Transition Temperatures in Yttrium Barium Copper Oxide (YBCO)

Department of Physics: PH 2651,
Worcester Polytechnic Institute,
Worcester, MA 01609
(Dated: February 24, 2015)

In 1911 it was observed that mercury, when cooled below a critical temperature (T_C) would exhibit no electrical resistance. This effect, called superconductivity, occurs in many materials at varying T_C's. This paper attempts to measure by direct observation the critical temperature of Yttrium Barium Copper Oxide (YCBO) as well as the dependence of resistance on temperature in classical resistors and semiconductors. The results were found to agree well with previous experiments and with theory. A measurement of the dependence of T_C on the magnetic field was attempted. However, experimental limitations prevented significant results from being derived.

INTRODUCTION

Superconductivity was first observed in 1911 by Dutch scientist Heike Kamerlingh Onnes in the metal mercury. He found that when the material was cooled below 4.4K it would have no electrical resistance. The temperature below which this effect was observed was called the critical temperature and is denoted by the symbol T_C. Many other materials were found to exhibit superconductivity including many metals and alloys.

In 1933, Walther Meissner and R. Ochsenfeld observed that superconductors are more than just good conductors. They found that superconductors do not allow magnetic fields to penetrate their interior. This effect, called the Meissner effect, causes permanent magnets to be repelled by and "levitate" above superconducting materials.

Theoretical Background

Classically, resistance increases nearly linearly with temperature. This is because greater temperature corresponds to greater thermal interactions which in turn decreases the electron mobility and increases resistance. Superconductivity flies in the face of this classical result. According to BCS theory there is an effective pairing of electrons which are then called Cooper pairs. An electron attracts and deforms the lattice of ions, resulting in an effective pairing of electrons that travel through the lattice together. These pairs allow electrons to move through the atomic lattice more efficiently than they would if traveling alone making a material with effectively no resistance.

Figure 1 details electrons moving in Cooper pairs through a lattice. This theory is a simplification of the quantum mechanical effects behind superconductors, but provides a good idea into why the resistance drops suddenly at the superconducting transition temperature. The general plot of resistance versus temperature is shown in figure 2.

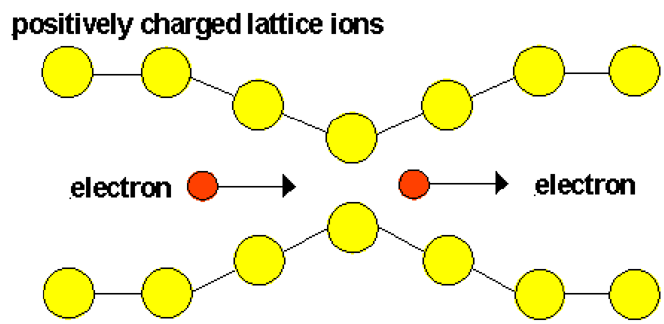

FIG. 1: Cooper Pairs Moving Through an Ion Lattice Obtained from: http://webs.mn.catholic.edu.au/physics/emery/hsc_ideas_implementation.htm

Type I and Type II Superconductors

Superconductors may be divided into two categories, Type I and Type II superconductors. Type I superconductors are mainly metals and metalloids and are relatively insensitive to material impurities. These materials have some conductivity at room temperature, but they require extremely low temperatures ($< 10K$) to transition to superconductivity. Additionally, type I superconductors are disabled by relatively low applied magnetic currents. They completely exhibit the Meissner effect and conduct only on their surface.

Type II superconductors are similar to type I superconductors in many ways. Type II superconductors can be metal compounds or even ceramics and generally transition to superconductivity at temperatures around 100K. Compared to type I superconductors, type II superconductors are much more sensitive to impurities. Even minuscule impurities can remove superconducting ability from type II superconductors. They also are much less sensitive to magnetic fields, although magnetic fields do lower their transition temperature. In fact, there are actually a range of magnetic field magnitude that will create a mixed state (between supercon-

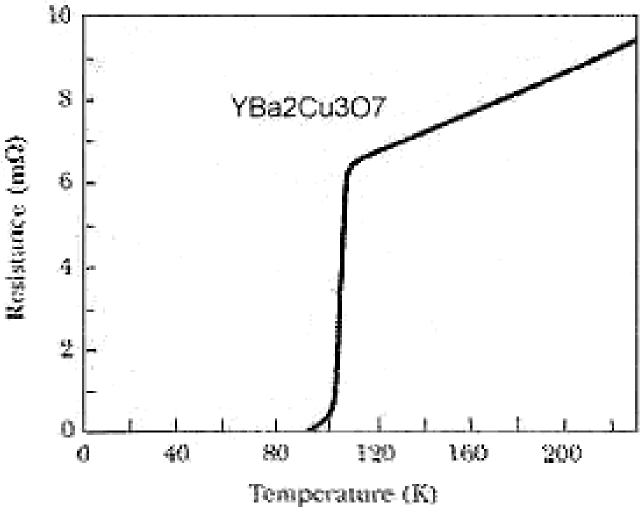

FIG. 2: General Resistance vs Temperature for YBCO
Obtained From:
http://www.superconductors.org/Y258.htm

