Effect of the Orientation of a Magnetic Field on the Resistance of a YBCO Superconductor

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The resistance of a Yttrium Barium Copper Oxide (YBCO) superconductor in an external magnetic field was measured as a function of the angle between the current and the magnetic field. It was expected that the resistance would be a function of the magnetic flux in the conducting planes of YBCO. The resistance of the sample was measured and a 50mT magnet which was oriented through the angles 0° to 120° in both directions and then both polarities relative to the face of the sample. An attempt to fit a sine function to the data succeed for two of the four trials. Magnetic hysteresis was clearly observed, because identical fields on the superconductor would have different affects on the resistance. There was a trend for the increase to be most at 100°, which suggests that it follows a Cosine function. Whether or not the magnetic field created a change in the resistivity of the superconductor or created a voltage across the superconductor that was measured as a resistance was not determined.

I. INTRODUCTION

Superconducting materials are known to have two properties. First, they become ideal conductors in their superconducting state, which means they will have a resistivity of zero. Second, any external magnetic field is expelled from the superconductor by an equal and opposite magnetic field created by the superconductor. The second property is known as the Meissner effect and is often demonstrated by levitating a magnet above a superconductor. [1]

The initial experiment was an attempt to recreate an anomaly that was observed twice during a previous experiment. The anomaly was a prolonged decreased period of negative resistance that occurred between 85°K and 87°K, which was before the YBCO superconductor began the transition from superconducting to normal conduction at 88°K. (see Figure 1)

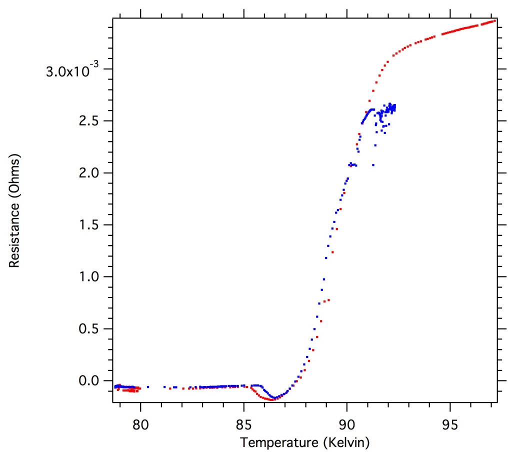

FIG. 1: The two trials that exhibited negative Hall resistivity in the previous experiment.

My attempts in recreating the anomaly were unsuccessful and due to time constraints the experiment was changed to the investigation of a new effect which was observed during experimentation. Having a sufficiently strong external magnetic field on the superconductor sample affected the recorded resistance of the sample as did the angle that the field was with the current direction in the sample.

Superconductors are defined as having a resistivity of zero when superconducting. So the notion of the superconductor ever changing its resistivity from zero in a superconducting state would be impossible. However, the experiment measured the voltage drop across the sample and the resistance was calculated from that and the known constant current. So it could be considered that the magnetic field affected the voltage across the sample instead of its resistance.

A problem faced with this experiment was magnetic hysteresis, which is where a material that was in an external magnetic field will partially maintain the magnetic induction after the external magnetic field has been removed. This affected the experiment because when the magnet was rotated around the superconductor, the superconductor would remember the previous states of magnetic induction. This meant that after one data point was taken the next data point would be skewed by the residual induction from the previous point.

II. THEORY

In order to be superconducting, a superconductor's temperature must be below it's critical temperature T_c. Not only must that condition be met but it also cannot be in a magnetic field above a critical induction, B_T nor can it carry a current above the a critical current, J_c. B_T is temperature dependent and is calculated for the superconductors current temperature T as,

$$B_T = B_c\left[1 - \left(\frac{T}{T_c}\right)^2\right]. \quad (1)$$

Where B_c is the critical field strength when the temperature is 0°K **??**

The critical current is simply the current that will produce a critical magnetic field. By ampere's law the magnetic field strength at distance a from a wire is,

$$\mathbf{B} = \frac{\mu_o \mathbf{I}}{2\pi a}. \tag{2}$$

So it follows that the current which would produce a critical magnetic field is,

$$I_c = \frac{2\pi a B_c}{\mu_o}. \tag{3}$$

Magnetic Flux is the amount of magnetic field passing through a surface. For a flat surface, the magnetic flux Φ is given by,

$$\Phi = \vec{\mathbf{B}} \cdot \vec{A} \tag{4}$$

Where $\vec{A}$ is the normal vector to the plane. This can also be expressed as,

$$\Phi = |\mathbf{B}||A|\cos(\theta). \tag{5}$$

Where θ is the angle between the magnetic field and the normal vector to the surface.

