Electrical and Magnetic Properties of High Temperature Superconductors Using Varying forms of Data Acquisition

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Introduction

Physicist Heike Kamerlingh Onnes discovered superconductivity in 1911 in the element mercury.[1] Superconductivity is described as zero electrical resistance below a characteristic critical temperature. An electric current flowing through a loop of superconducting wire can persist indefinitely with no power source.

Superconductors also have interesting magnetic properties. The Meissner effect, discovered in 1933 by Meissner and Ochsenfeld[2] is the expulsion of a magnetic field when the superconductor is cooled below the superconductor's critical temperature. Once this temperature is reached there is no electrical resistance, and electrical currents are created on the surface of the superconductor in order to shield the superconductor from the applied magnetic field. A magnet can levitate above a superconductor because the surface electrical currents generate a magnetic field opposing the field of the magnet.

There are two types of superconductors, as shown in Figure 1. Type I superconductors display the normal phase and the Meissner phase, in which the magnetic field is completely expelled from the superconductor. Type II superconductors also display the normal and the Meissner phases. However, at intermediate temperatures and magnetic fields, they are in a mixed state, in which the magnetic field penetrates in the material in the form of vortices (normal cores surrounded by superconducting currents).
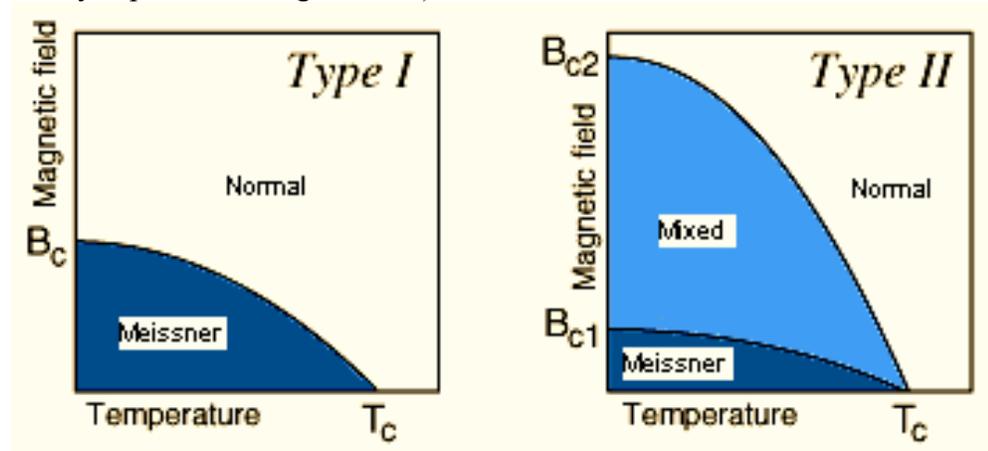

Figure 1. Phase diagram of a Type I superconductor (left) and Type II superconductor (right). For Type I, at temperatures above T_C and magnetic fields above B_C the material is normal the normal state, while at temperatures below T_C and magnetic fields below B_C the material is normal the Meissner phase. For Type II, at temperatures above T_C and magnetic fields above B_{C2} the material is in the normal state. At temperatures below the T_C and magnetic fields between B_{C1} and B_{C2} the material is in the Mixed state, while at temperature below T_C and magnetic fields below B_{C1} the material is in the Meissner phase.

Although it was initially thought that the phenomenon of superconductivity is rare, scientists later learned that it is rather common. As shown in Figure 2, about two thirds of the known elements display superconducting properties.[3]
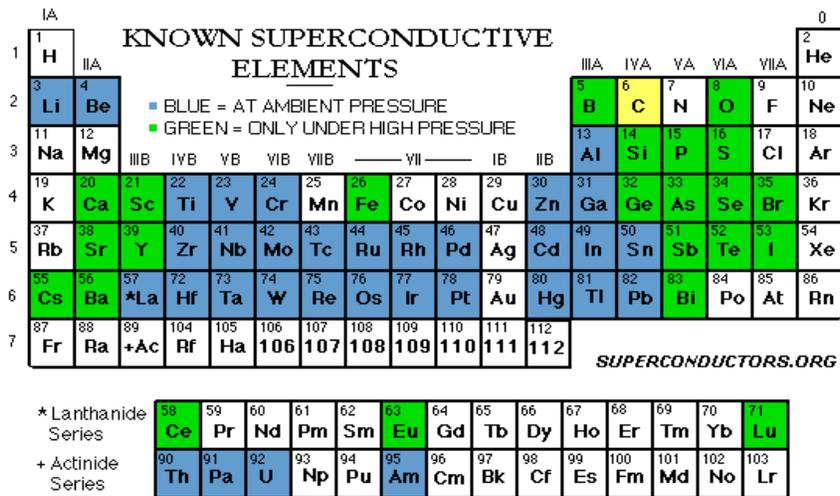