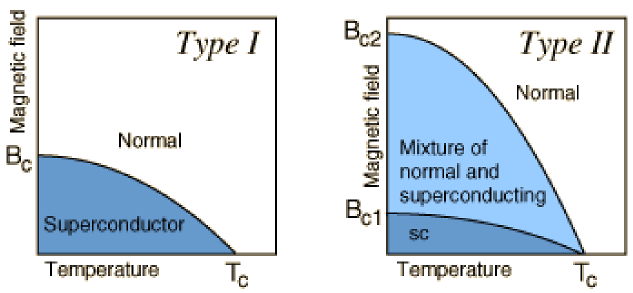

FIG. 3: Differences in Magnetic Field Effect for Type I and Type II Superconductors
Obtained From:
http://www.gitam.edu/eresource/Engg_Phys/semester_2/supercon/type_1_2.htm

ducting and normal). The differences in magnetic field sensitivity between type I and type II superconductors is shown in figure 3. Finally, type II superconductors only partially exhibit the Meissner effect, with most magnetic field being repelled but some becoming trapped within the material.

The YBCO sample we tested in this experiment is a type II superconductor, and we hope to compare its behavior to many of the expected behaviors stated above.

Applications

Resistance in electrical circuits causes energy dissipation which reduces efficiency and results in an overall waste of energy. Superconductors, due to their lack of resistance, greatly increase the efficiency of power systems. Significantly less energy is lost and less stray heat is developed, leading to the effectiveness of superconductors in numerous settings including delicate electronics, magnetic field detection, and acceleration of small particles.

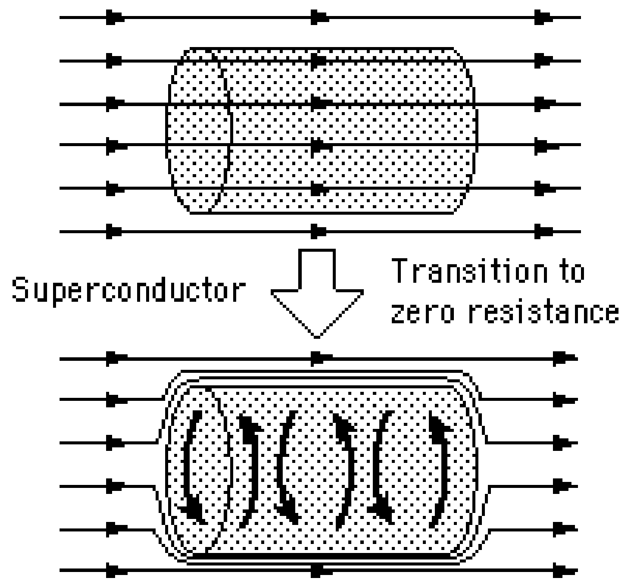

FIG. 4: Internal Transition in a Superconductor Leading to the Meissner Effect
Obtained From:
http://hyperphysics.phy-astr.gsu.edu/hbase/solids/meis.html

The Meissner Effect

One interesting effect of superconductivity is the repulsion of magnetic fields, known as the Meissner effect. Surface currents produce magnetic fields which cancel applied magnetic fields, and the magnetic fields are repelled from the inside of the superconductor. This effect is shown in figure 4. The Meissner effect is key in many applications of superconductivity that involve levitation of bodies. Specifically, Maglev transportation uses superconductors and magnets to levitate trains above tracks to greatly minimize the friction of transportation systems. A diagram of a Maglev train is shown in figure 5.

Converting Voltages to Resistivities

The raw data taken through MATLAB in this experiment comes in the form of three variables: time, voltage, and temperature. By ohm's law (equation 1), the voltage is linearly related to the resistance by the current.

$$V = IR \tag{1}$$

However, resistance is not the best quantity to measure because it depends on the geometry of the sample. Resis-

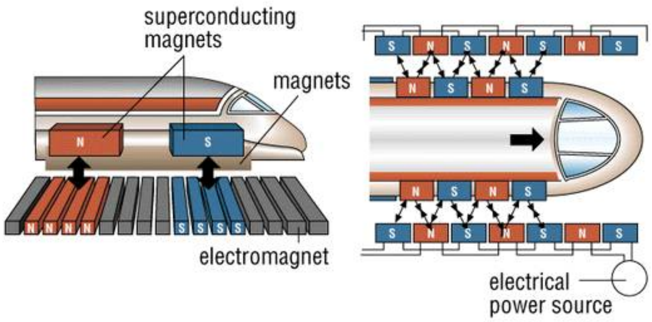

FIG. 5: Diagram of a Maglev Train Obtained From: http://www.wou.edu/∼rmiller09/superconductivity/