When a material is placed in a magnetic field, charges near the surface are magnetically induced by the change in magnetic flux forming diamagnetic currents that repel the magnetic field. The internal resistance of most materials is nonzero, so the diamagnetic currents are not enough to produce a magnetic field strong enough to fully repel the external magnetic field. As a result, the external magnetic field penetrates the material. [6]

With a superconducting material, the internal resistance is zero so the diamagnetic currents produced form a magnetic field that perfectly repels the external magnetic field. Therefore, the magnetic field inside the conductor ($\mathbf{B}$) is zero. Since $\mathbf{B}$ is given by,

$$\mathbf{B} = \mu\mu_o\mathbf{H}. \tag{6}$$

Since μ_o and $\mathbf{H}$ are not zero, then the magnetic permeability μ of a superconducting material is zero. The complete repulsion of the magnetic field from the superconductor is known as the Meisner effect.

For type-I superconductors if the magnetic field reaches H_T then the magnetic field will enter the superconductor and it will stop superconducting.

Type-II superconductors, like YBCO, will repel an external magnetic field as a Type-I would. However, when the magnetic field becomes too strong and enters the superconductor, type-II superconductors will localize the magnetic field into vortices. These vortices are columns of diamagnetic currents surrounding the magnetic field.**??** Vortices are pinned to deformations in the lattice (Yttrium in the case of YBCO) and will also space themselves apart evenly. The space that the vortices occupy are not superconducting, which does not stop the material from superconducting because the current can travel around the vortices. Once the vortex lattice becomes too crowded, there will be no superconducting path for the current to follow and the superconductor will stop superconducting. At this point the superconductor has reached its upper critical limit (H_{c_2}); its lower limit (H_{c_1}) is defined as when the vortices form.[7] In order

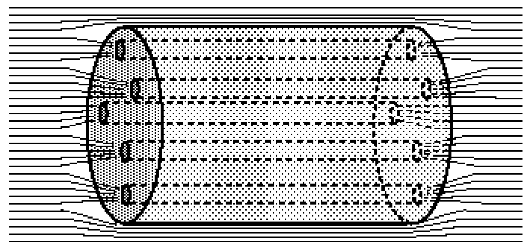

FIG. 2: Magnetic field lines penetrating a cylindrical type-II superconductor in localized vortices.

to create Negative Hall Resistivity, there must be a gap between the vortices and the anti-vortices.[2] For YBCO H_{c_1} is 5×10^{-3} Tesla at 77°K when the magnetic field is perpendicular to the current, which is when vortices form.[5] The anti-vortices are essentially vortices in the opposite direction of normal vortices. This makes anti-vortices paramagnetic in nature while normal vortices are diamagnetic.[4] Since I could not find any reference as to how anti-vortices are formed, and I could not observe it again, I forfeited the attempt to create negative Hall resistivity.

III. PROCEDURE

The YBCO sample was fitted in a brass socket that integrated the sample into a circuit. The circuit had a DC power supply run a constant current of 100mA through the YBCO sample and a 5Ω resistor in series. A Keithley 2010 Multimeter measured the voltage across the 5Ω resistor and the voltage across the sample. There was also a thermocouple with one junction attached to the brass socket and another was left at room temperature.