Figure 2. Periodic table of the elements. The elements with blue background are superconducting at ambient pressure, the ones with green background are superconducting under high pressure, while carbon is superconducting only in the form of carbon nanotubes.

High Temperature Superconductors were discovered in 1986 by Bednorz and Muller.[4] Their critical temperatures are higher than the 77K of liquid nitrogen. Some of the most studied High Temperature Superconductors are $YBa_2Cu_3O_7$, commonly known as YBCO, and $Bi_2Sr_2Ca_2Cu_3O_9$, commonly known as BSCCO.

Superconductors are used in many areas of everyday life. They can be found in Magnetic Resonance Imaging (MRI), the Large Hadron Collider at CERN, Magnetically levitated trains (MagLev), energy transmission, transformers, and motors.[5,6]

Experimental Method

The superconductors used in this experiment were manufactured by Colorado Superconducting, Inc. Our superconductor samples have a four-point probe and a thermocouple attached to them, as seen in Figure 3.
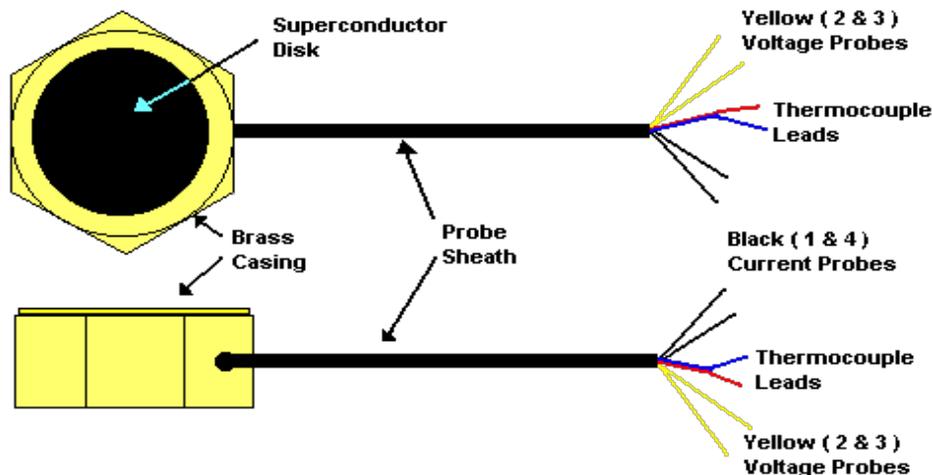
Figure 3. Schematic of the superconductor and the attached wires.[7]

With this four-point probe we can measure the voltage across the sample while we send a current through the sample, and also measure the temperature of our sample with the thermocouple. A thermocouple is a device in which two wires, made of different metals, are joined at one end, called a junction.[7] The other end is called the reference end. (See Figure 4) The junction is placed in contact with the superconductor, inside the brass casing. The reference end can either be held at room temperature (if that temperature is known accurately), or placed in an ice bath at ^{0}C. When there is a difference in temperature between the junction and the reference end, a voltage appears across the thermocouple. Our probe has a type T thermocouple that consists of two different metals, copper and constantan. As the sample goes between room temperature and liquid nitrogen temperature (77K), the voltage across the thermocouple changes by less than 7 mV. Due to the small change in voltage, we need a high-resolution voltmeter, higher than the one of typical hand held digital multimeters (DMMs). We are employing a Hewlett Packard HP 3478A voltmeter. Published values and tables provided by the manufacturer of the four-point probe are used to convert the voltage into temperature.[7]
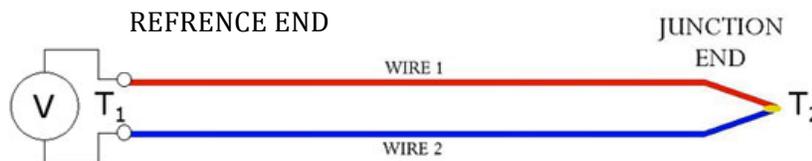

Figure 4. Schematic of a thermocouple.