TABLE I: Measured Parameters to Calculate Resistivity

A	5.613x10$^{-5}m^2$
ℓ	0.0147m

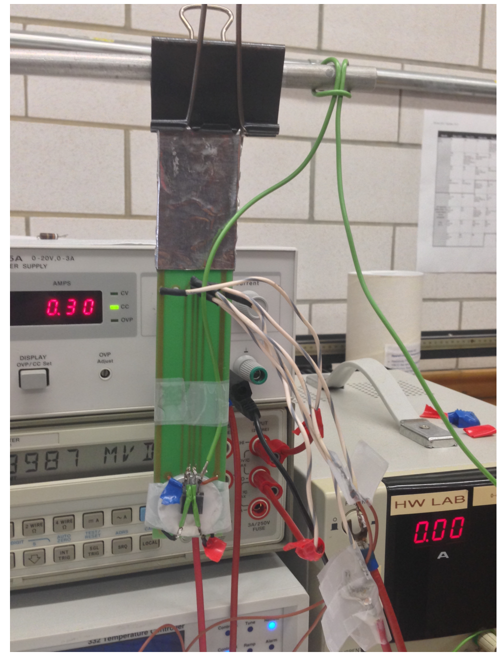

FIG. 6: Setup of Sample on Circuit Board

tivity is a better quantity because it is a material property and not dependent on geometry. The formula for resistivity of a bar is

$$\rho = \frac{RA}{\ell} \tag{2}$$

where A is the cross sectional area of the sample and ℓ is the length between the two voltage leads on the sample. The parameters needed to calculate resistivity for this experiment are shown in table I. Combining equations 1 and 2 gives the resistivity in terms of the measured voltage and the known current (equation 3.

$$\rho = \frac{VA}{I\ell} \tag{3}$$

The data represented in the plots will all be kept in voltage because equation 3 proves that voltage transforms linearly to resistivity. When resistivity drops to zero, so will the voltage. The superconducting transition can still be calculated (and viewed) from a plot of voltage versus temperature.

Hysteresis

The experimental setup of the YBCO has it mounted on a piece of aluminum. The temperature of the aluminum is the actually reported temperature during the data recording process. Because the aluminum cools and warms at a different rate than the YBCO, a slight hysteresis effect should be observed. Hysteresis means that the output of a process depends not only on input but also previous states. What this means is that the measured superconducting transition temperature of the YBCO will depend on whether it is warming up past T_c or cooling down below T_c. Specifically, the measured transition temperature should be slightly high when putting in the YBCO (cooling it down) and slightly high when taking it out (warming it up).

PROCEDURE

In order to record the voltages and temperatures of the YBCO, the lab setup included Styrofoam containers to hold the liquid nitrogen and the YBCO sample and aluminum temperature sensor mounted on a printed circuit board. The general configuration of the sample's setup is shown in figure 6. When dunked into liquid nitrogen, the YBCO was also covered in a plastic cover so that condensed water would not continuously freeze and refreeze on the YCBO (which would cause it to degrade and crumble). Additionally, figure 7 shows three pieces of equipment that measured various parameters. From top to bottom, there is a current supply, a multimeter used to measure voltage, and the temperature controller. The temperature and voltage data were transmitted to MATLAB, which recorded them continuously (taking approximately one data point per second).