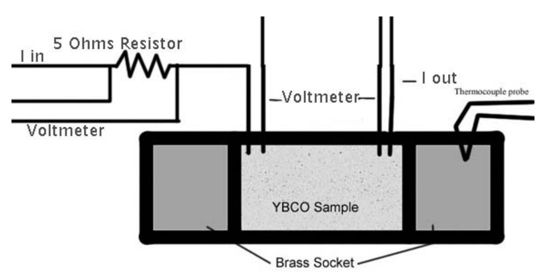

FIG. 3: Schematic of the circuit. The multimeter would measure the voltages across the 5Ω resistor, the sample and the thermocouple.

The multimeter repeatedly measured the voltages across the sample, the resistor and the thermocouplein sequence and transferred the values to a computer running LabView that calculated and recorded the resistance of the YBCO sample using the voltage across the 5Ω resistor to calculate the current, the voltage across the sample to determine it's resistance as $R = \frac{V}{I}$, and the temperature using a polynomial fit created using the thermocouple data from the charts.

Another attempt used a large solid steel cylinder inside both of the solenoids to create the largest electromagnet available to me. The electromagnet was placed perpendicular to the current of the sample and produced a magnetic field of 6.8×10^{-3}T. The magnetic field created was above H_{c_1} but at 2.5cm the magnetic field was not enough.

A dewar containing liquid nitrogen and the sample was on top of a protractor taped to the table. The YBCO sample was suspended so that it was directly over the center of the protractor and was parallel to zero degrees on the protractor and 2 cm outside wall of the dewar, as shown in figure 4.

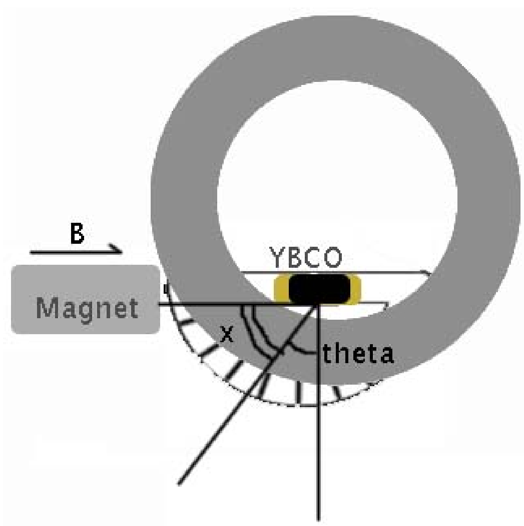

FIG. 4: Schematic of the experiment. The angle labeled "Theta" is θ from 2. X is the angle measured.

The DC power supply was turned on and was producing a constant current of 100mA. The YBCO sample was positioned as aforementioned, and liquid nitrogen was poured into the dewar using a thermos. A neodymium magnet that created a field of 50mT at the poles, was raised 3 cm. The field strength of the magnet was measured using a gauss-meter. The mounted magnet was placed at the edge of the protractor at 7.5 cm away from the sample and produced a 5×10^{-3}T field where the sample was inside the dewar at 0° with the North pole of the magnet facing the sample in the dewar. Once the resistivity stabilized, which was usually after two hundred points, the program was run again for twenty-five points. Then the magnet was moved to 10° and twenty-five more points were taken. This process was repeated to 120°. The whole trial was repeated with the magnet initially being at 120° and increments moving towards 0° and both of those trials were repeated with the south pole facing the superconductor instead.

In order to counteract the affects of magnetic hysteresis, after each trial, the current was turned off and the magnet was placed in the initial position of next trial. Then the current was turned on and the program was started again to wait for the resistance to stabilize as mentioned before. However, this was not done for each point during a trial.

IV. ANALYSIS

The averages and standard deviation of the resistances from each 25 point set were calculated and those values were plotted in IgorPro. Weighted fits following the equation $y_0 + A\sin(f \cdot x + \phi)$ were used on each, where x was the angle measured in radians. The trial which took data from 120° to 0° with the south pole facing the sample showed significant outliers in the points at $0°, 110°, 120°$ and those points were not included in the fit.

For the trials with initial positions with the north pole at at 0° and with the south pole at 120°, the fit function would not converge after 40 iterations. The strong deviation at the endpoints for the south pole might be due to experimental error, because the resistance did change as a function of the distance between the magnet and the sample. If, for those outlier points, the magnet was not at the same radius from the sample as it was for the other points then there would be a strong deviation from the expected values.