Magnetic properties - Method A.

The first method of determining the critical temperature involves observing the levitating effect after the superconductor has been cooled below its transition temperature, and recording the temperature at which the magnet stops levitating, as it warms up and it undergoes the transition from superconducting to normal.

Electrical properties - Method B.

The sample is first cooled to liquid nitrogen temperature (below its critical temperature). Subsequently the sample is allowed to warm up back to room temperature while we monitor the voltage across the sample as a current is sent through the sample. If we were to connect only two wires to the sample, the voltmeter would record the sum of the voltages across the sample and the contacts. The contacts have a resistance much higher than the sample, and the voltage recorded would be mostly due to the contacts, hence we would not be able to extract the sample resistance. The four-point probe eliminates this problem. Figure 5 shows a schematic of the sample, the wires attached, and the contact resistance due to each of the four wires.
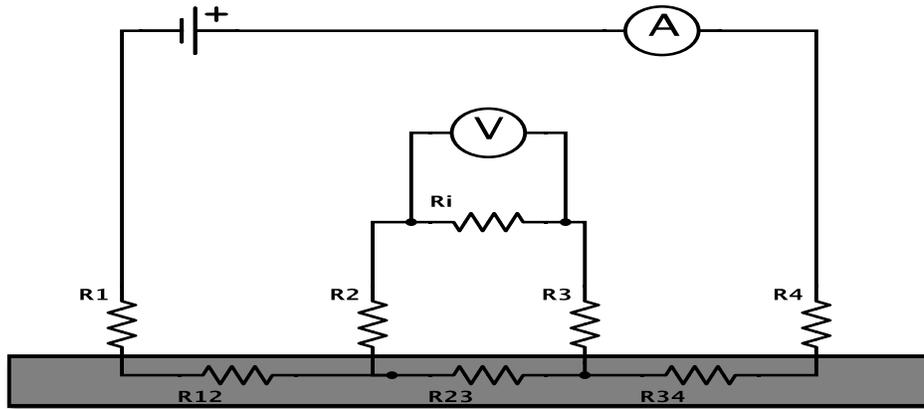

Figure 5. A schematic of the breakdown of the sample and contact resistance. Four contacts are applied to the sample, yielding R_1, R_2, R_3, and R_4 as contact resistances. The different sections of the sample, between the points were the contacts were made, have resistances R_{12}, R_{23}, and R_{34}. The voltage wires are connected to a voltmeter of input resistance R_i.

When a power supply is attached to the system, a current is set up in the circuit. Most of the current circulates on the path containing R_1, R_{12}, R_{23}, R_{34}, and R_4. Due to the high internal resistance R_i of the voltmeter (of the order of MΩ), the current on the R_2, R_i and R_3 path is negligible. Therefore, the voltage that the voltmeter will record is mostly due to the voltage across R_{23}, which is part of our sample. The resistance can be determined through the relationship described in

equation 1 between voltage (V), resistance (R) and current (I) known as Ohm's Law.

$$\text{Eq. (1)} \qquad R \text{ (ohms)} = V\text{(volts)} / I\text{(amperes)}$$

Method B1.

In this method the experimenters use the four-point probe, a BK ToolKit 2704B ammeter to view the current through the sample and a Hewlett Packard HP 3478A voltmeter to record the voltage between points 2 and 3 of the sample. The experimenters enter the values in the laboratory notebook, and then use data analysis software to calculate the resistance and plot it as a function of temperature. With this approach it is hard to record all the values from the ammeter and two voltmeters (one for the voltage across the sample, the other across the thermocouple) at the same time, making it difficult to obtain accurate results.

Method B2.

In this method the experimenters use the four-point probe in conjunction with a LabVIEW (Laboratory Virtual Instrument Engineering Workbench), created by National Instruments. LabVIEW is a program is a graphical programming language that uses icons instead of lines of text to create applications. LabVIEW programs are called Virtual Instruments, or VIs for short. Many VIs are already developed by National Instruments programmers, and can be used by the experiments in their particular application. In our experiment, the Ammeter and the Voltmeters are replaced by a NI 9219 DAQ (data acquisition) board, and the wires are connected to the analog input and thermocouple input pins on the DAQ board. The DAQ transmits the data to the computer and subsequently data analysis software is used to calculate the resistance and plot it as a function of temperature. This method is automated and data can be collected fast and accurately.

