point where the Meissner effect was displayed qualitatively. The trails were timed from the movement the cubic magnet was placed in the interconnected magnetic field to the moment it was expelled from the BSCCO SC disc's area. These values gave us an idea of the time it took for the SC disc to thermally warm back to a nor-

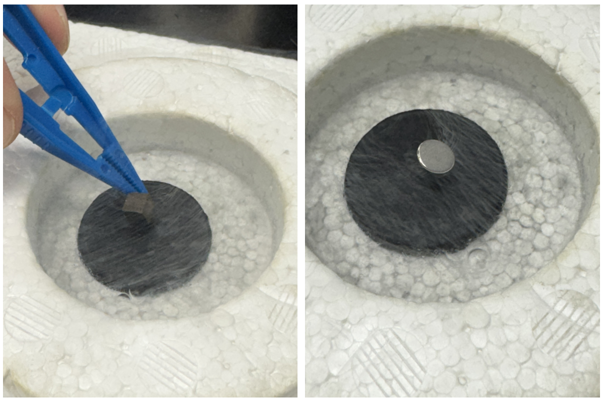

FIG. 1: Left: Cubic Magnet Suspended on BSCCO SC disc — Right: Cylindrical Magnet on BSCCO SC disc

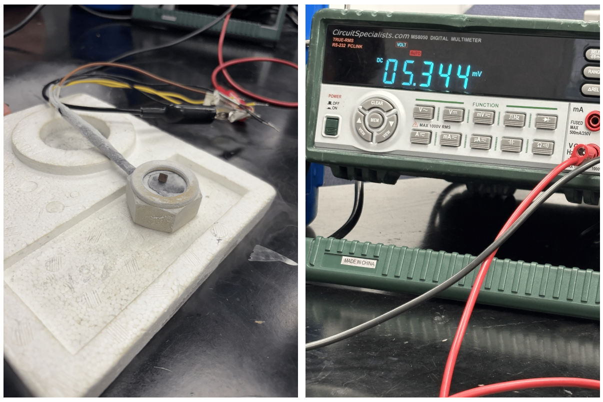

FIG. 2: YBCO Four-Point Probe being measured through a thermocouple with an MS8050 Digital Multimeter

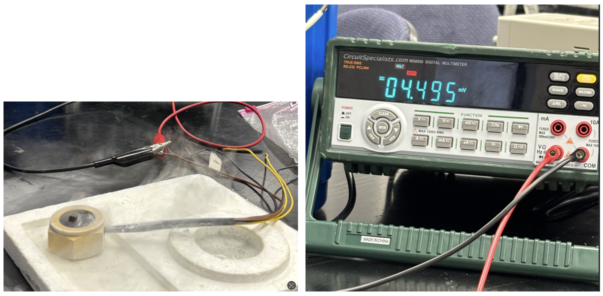

FIG. 3: BSCCO Four-Point Probe being measured through a thermocouple with an MS8050 Digital Multimeter.

mal properties state in a room-temperature environment. The timer used for these trials was an iPhone 15 Pro Max with a precision of 0.01 seconds, meaning the uncertainty in the last decimal place is ± 0.01s.

Trial	**Time (seconds)**
1	61.86 ± 0.01
2	59.64 ± 0.01
3	62.03 ± 0.01

TABLE I: Cubic Magnet on BSCCO SC Disc Time Trials with Uncertainty

This section of the experiment utilized the YBCO and BSCCO SC four-point probes cooled using LN. A precision voltmeter was attached to the thermocouple wires on the individual probes separately to read the TC voltage. They were both cooled to 6.1mV, equivalent to (85K). Following this, a cubic magnet was levitated and placed in the center of the probes, proving the superconducting probes were below their respective critical temperatures. Each probe was observed for three separate trials as it warmed beyond the critical temperature, indicated by the expulsion of the cubic magnet from the magnetic field entanglement.