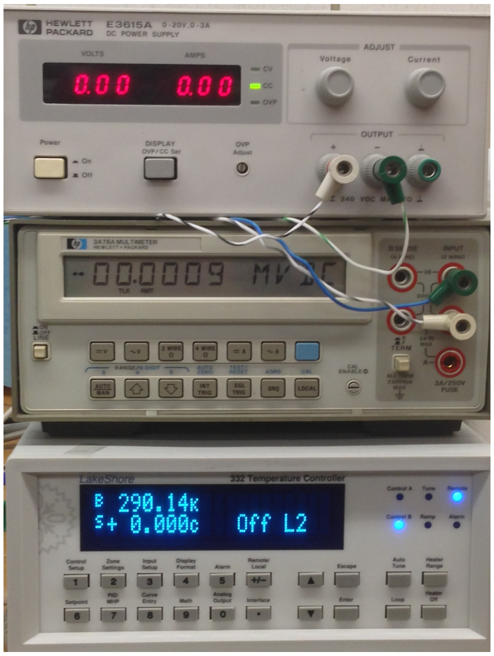

FIG. 7: Various Equipment Used in Data Collection

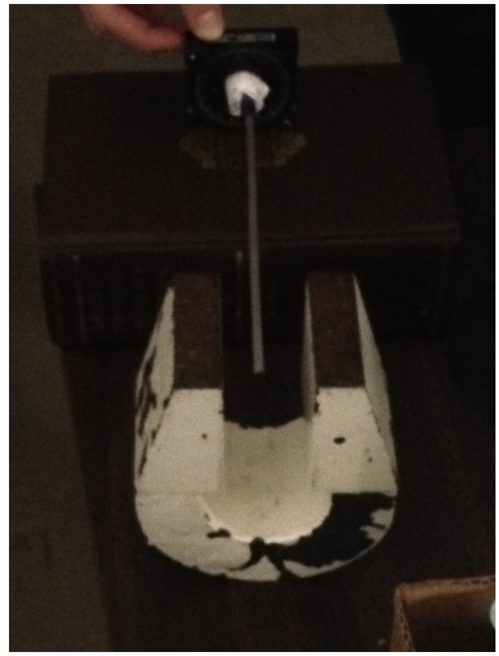

FIG. 8: Hall Probe Testing Setup

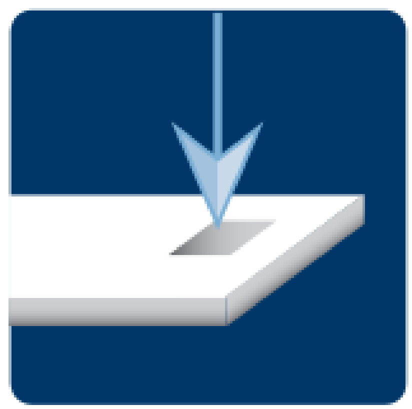

FIG. 9: Geometry of Hall Transverse Hall Probe Obtained From: http://www.lakeshore.com/products/hall-probes/transverse-probes/Pages/Overview.aspx

Data Acquisition Without Magnetic Field

In order to get multiple trials of the YBCO transition, the YBCO was dipped down into the liquid nitrogen with the MATLAB logger running. After the temperature had settled out around $75K$, the sample was removed from the liquid nitrogen. The sample heated up much more slowly than it cooled down, so once the temperature was above 150K, the sample was put back into the liquid nitrogen. The MATLAB logger gave a continuous plot of voltage versus temperature, so heating and cooling progress of the YBCO could be observed. After two cycles on each current, the current was turned up. Currents used were $0.1A$, $0.3A$,$0.5A$,$0.9A$,$1.5A$, and (at the end) $0.05A$. It was evident on the voltage versus temperature plot each time the YBCO crossed through the superconducting temperature range.

Magnetic Field Addition & Measurement

In order to measure the magnetic field between the poles of the permanent magnets, a transverse hall probe was used. This hall probe is able to measure magnetic fields that arrive perpendicular to the probe. A photo of the hall probe used in the experiment is shown in figure 8.

This setup was used to determine the most sensitive orientation of the hall probe. The hall probe was rotated about its long axis 180^o in increments of 10^o. The hall probe is a long rod with a cross section that is a rectangle with a longer and shorter side (as shown in figure 9. It was determined that the hall probe measures perpendicular to the longer side of the cross section, as shown. A plot of the relative magnetic field ($\frac{B}{B_{max}}$) versus θ of rotation is shown in figure 10. The plot of relative magnetic field versus $\cos\theta$, meanwhile, produces a linear plot and is shown in figure 11. The results for the sensitivity of the hall probe were used in accurately measuring the magnetic field that the YBCO is placed in.

Magnetic Field Application to YBCO To add a magnetic field to the area where the YBCO was placed, two magnets were taped onto the outside of the Styrofoam container with liquid nitrogen in it. Great care was taken to measure the magnetic field in the precise spot where the YBCO would be placed. The YBCO went into the liquid nitrogen and cooled as with the sample not in a

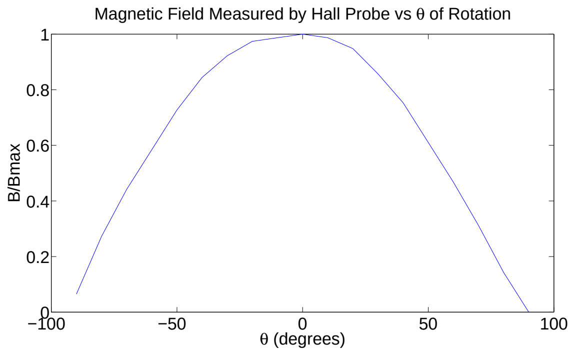

FIG. 10: Graph of Relative Magnetic Field vs θ

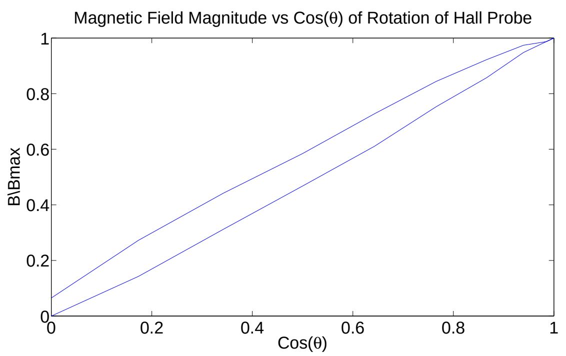

FIG. 11: Graph of Relative Magnetic Field vs $\cos\theta$

magnetic field. Next, when the YBCO needed to be removed, it was removed and heated. After it warmed through its transition temperature, the magnetic field at the location where the YBCO was left to warm up was taken. Because this was not directly in between the magnets, the magnetic field that it warmed up in was significantly less than the magnetic field it was cooled down in. The transition temperature in a magnetic field were measured to compare to YBCO transition without a magnetic field.