A program in LabVIEW has two different windows. One of these windows is called the front panel. The front panel is what the user sees and also displays the data while it is being taken. The second window is called the block diagram. This is where the programmer uses VIs to execute the program. We developed our own program in order to measure our HTS samples. Figure 6 shows the block diagram, while Figure 7 shows the front panel of the LabVIEW program we built. With our program we simultaneously measured a YBCO and a BSCCO sample.
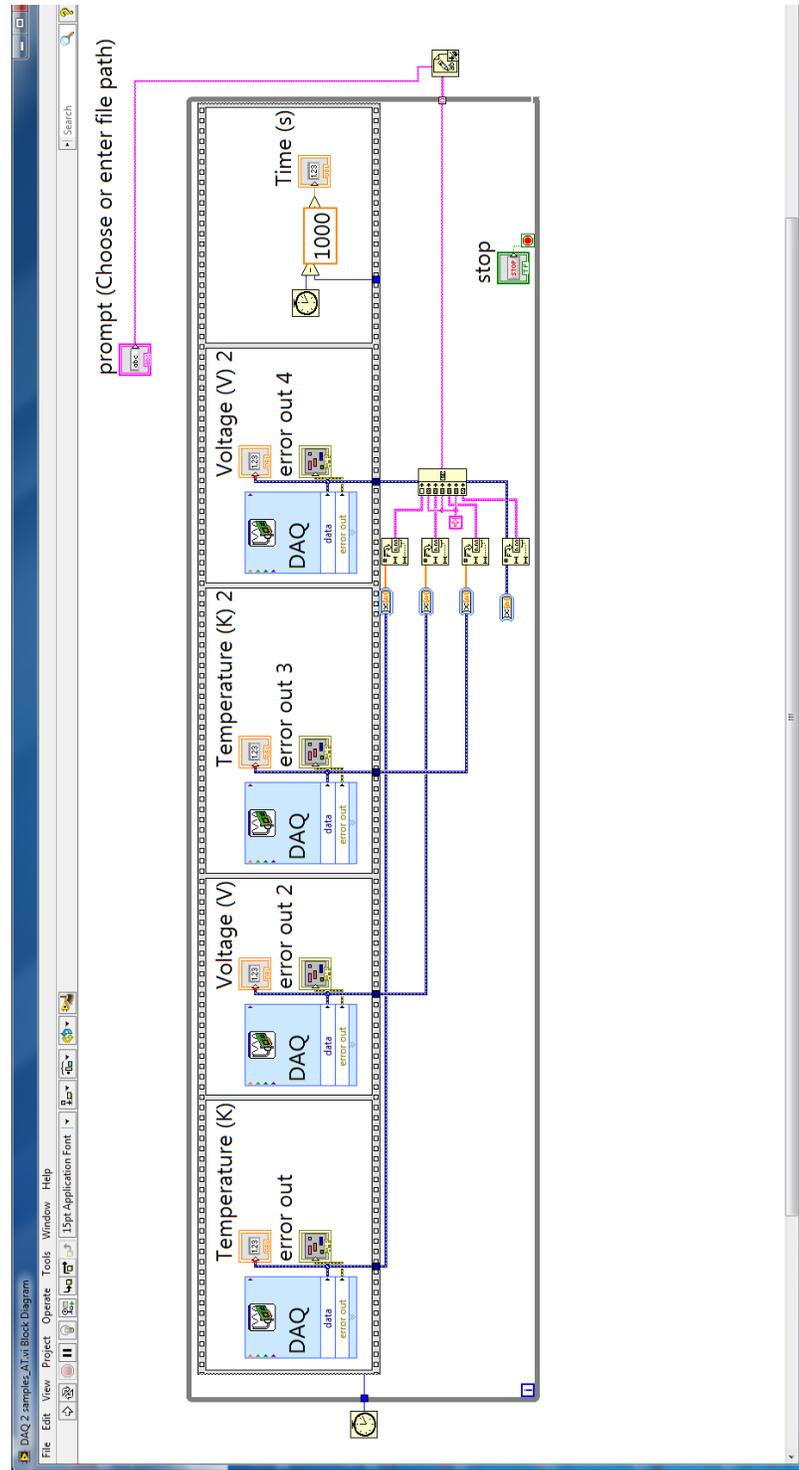
Figure 6. The block diagram of the program we built to collect the voltage vs. time data for the two superconductors.
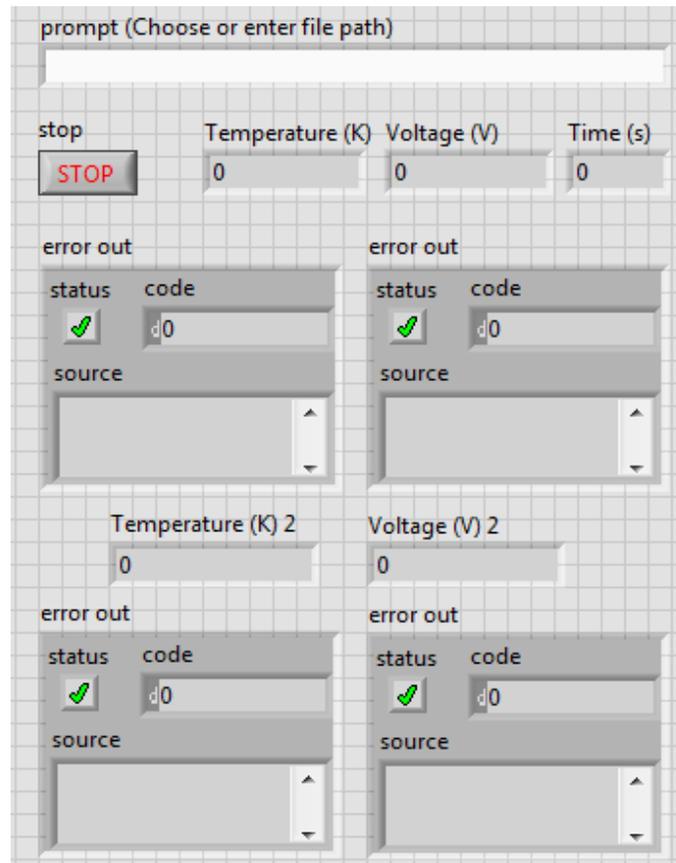
Figure 7. The front panel of the program we built to collect the voltage vs. time data for the two superconductors.