Uncertainties considered for the measurement reading are given as ± 0.005, as the uncertainty of the MS8050 Digital Multimeter is around ± 0.0045. This conversion of uncertainty was extrapolated to the temperature conversion from mV to K. Plotted in the graph below is the average critical temperature measurement for each YBCO and BSCCO SC four-point probe.

The critical temperature (T_c) of a superconductor acts as the barrier at which the SC transitions to a zero-resistance state due to the formation of Cooper pairs. This phase transition results from electron-phonon interaction, leading to quantum coherence and diamagnetism (Meissner Effect).

In order to measure the critical temperature utilizing resistance, the BSCCO four-point probe was attached to two different MS8050 Digital Multimeters, with one connected to the probe thermocouple cables and the other to the SC voltage cables. As before, the thermocouple was measured in mV and converted to K. This process involved using LN to cool the BSCCO probe down to 6.1mV (85K), measuring its incremental change downward every 0.005mV until it thermally warmed to 4.4mV (130K). This process was thermally insulated using an insulated mug, aluminum can, and quartz sand. This enclosure was created to inject current into the reaction, allowing the resistance (mΩ) to be measured as the BSCCO probe warmed. This relationship utilized $V = IR$, using the SC voltage measured in mV to show this change. The sigmoidal curve for the 0.12A trial was shown indicating the critical temperature was reached at 113 ± 2 K with a Linear Fit and 114 ± 1 K with a Sigmoid Fit. This uncertainty was gathered from averaging the differences in average steps of the point before and after the midpoint critical temperature value to get a rational scope of uncertainty for the measurement.

The BSCCO SC trial at 0.12A yielded a critical temperature of 114 ± 1 K. This compares amicably to the value obtained in the qualitative trials in Part B, yielding a critical temperature of 128 ± 6 K. Taking into account the lack of induced current in the reaction, which causes the critical temperature to be reached at lower temperatures than without, this is a reasonable discrep-

SC	Trials	mV Reading (mV)	Temperature (K)
BSCOO	3	4.646 ± 0.005	128 ± 6
YBCO	3	5.363 ± 0.005	104 ± 2

TABLE II: Average Critical Temperatures T_c for BSCCO and YBCO Superconductors Using Four-Point Probes

ancy compared to analytical values obtained from qualitative tests done by plotting the thermocouple and SC voltage of the BSCCO four-point probe. Adding amps to a superconductor distorts the lattice, disrupting Cooper pair interactions, causing impurities, increasing the electron resistivity, and preventing superconducting properties from being present.

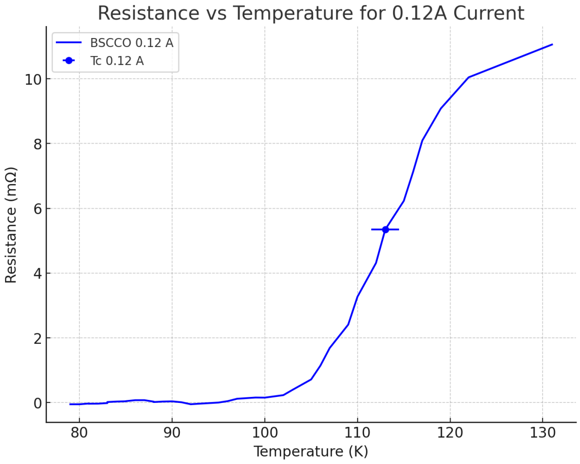

FIG. 4: Linear Fit: BSCCO SC Four-Point Probe Tested for Critical Temperature (T_c) with 0.12A Applied