Meissner Effect

The final part of the experiment was meant to observe the Meissner effect. In order to observe the repulsion of magnetic flux of a superconductor, YBCO sat in a small Styrofoam cup with a foam like material surrounding it. This setup is shown in figure 13. Liquid nitrogen was poured into the container and placed a rare earth magnet on top of the YBCO. Once the YBCO cooled into its superconducting region, the magnet began to float above the YBCO. The magnet was be spun above the YBCO in order to show that the magnet is effectively held in place above the YBCO due to the Meissner effect.

TABLE II: Data Points for a Particular Superconducting Transition

Temperature (K)	Voltage (mV)
106.1	0.5764
105.3	0.5724
104.6	0.5683
103.8	0.5590
102.8	0.5495
101.7	0.5364
100.4	0.4089
99.08	0.2156
97.56	0.0306
96.18	0.0090
94.85	0.0082
93.60	0.0073
92.41	0.0068
91.31	0.0060
90.31	0.0060

MEASUREMENTS, OBSERVATIONS AND DISCUSSION

Many trials were run to test the transition temperature of the YBCO. Each trial gave pretty consistent results, with the transition temperature ranging from just under $90K$ to just over $100K$. Tables III and IV show the results for cooling down and heating up the YBCO respectively. They are separated because of the expected hysteresis effect mentioned in the methodology. In both tables, there is a T_{upper} value and a T_{lower} value. Those two values were measured at both ends of the transition to superconductivity. Because the transition is pretty rapid but not instantaneous, the one temperature was measured when the voltage first began to rapidly drop and the other temperature was measured at the first voltage that seemed to be nonzero. The average of these two values is shown in the T_{avg} column and is the value taken to be the actual transition temperature. Additionally, an example of data points (taken at constant time intervals) approaching and departing the superconducting transition are shown in table II. Notice that as the YBCO begins to become superconductive, it begins to temporarily cool more quickly. This is due to I^2R heating vanishing when the material becomes superconductive, which is discussed later on. For the particular transition shown in the table, the upper temperature where the transition begins would be read as $101.7K$ and the lower temperature would be read as $97.56K$.

Meissner Effect

Because YBCO is a type II superconductor, it does not exhibit the complete Meissner effect. Some of the magnetic flux becomes trapped within its fibers, which creates an interesting levitation effect. A rare earth mag-

TABLE III: Superconducting Transition Temperature when Cooling Down YBCO

B(G)	I(A)	$T_{upper}(K)$	$T_{lower}(K)$	$T_{avg}(K)$
31.5	0.1	100	95.49	97.75
0	0.1	101.7	97.56	99.63
0	0.1	104.8	98.7	101.75
0	0.3	101.3	96.05	98.68
0	0.3	102.9	97.37	100.14
0	0.5	97.68	93.74	95.71
0	0.5	97.15	94.55	95.85
0	0.9	97.76	92.08	94.92
0	0.9	104.1	97.83	100.97
0	1.5	99.44	94.56	97.00
0	0.05	94.28	93.69	93.99
0	0.05	98.69	96.16	97.43

TABLE IV: Superconducting Transition Temperature when Up YBCO

B(G)	I(A)	$T_{upper}(K)$	$T_{lower}(K)$	$T_{avg}(K)$
0.36	0.1	93.09	90.89	91.99
0	0.1	94.52	91.14	92.83
0	0.1	94.11	92.2	93.16
0	0.3	93.82	90.87	92.35
0	0.3	93.75	91.32	92.54
0	0.5	93.48	90.32	91.90
0	0.5	93.54	90.28	91.91
0	0.9	92.35	89.38	90.87
0	0.9	92.93	88.93	90.93
0	1.5	91.95	87.03	89.49
0	0.05	93.41	92.23	92.82
0	0.05	93.53	92.14	92.84

net will still levitate above the superconductive YBCO, but it will actually be held in place by the trapped magnetic field. Therefore, the magnet will actually be able to spin freely and will not be knocked out of levitation by small disturbances. In the experiment, the magnet built up ice soon after being placed above the YBCO, so it oscillated instead of rotating freely. Diagrams of the Meissner effect the actual observation are shown in figures 12 and 13, respectively.

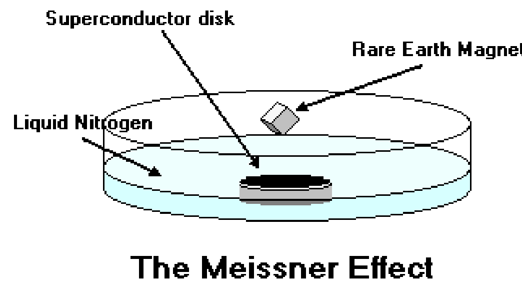

FIG. 12: Diagram of Rare Earth Magnet Exhibiting Meissner Effect
Obtained From:
http://www.imagesco.com/articles/superconductors/superconductor-meissner-effect.html

FIG. 13: Experimental Setup With the Meisser Effect Shown

Superconducting Transition Temperature Without Magnetic Field

As seen in table V, the result observed and calculated for the superconducting transition temperature is $94.89K \pm 3.57K$. The lab manual mentions that the transition temperature should be around $95K$, which $94.89K$ clearly is. All of the data included in the calculation of this value showed consistency, and no values were significantly outlying from the calculated value. The table also shows the effect of hysteresis as described in the methodology. The average difference in transition temperature when heating up and cooling down was $5.85K$, which is a around 7% of the measured transition temperature. This shows that hysteresis in this experiment is significant.