Experimental Results

Magnetic properties - Method A

As the sample warmed up, we observed a voltage of 5.71 mV across the thermocouple when the magnet no longer levitated. This corresponds to a temperature of 95 Kelvin. Our experimental measurement was fairly close to the accepted value of 92 Kelvin for the critical temperature of YBCO.

Electrical Properties - Method B1

Figure 8 depicts our measurements of electrical resistance versus temperature. The critical temperature is where YBCO, as it is warming, no longer

has zero resistance. Our graph shows the transition temperature at approximately 103 Kelvin, higher than the expected 92 Kelvin.
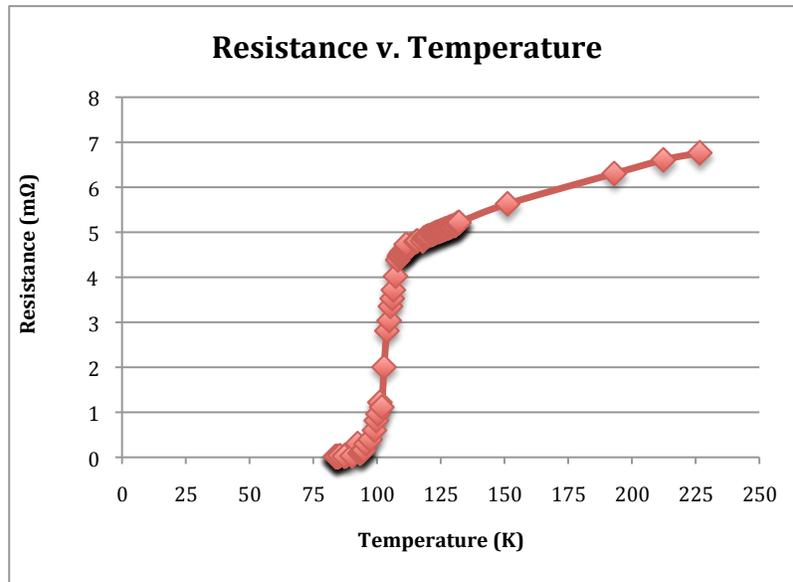
Resistance v. Temperature

Figure 8. The Resistance vs. Temperature for the YBCO superconductor, as measured through Method B1.