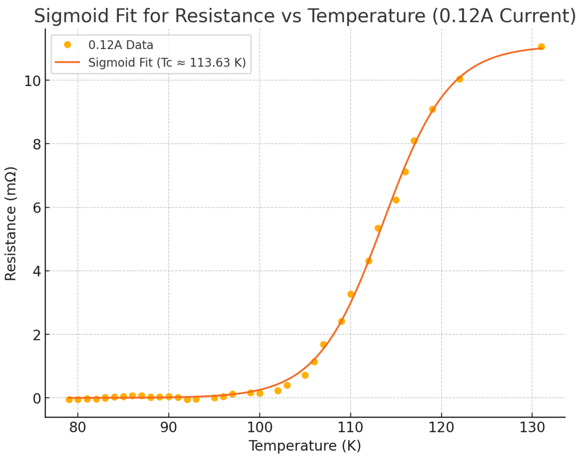

FIG. 5: Sigmoid Fit: BSCCO SC Four-Point Probe Tested for Critical Temperature (T_c) with 0.12A Applied

The BSCCO superconductor (SC) four-point probe was tested three more times, with the only change being the induced current on the reaction, which increased

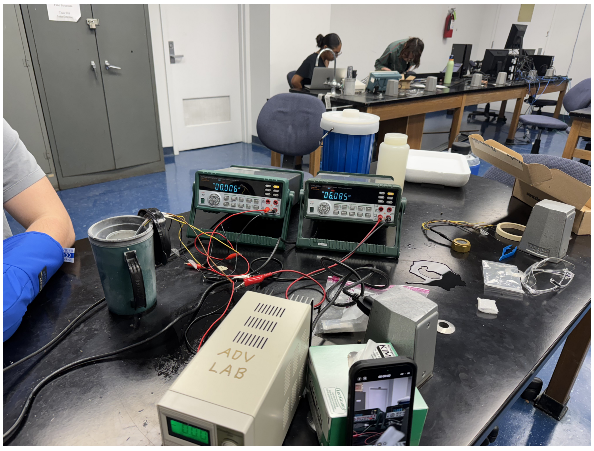

FIG. 6: Setup to Inject Current into the BSCCO Four-Point Probe

from 0.12 A to 0.21 A, 0.33 A, and 0.42 A. Similar to before, these sigmoid thermal warming curves were plotted as resistance (mΩ) versus temperature (K). The critical temperatures from the four different ampere trials followed the expected analytical trend: the critical temperature decreases with higher current.

These critical temperatures were then plotted against current to extrapolate, using a sigmoid fit model, the critical current required to cause the critical temperature T_c to occur at 77K. The critical current I_c is the desired current at which the BSCCO SC transitions from a superconducting state to a normal resistive state at $T_c = 77K$. This temperature corresponds to the boiling point of liquid nitrogen, which is also 77K. The sigmoid fit follows the form:

$$S = \frac{L}{1 + e^{-k(T - T_c)}} \tag{6}$$

where L is the plateau your data reaches, k is the steepness of the curve, and T_c is the critical temperature we are interested in.

Current (A)	Linear Fit T_c (K)	Sigmoid Fit T_c (K)
0.12	113 ± 2	114 ± 1
0.21	111 ± 2	111 ± 1
0.33	109 ± 2	109 ± 1
0.42	107 ± 2	107 ± 1

TABLE III: Measured Critical Temperatures (T_c) at different current values with corresponding voltages

After running an linear fit on the modeled data, it was determined that the critical current I_c is 1.74 ± 0.08 A for the critical temperature $T_c = 77$ K. This model uses a linear regression to find the best-fit line in the form:

$$T_c = T_{c0} - mI \tag{7}$$

where T_{c0} is the y-intercept (critical temperature at zero current), and m is the slope of the line. Substituting

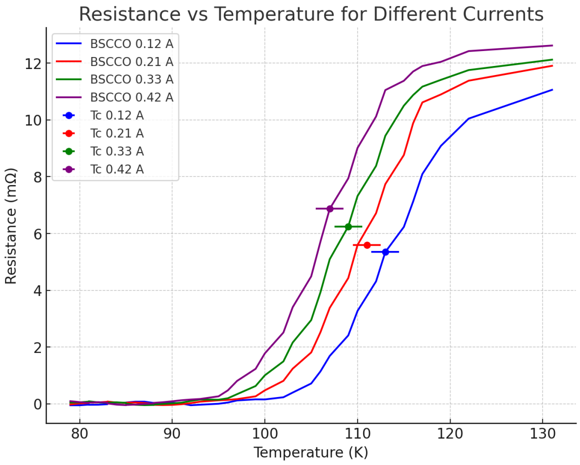

FIG. 7: Linear Fit: Resistance vs Temperature: Mapping T_c at Different Amp Values