In addition to the hysteresis effect from the difference in heating and cooling rate, there is an extra element of heating on the YBCO. This heat source, known as I^2R heating, comes from power generated from current running through the YBCO. The concept of I^2R heating comes, not surprisingly, from the equation for power $P = I^2R$. Because of this heating effect, the cooling effect from the liquid nitrogen is slightly counteracted. Similarly, the heating effect from the room is slightly boosted. In order to counteract this I^2R heating, the last two trials were run with a very low current, which led to a very low resistance. Smaller values of resistance do give rise to slightly higher relative uncertainties, but there were not extensive calculations done that would

TABLE V: Compiled Results of All Trials

Magnetic Field Trials Cooling	$97.75K \pm 2.23K$
Magnetic Field Trials Warming	$92.00K \pm 1.10K$
All Trials With Magnetic Field	$94.87K \pm 4.07K$
Trials w/o Magnetic Field Cooling	$97.82K \pm 2.59K$
Trials w/o Magnetic Field Warming	$91.97K \pm 1.12K$
Average Hysteresis Effect	$5.85K$
All Trials w/o Magnetic Field	$94.89K \pm 3.57K$

propagate these uncertainties. The hysteresis effect is still present in the low current trials, but the effect of the extra heating is nearly eliminated at minimal currents.

TABLE VI: Resistivity Values for Various Currents and Voltages (in $\Omega \cdot m$)

	$0.1A$	$0.5A$	$0.9A$	$1.5A$
$0.1V$	0.00382	0.00076	0.00042	0.00025
$0.3V$	0.01146	0.00229	0.00127	0.00076
$0.5V$	0.01909	0.00382	0.00212	0.00127
$1.0V$	0.03818	0.00764	0.00424	0.00255
$1.5V$	0.05728	0.01146	0.00636	0.00382
$2.0V$	0.07637	0.01527	0.00849	0.00509
$2.5V$	0.09546	0.01909	0.01061	0.00636

Revisiting Resistivity vs Voltage

In the methodology, it was mentioned that the readings taken in voltage were left in voltage in all plots because voltage transforms linearly to resistivity. To give an idea of values of resistivity, table VI shows the resistivity of the YBCO at given current and voltage reading, based on equation 3. Note that not all current-voltage combinations shown in the table are obtained in this experiment. The table is mainly meant to show how resistivity varies as current and voltage vary. As current goes up and voltage goes down, resistivity drops. Conversely, as current goes down and voltage goes up, resistivity increases. Resistivity, as previously mentioned, is more of a material property than resistance, because resistance depends on geometry. If this experiment were to deal with more materials than just YBCO, it would be ideal to report the resistances in terms of resistivity instead of reporting voltages.

Voltage Versus Temperature Plots

The curve of temperature plotted versus voltage for a superconducting transition should produce a shape similar to that in figure 2. Figure 14 shows voltage plotted versus temperature for many of the transitions observed. There is a convincing similarity between the two figures, which shows that the physical transition observed in the YBCO is likely very similar to the expected transition.

YBCO Transition in Presence of Magnetic Field

The theory of superconductors suggests that when the YBCO is cooled down in the presence of a magnetic field, the transition temperature will be lower than the transition temperature in zero magnetic field. In order to observe this, the YCBO was cooled down in a $31.5G$ magnetic field. Unfortunately, it was discovered that a magnetic field of this magnitude did not noticeably affect the transition temperature. When taken out of the liquid nitrogen, the YBCO was subjected to about one one-hundredth of that magnetic field, which, not surprisingly, did not affect the transition temperature either. The lab manual suggests that a magnetic field of several hundred Gauss would affect the transition temperature, which was not attainable with the setup and the magnets used.

Resistivity vs Temperature Properties for Non-Superconducting Materials

After performing all tests with the superconducting YBCO, the temperature dependence of resistivity on other materials was tested. Results from a typical metal and a semiconductor were compared to their respective theories.

Metal (Copper) In order to investigate the resistance versus temperature properties of a metal, copper was studied. The setup of the copper mounted on the circuit board can be viewed in figure 15. Theory suggests that as temperature drops, resistance drops somewhat linearly. Figure 19 shows the general difference in resistance versus temperature for superconductive materials and non-superconductive metals.

This decrease of resistance with temperature is not what was observed, likely due to copper's very low resistivity. The graph obtained, shown in figure 16 shows a rise in resistance with a decrease in temperature, which is likely due to noise of the power supply and the sensor recording the voltage. If copper had a higher resistivity to begin with, it would have dominated the graph instead of the noise.

