Understanding Magnetometry Using Optimally Doped BSCCO

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The current method of obtaining T_c values of superconducting material such as BSCCO-2212 in the Dessau Lab is with the magnetometer. Up to this point, the magnetometer has been used to measure a rough estimate, with an uncertainty of 2-3 K, of the temperature at which the superconductor transitions into its superconducting state. New methods have been developed in order to increase the accuracy of this measurement, specifically regarding the system's hysteresis and thermal gradient. These new methods have been able to decrease the uncertainty of the measurement to less than 0.05 K. This paper explores the inner workings of the magnetometer in order to achieve the most precise and accurate measurements of T_c.

INTRODUCTION

What are Superconductors?

Superconductivity is a branch of condensed matter physics that was first discovered by Heike Kamerlingh Onnes in 1911. Since then many types of superconductors have been studied yet there are many aspects of superconductor properties that are not well understood.

There are three main properties that help define a superconductor: perfect conductivity, perfect diamagnetism, and quantized flux lines [13]. Perfect conductivity is the feature that led Onnes to note that some materials transition to a superconducting state at a certain critical temperature. Perfect conductivity is where the electrons in a material can flow with zero resistivity (R = 0). Therefore these materials do not produce losses [9].

Perfect diamagnetism, discovered by Meissner and Ochsenfeld, is where there is complete magnetic expulsion from the material. Therefore, B = 0 in the interior of the material. If a magnetic field is applied below T_c, the critical temperature value where the sample becomes superconducting, screening currents on the surface of the material are induced in order to have an unchanged magnetic field in the interior. If a magnetic field is applied above T_c, then the magnetic field is expelled from the interior as it is cooled through T_c [13]. The screening currents that arise flow in the opposite direction as the applied field in order for them to cancel (except on the surface). The rise of these screening currents to expel the magnetic field from the interior is call the Meissner Effect.

The third defining feature is that magnetic flux passing through a material in a superconducting state can only take on discrete values (i.e. quantized flux) [13]. These quantized flux lines are "pinned" at specific locations on the material, hence they are called pinning sites. This feature is specific to type-II superconductors and therefore will be discussed further in the paper.

It is important to recognize that these features only occur when the material is in a superconducting states. This occurs when below some critical temperature, T_c, and magnetic field, H_c. ($T<T_c$, $H<H_c$).

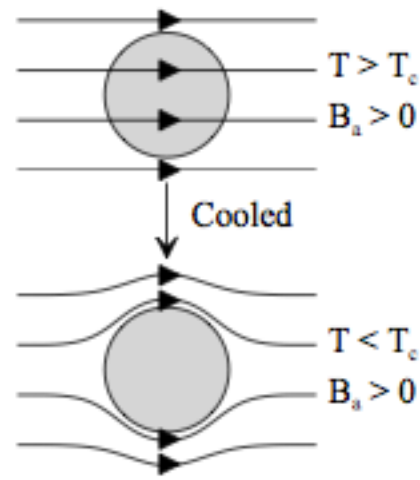

FIG. 1: [14] This image shows a sample being cooled through T_c and the expulsion of the magnetic field that results. This is called the Meissner Effect.

Models of Superconductors

The first theory to explain superconductivity with quantum mechanics was developed by Bardeen, Cooper, and Schrieffer. This BCS theory focuses on conducting super-electrons that form Cooper pairs due to the mechanical vibrations (phonons)in the crystalline lattice. This movement in the lattice diminishes the repulsion between the electrons and causes them to attract. This is only possible below T_c [4].

In 1950 a wave function model was presented as a alternate theory for superconductivity. The Ginzburg-Landau theory focuses on the superconducting elections themselves and not the excitations of them as in the BCS theory. This wave function is related to the density of super-electrons and "can be considered the center of mass of the cooper pairs" [13]. In this model, there is a temperature-dependent coherence length, ξ, which is the distance where the super-electron density changes from maximum to minimum. This model also defined a penetration depth, λ, which is the shortest distance that a Magnetic field can change in the superconductor [6]. In other words, this is the distance into the surface where the screening currents of the Meissner effect take place. This is also called London penetration after the London equations that derive this distance. This led to the Ginzburg-Landau ratio:κ=λ/ξ [6].

When κ is very large, this causes a negative surface energy which means that the superconductor experiences a mixed state. This mixed state is where the normal and superconducting states can co-exist [13]. Mixed states are a specific property of Type-II superconductors which will be discussed in more detail in the next section.

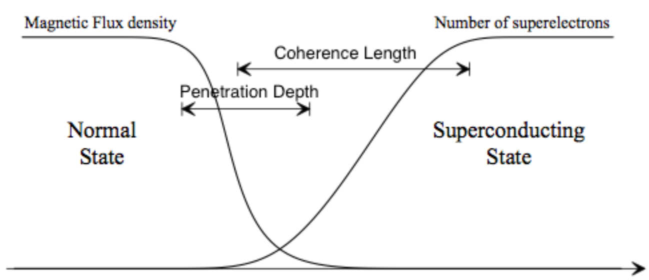

FIG. 2: [15] This image defines the coherence length and the penetration depth that are important properties in the Ginzburg-Landau theory. These two values make up the Ginzburg-Landau ratio which defines a negative or positive surface energy. The coherence length and penetration depth also indicate whether the sample is in a mixed state.