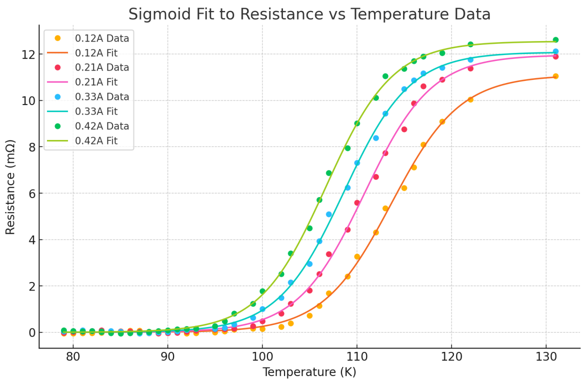

FIG. 8: Sigmoid Fit: Resistance vs Temperature: Mapping T_c at Different Amp Values

$T_c = 77$ K into this equation yields the intersection point, corresponding to the calculated I_c. The slope of the line is -22.36 K/A, and the y-intercept is 115.97 K.

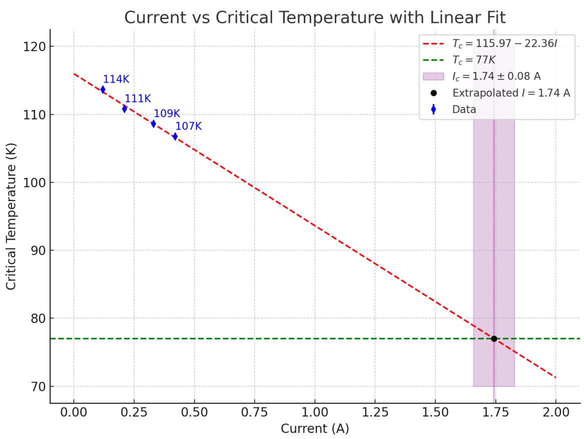

FIG. 9: Current vs. Critical Temperature with Extrapolated Critical Current $I_c = 1.74 \pm 0.08$ A

The critical temperatures of the sigmoid fit differ by approximately 1–2 K from the linear fit calculations. The uncertainties of the linear fit values encompass the sigmoid fit value ranges, which proves that the original linear fit was sufficient to calculate T_c. Furthermore, the critical current differs by approximately 0.22 A; 1.74 A with the sigmoid fit and 1.96 A with the linear fit. Although in general these trends agree qualitatively, the fitting of a sigmoid to the data provides a more precise result in determining I_c, where small differences T_c cause noticeable changes.

Conclusion

The experiment demonstrated the fundamental properties of high-temperature superconductors (HTSC), displaying the Meissner Effect, the resistance versus temperature relationship, and the dependence of the critical temperature on current. The finalized observed critical temperatures for YBCO are $104 \pm 2\,K$ and BSCCO are $128 \pm 6\,K$, which, when compared to the expected values of YBCO $T_c = 105\,K$ and BSCCO $T_c = 128\,K$, show minor discrepancies.

These discrepancies between experimental and expected values can be attributed to impurities in the superconducting samples used, thermal losses, and limitations in voltage measurement accuracy. However, the experimental values, with uncertainties taken into account, fall within the expected ranges for the actual T_c values of YBCO and BSCCO. Additionally, the dependence of T_c on current followed the expected linear trend, confirming that increasing current disrupts the Cooper pair interactions, reducing the superconducting properties at a lower critical temperature as more current is applied. The experimentally determined $I_c = 1.74 \pm 0.08\,A$ at $T_c = 77\,K$.

References

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