Semiconductor (MOSFET) The second non-superconducting material tested was a metal-oxide-semiconductor field-effect-transistor (or MOSFET). The setup for the MOSFET on the circuit board is shown in figure 17. For a MOSFET, the theory and actual experimental observations matched together quite well. Semiconductors conduct electricity when their valence electrons jump to the conduction band across a small band gap. The band gap for semiconductors is much smaller than that of insulators, which gives them their

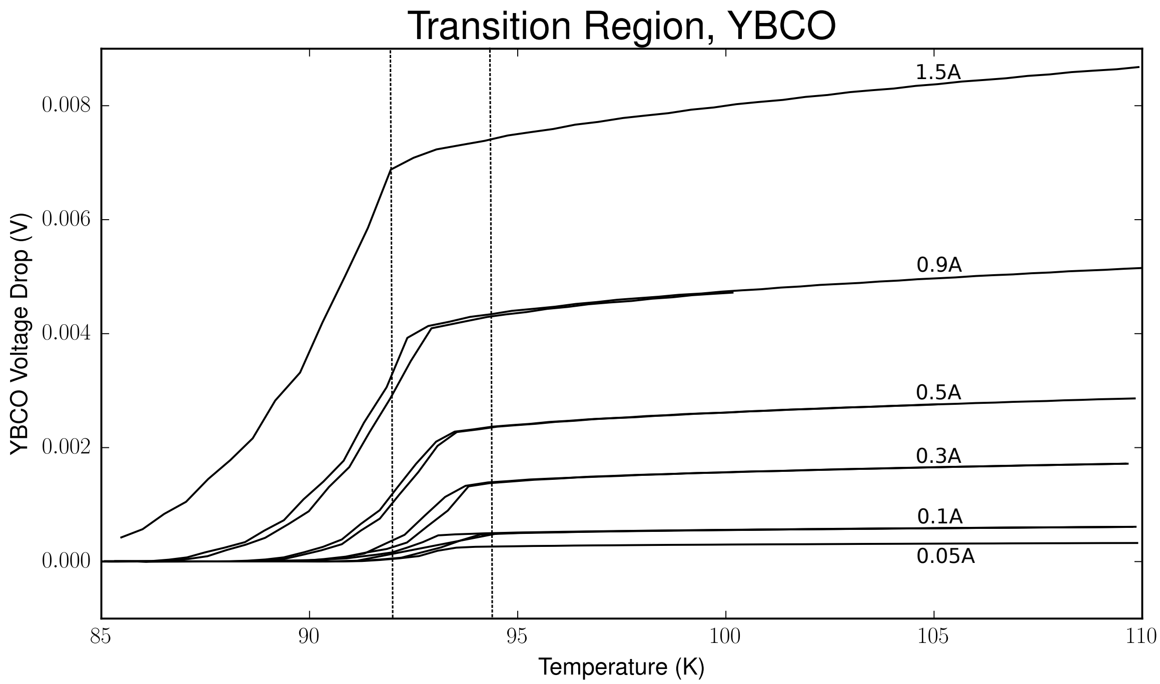

FIG. 14: Voltage versus Temperature for Many Transitions to Superconductivity

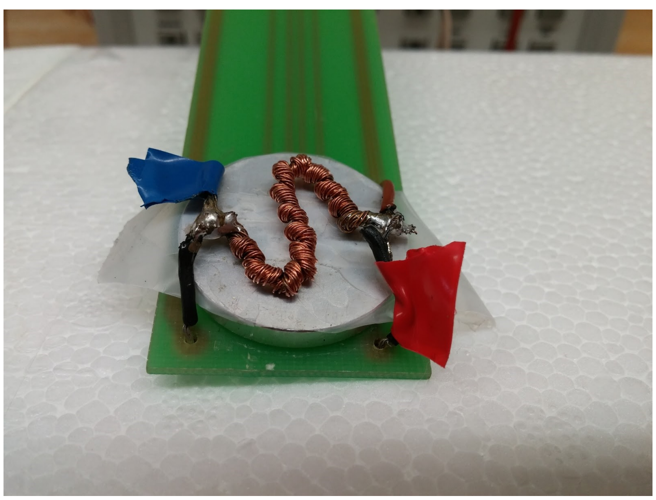

FIG. 15: Copper Test Setup

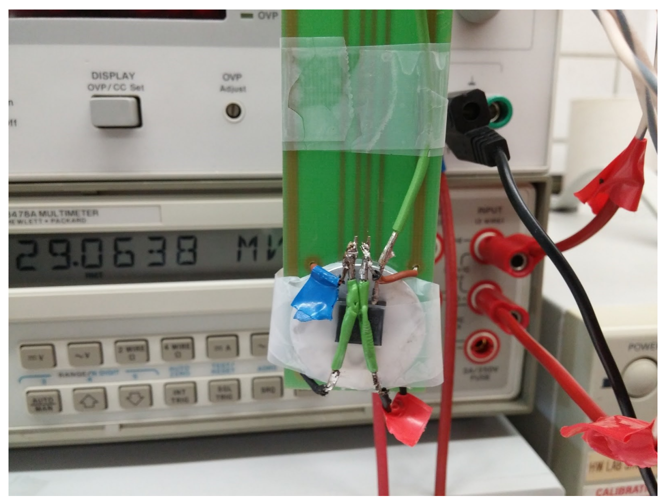

FIG. 17: Setup of the Mosfet Semiconductor

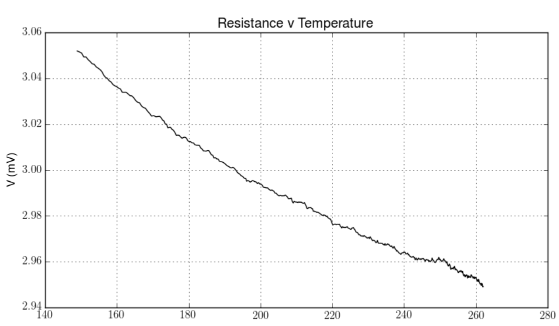

FIG. 16: Voltage vs Temperature Curve for Copper

limited conductivity. The conductivity versus temperature curve theoretically will follow that of metals at higher temperatures (by increasing as temperature drops) and decrease exponentially once temperature gets low enough. These expectations come from the probability of electrons being in the conduction band (predicted by statistical mechanics).

Figure 18 shows the voltage versus temperature curve measured for the Mosfet. As was mentioned, this curve is linearly related to the resistivity versus temperatrue curve. Because resistivity is the inverse of conductivity, the general shape of the curve observed matches theory

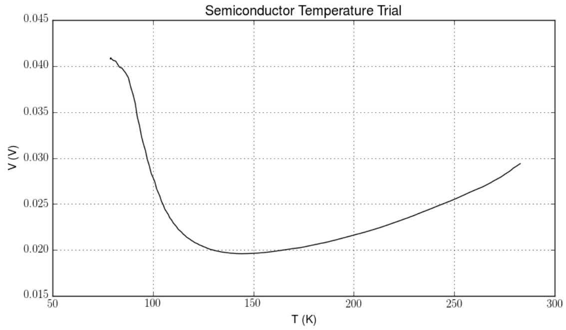

FIG. 18: Voltage versus Temperature Curve for the Semiconducting Mosfet

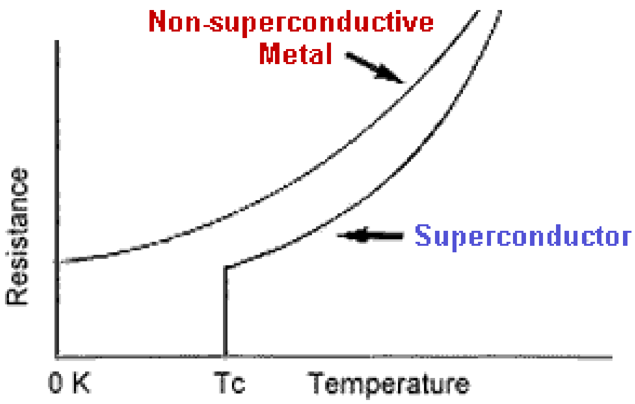

FIG. 19: Resistance versus Temperature for Superconductors and Ordinary Metals Obtained From: http://www.superconductors.org/type1.htm

pretty well. As temperature drops, the resistivity drops, and once the temperature gets down to about $125K$, the resistivity exponentially increases.

