Measuring the Critical Temperature of YBCO using the Meissner Effect

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(Dated: December 10, 2008)

Since the discovery of superconducting materials in 1911 by Heike Kamerlingh Onnes scientists have struggled to make superconducting materials with higher critical temperatures. An accurate measurement of the critical temperature of the material is very important to determine where exactly the properties of a material begin or stop being superconducting. We measured the critical temperature of the superconductor, YBCO, by observing the change in potential across coils with a superconductor in between as the temperature changed from 300 K to 77 K. We found the critical temperature of the YBCO sample to be $T_c = 90.6 \pm 2.2$ K (95% CI). This is in agreement with the accepted value of approximately 90 K.[1]

In 1911 Heike Kamerlingh Onnes discovered the first superconductor when he observed that the resistance of solid mercury dramatically dropped off when it reached 4.2 K. Superconductivity can occur in many different materials including tin, aluminum, metallic alloys, semiconductors, and even some ceramic materials. Since Onnes’ discovery there have been numerous superconducting compounds created that combine different superconducting materials.

A superconducting material has many unique properties. These properties, that other conductors do not have, vary with each superconductor. For example in metallic conductors the electrical resistivity gradually decreases as the temperature decreases but eventually reaches some limit. With superconductors the electrical resistance abruptly drops to zero at a certain temperature. This temperature is called the materials critical temperature. In superconductors a small amount of the electrons are bound together in groups called Cooper pairs. At temperatures below the critical temperature the pairs form a single quantum state that allows them to flow without resistance.

At this temperature the material also has another peculiar property. In 1933 Walther Meissner discovered that at critical temperatures superconductors completely cancel all the magnetic flux that is traveling through the material. These properties are caused by surface currents that arise and generate a magnetic field that creates a net zero magnetic field in the material. This effect does however break down when the magnetic field becomes too strong.

In 1957 John Bardeen, Leon Cooper, and Robert Schrieffer developed the BCS theory of superconducting that would later win the Nobel Prize in Physics. This theory explains why Type 1 superconductors behave as they do. In 1986 a superconductor made up of yttrium barium copper oxide, YBCO, was created that reached its critical temperature at a point higher than the boiling point of liquid nitrogen. This new type of superconductors, called Type 2 superconductors, have a higher critical temperature and do not follow the BCS theory. The search for higher temperature superconductors that are more applicable continues on today. Currently superconductors are used for magnets, MRI and NMR machines, particle accelerators and many other things.

We wanted to measure the critical temperature of the superconductor YBCO using liquid nitrogen to cool it. To do this we used the Meissner effect. From Lenz’s Law we know that a current loop will create a magnetic field and when the magnetic field passes through another coil it creates an induced Emf in the wire. When the superconductor is placed in between the coils and it reaches critical temperature there will be no induced Emf due to the Meissner effect. We can then measure the critical temperature by finding where the change in potential in the second coil occurs.

For our experiment we used the setup shown in FIG. 1. We made two coils with $200 \pm 5$ turns of wire with a radius

![FIG. 1: This figure shows the experimental setup we used for the experiment. We have two $200 \pm 5$ (95% CI) turn coil that are separated by a superconducting disk with width $s = 0.42 \pm 0.01$ cm (95% CI) and diameter $D = 2.19 \pm 0.001$ cm (95% CI). We used three different superconducting disks, each with a different width $s$. The coils had radii of $R_{in} = 0.74 \pm 0.01$ cm (95% CI) and $R_{out} = 0.75 \pm 0.01$ cm (95% CI) and a length of $L = 1.01 \pm 0.01$ cm (95% CI). In each coil we epoxied a thermocouple that we used to get the temperature reading of the superconductor.](image-url)
of \( r_{in} = 0.74 \pm 0.01 \text{cm} \) (95% CI) and \( r_{out} = 0.75 \pm 0.01 \text{cm} \) (95% CI). We then epoxied a thermocouple in each coil to read the temperature throughout the experiment. For each data run we inserted one of three YBCO samples between the coils. Each superconducting disk has a slightly different width but the approximate for all is \( s = 0.42 \pm 0.01 \text{cm} \) (95% CI) and has a diameter of \( D = 2.190 \pm 0.001 \text{cm} \) (95% CI). We then connected the transmitting coil, coil \( r_{in} \) with resistance \( R_{in} = 2.2 \pm 0.1 \Omega \) (95% CI), up to the PASCO AC power source, as shown in FIG. 2. We then connected the receiver coil, coil \( r_{out} \) with resistance \( R_{out} = 2.0 \pm 0.1 \Omega \) (95% CI) to a lock-in detector to eliminate white noise and allow for a better measurement. We also connected the transmitter coil to the lock-in. We then connected the lock-in detector to an oscilloscope and LoggerPro to measure the change in potential.

For each data run we chose a YBCO sample and placed it between the coils and secured it. We then set a driving potential of 2.0 V through the transmitter coil and started the data collection. We took data for approximately 120 seconds at room temperature of 300 K and then submerged the entire two coil apparatus in liquid nitrogen. We then left the apparatus there until in reached equilibrium at 77 K. We then removed the apparatus and allowed it to heat up to room temperature. We averaged the temperatures from the two thermocouples to get the temperature during the process. We repeated this process 15 times with three different YBCO samples.

We then went through our trials and found the temperature where the potential abruptly changed, as shown in FIG. 3. We should note that the potential did not decrease all the way to zero. This is due to the fact that some of the induced Emf goes around the edges of the superconducting disk. The change happened over a range of temperatures so we took the average of the temperatures where the the potential change occurs.

We then had to calibrate the thermocouples so that we got an accurate value. We took measurements of five different temperatures and plotted the accepted value versus the measured value, as shown in FIG. 4. We used

\[
\text{Actual (K)} = \frac{\text{Measured (K)}}{1.05}
\]

FIG. 3: The graph shows the change in potential over time as the temperature changes. The abrupt changes in potential is where the material transitions to a superconducting material and where we can find the critical temperature.

FIG. 4: The graph shown in this figure is the temperature calibration for the thermocouples. We measured the temperatures of room temperature, an ice water bath, a hot water bath, dry ice in acetone, and liquid nitrogen. We then plotted the accepted values against the values that the thermocouples measured in Kelvin. We then found the best fit and used the equation, Eq. 1, to find the calibrated critical temperature measurement.

room temperature, an ice water bath, a hot water bath, dry ice in acetone, and liquid nitrogen to calibrate. We
then applied a curve fit to the data and got the equation

\[ y = -234.82 + 3.1452x - 0.0063x^2 + 5.94 \times 10^{-6}x^3, \]  

(1)

where \( y \) is the calibrated temperature and \( x \) is the measured temperature. We then used this equation to get the calibrated measurements of the critical temperature, shown in FIG. 5. We noted that there is some systematic error in our value. This is seen by the spread in the measurements from each sample. Sample 1 was much higher than the average value while Sample 2 was lower. These discrepancies were taken into consideration when our error was calculated. We repeated the fit with Celsius and Kelvin values to get statistical error values. We added the statistical error and the systematic error to get the total error. We found the critical temperature of the superconductor YBCO to be \( T_c = 90.6 \pm 2.2 \) K (95% CI), which is in agreement with the accepted value of approximately 90 K[1].

For future trials we should make some adjustments. We would get better results if we constructed a case that kept all the components of the setup in thermal equilibrium. We found that the superconductor did not heat and cool evenly and the thermocouples changed at a different rate too. We also needed to add more thermocouples to get a better idea of the actual temperature. Three or four values will give a more accurate average. We should also try more temperatures for our calibration to get a better estimate.

[2] superconductor.org  