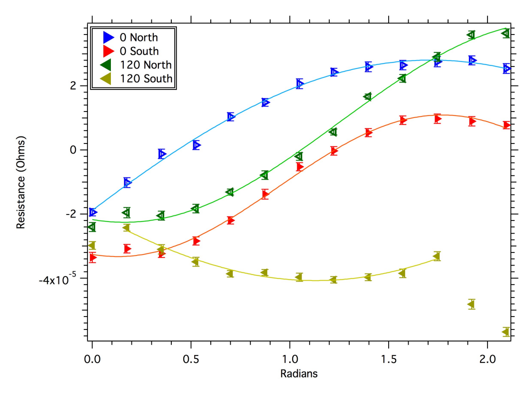

FIG. 5: There are only two points of intersection. The trials with the north pole facing the sample intersect at 100°and the trials with the south pole facing the sample intersect at 20°.

As expected, there was general trend for the measured resistance to be greatest around where the orientation of the magnetic field is perpendicular to the current, and least when the magnetic field is parallel to the current. Since YBCO conducts in lattice planes, the effect can be explained as proportional to the magnetic flux through those planes.

TABLE I: Comparison of the calculated parameters of the trials.

Parameter	origin at 120° North	origin at 0° South
y_o	$8.77 \times 10^{-6} \pm 1.1 \times 10^{-6}$	$-1.12 \times 10^{-5} \pm 5.5 \times 10^{-7}$
A	$3.13 \times 10^{-5} \pm 1.2 \times 10^{-6}$	$2.21 \times 10^{-5} \pm 5.1 \times 10^{-7}$
f	1.44 ± 0.08	1.92 ± 0.07
ϕ	-1.80 ± 0.08	-1.82 ± 0.09

For the converging trials (0°S and 120°N) the y_o parameter is incomparable. However, the other parameters are consistent especially the phase shift, ϕ, that is nearly identical at -1.81 radians, which is a phase shift of 100°. Since the fit was a sine function, the phase shift was expected to be 90° to make a Cosine function. The extra 10° could be because the lattice planes are not parallel to the length of the sample. If my hypothesis that the resistance is a function of the flux through the conducting planes is true, then the affect could be used to measure the orientation of the planes of a YBCO crystal.

Interestingly, for trials of the same polarity, the resistances measured for the same angle do not match. While the effect can be explain as a consequence of magnetic hysteresis , the resistances do not behave the same way as the magnetic induction of a material would. For magnetic hysteresis, the absolute change in internal magnetic induction is initially less but then increases until it begins to approach unity with the external magnetic field. Then the absolute change in magnetic induction decreases. For the trials with north polarity, the absolute change in resistance was greater when the external magnetic field was closest to the origin. This implies that the resistance does not have a linear dependance on the orientation of the magnetic field.

The experiment might have been more revealing if a full sweep of 0°to 360°could be taken. This would have been possible to do if the radius of the dewar was smaller. However, because the dewar was so large, 10.5cm, the magnet could not produce H_{c_1} at that distance, so the sample was suspended off center from the dewar. This prevented the magnet from sweeping through all possible angles.

V. CONCLUSION

The initial experiment was to recreate negative hall resistivity in YBCO. During this experiment, it was observed that the orientation of a magnetic field had an effect on the measured resistance of the superconductor in a superconducting state. The experiment was changed to explore this affect. Due to magnetic hysteresis and limited angles of magnetic orientation to measure, no conclusive model could be determined. However, it was observed that the measured resistance was greatest when the magnetic field was perpendicular to the current and least when it was parallel to the current. This was in accordance with the hypothesis that the resistivity increased with an increase of magnetic flux through the conducting planes of the YBCO lattice. If this theory is true then the effect can be used to determine the orientation of the lattice for a YBCO crystal. Whether the change in resistance was cause by an actual change in the resistivity of the superconductor or from a voltage being created across the superconductor was never determined. Perhaps, if multiple full sweeps of the all 360° for each polarity and directions was done then more conclusive data would be gathered.

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