CONCLUSION

Superconducting Transition Temperature in YBCO As part of experimental focus, the properties of superconductors when the materials temperature dropped below its critical temperature were observed. The recorded results were what the theory accurately predicted, despite the significant (although expected and explainable) influence from the hysteresis effect. As the YBCO dipped into the liquid nitrogen, it began to quickly decrease its temperature while its voltage decreased as well. The data graph containing measurements for temperature vs voltage display the kind of plot curve similar to the theoretical result for the transition. However, the effect of an external magnetic field from two permanent magnets was not strong enough to significantly affect the transition temperature, probably due to the positioning versus strength of the magnets.

Resistance versus Temperature for Other Materials In addition to testing the YBCO, observations of the characteristics of a metal and a semi-conductor were taken. The metal did not give results that matched theory due to already low resistance and noise from the current supply. However, the semi-conductor gave a curve that matched theory extremely well. Neither of these device produced superconductive behavior, though, which is expected.

The Meissner Effect The Meissner Effect was clearly observed when liquid nitrogen cooled the YBCO, causing the rare earth magnet to levitate above the superconductor, held in place by the expelled and trapped magnetic field. The levitating is an excellent qualitative observation that strongly supports the superconductive properties of the YBCO. The magnet did not levitate until the liquid nitrogen had significantly cooled the YBCO, and the transition is clearly noticed when the magnet seemingly comes to life above the YBCO sample.