Method B2.

Figure 9 depicts our measurements of electrical resistance versus temperature. With this method the computer collected more data points, as it was able to take data at smaller time intervals. The critical temperatures for the YBCO and BSCCO samples were determined to be 115 K and 130 K, respectively, higher than the accepted transition temperatures of 92 K for YBCO and 110 K for BSCCO.
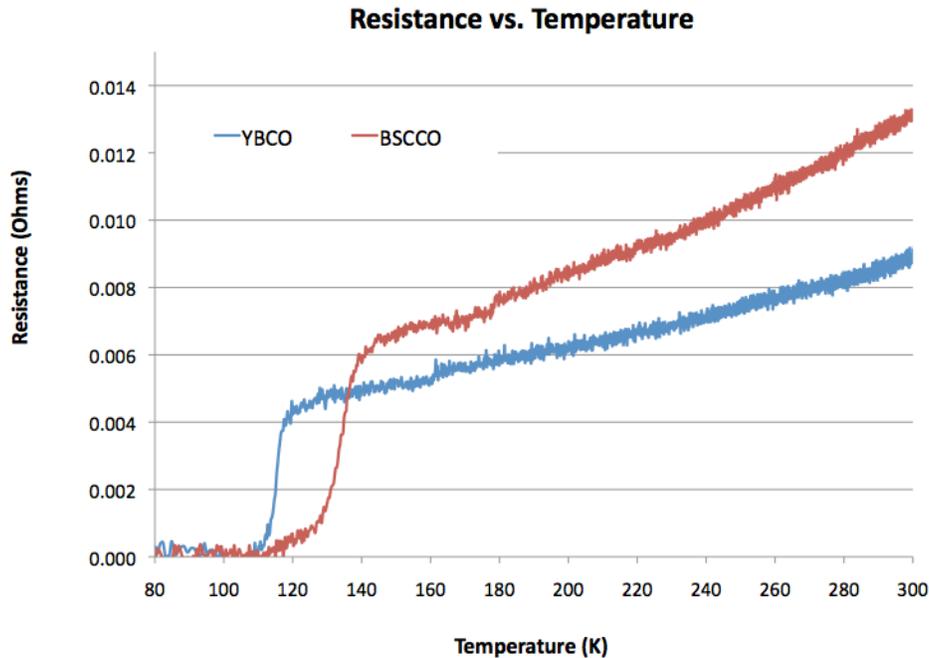
Figure 9. Resistance vs. Temperature for both YBCO and BSCCO
superconductors.

Discussion

Both methods, B1 and B2, show a transition temperature higher than the
accepted value. This discrepancy can be caused by a few factors: as shown in
Figure 4, T2 represents the temperature of the sample, while T1 is the reference
temperature. Most thermocouple data considers T1 to be room temperature, and
an inaccurate value of the latter can produce an offset in the data. For Method B1,
we placed the reference junction, T1, in an ice bath, and used the thermocouple
tables with 0° C reference. In Method B2, the NI 9219 DAQ board has a cold
junction compensation (CJC) that was supposed yield more accurate temperature
measurements. Given that we obtained more accurate results with Method B1
and the ice bath, we conclude that the CJC did not perform as expected.

Even with the ice bath, our results for the transition temperature are still
not consistent with the accepted values. This discrepancy could also be attributed
to artifacts in our measurements: the thermocouple measures the temperature on
the surface of the superconductor. We took our measurements while warming the
sample up. The surface warms up faster than the middle of the superconductor,
hence it is possible that we are recording higher values for the temperature, and
hence, for the transition temperature.

Future improvements would involve more accurately determining the temperature with the thermocouple. This can be accomplished by recording the temperature of ice water and liquid nitrogen, and seeing if there are any offsets from the accepted values. These offsets could then be subtracted from the recorded data. Devising a method to more slowly warming up the superconductor may result in less temperature difference between the surface and the middle of the superconductor, and yield better data.

Conclusion

We characterized HTS of YBCO and BSCCO through magnetic and electrical measurements. We were able to make our measurement process automatically recorded by the computer by writing a LabVIEW program. We observed the absence of electrical resistance and the Meissner effect while in the superconducting state. We also observed and characterized the transition from the superconducting to the normal state. Our results for the transition temperature are close to the accepted values. Future improvements involve a more accurate temperature measurement, possibly with an ice bath in conjunction with the DAQ board.

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