Why are High T_c Superconductors So Special?

The research in the Dessau lab focuses on Type-II superconductors, specifically high temperature superconductors, HTS. Type-II superconductors are mainly alloys as compared to the mainly pure metals of Type-I superconductors. The HTS that was used for the magnetometer experiments were under-doped, over-doped, and most commonly, optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (oxygen doped) 2212. It is the layers of copper-oxide that produce the screening currents. Therefore the more copper-oxide planes that are grouped together the larger the T_c of the sample [13]. This makes sense because the more screening currents the more the sample can expel the magnetic field, which in turn means that the temperature value where the magnetic fields become expelled increases.

In Type-II superconductors, the magnetic field is expelled perfectly up to a field H_c1. Above this value, the field is only partially expelled by the superconductor, so there is no longer perfect diamagnetism. The superconductor still maintains its perfect conductivity in this region though. This is referred to as a mixed state and occurs up until field H_{c2}. Above H_{c2}, the sample is no longer in its superconducting phase [10]. In its mixed state, a superconductor can have partial magnetic penetration. In this case, the material is never in a purely superconducting state, quantum flux of the magnetic field occurs through the interior of the sample [13].

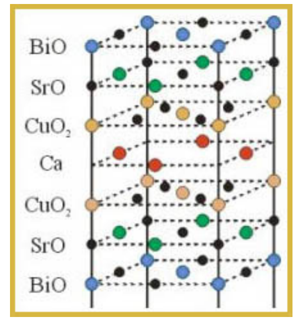

FIG. 3: [11] This is the crystal lattice structure of BSCCO materials. Then number of copper-oxide layers in a row can vary and this determines how high the T_c of the sample is.

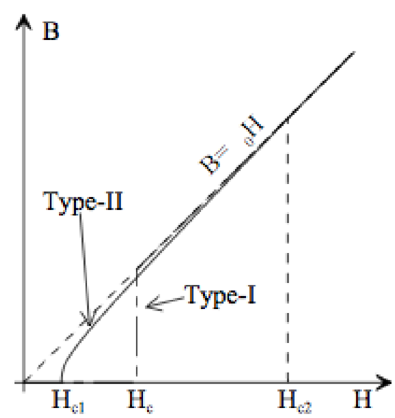

FIG. 4: [16] This image shows H_{c1} and H_{c2} for Type-II superconductors. Below H_{c1}, the superconductors are perfectly diamagnetic. Between $H_{c1}$and H_{c2}, the materials experience a mixed/vortex state. Above H_{c1}, the metal alloy is in its normal state.

Alexei Abrikosov theorized that the magnetic field would penetrate the material in an array of flux tubes each with a diameter equal to the coherence length, ξ. Each of these tubes would have the quantum flux ϕ=$h/(2e)$ passing through its normal state interior. Changes in the applied magnetic field will therefore cause the density of these flux tubes to change. Within each tube, there are super-currents that increase the flux toward the center of the tube. These super-currents are called vortices and they induce magnetic fields with the total flux equal to a single quantum of flux. These supercurrents prevent the surrounding regions of the superconductor from experiencing flux which in turn maintains the discrete pinning sites as well as the diamagnetism within the material [13].

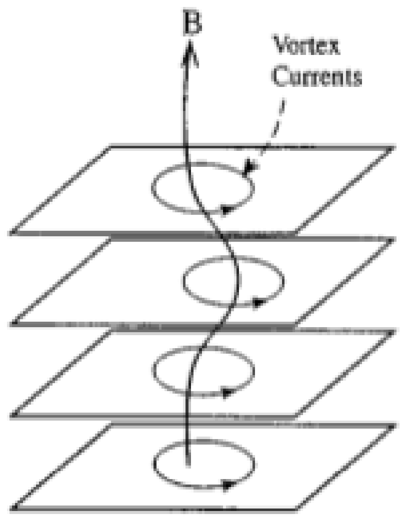

FIG. 5: [18] This image demonstrates what a flux tube looks like as well the super currents that are associated with it.

In HTS, the Ginzburg-Landau ratio, κ, is very large. This shows that HTS have a very large mixed state region. Due to its structure, though, it also exhibits large thermal fluctuations which cause the vortices to "melt" into liquid vortex states. This in turn causes the pinned flux tubes to freely move when subject to force. In other words, they are no longer pinned. In order to fix this problem, impurities are introduced into the structure of the superconductor. This will allow the vortices to be pinned at these impurity sites. Unfortunately since there is no pattern to the impurities in the material, there will also be an irregular pattern of the flux tubes [13].

What is Hysteresis?

There are two ways to define hysteresis. One is that there is a dependence of a system on its past. This is considered a type of "memory" where if the input alternately increases and decreases, the output produces a hysteresis loop. This intrinsic explanation of hysteresis is shown through the magnetic relaxation of a superconductor and the movement of the vortex tubes. Magnetic relaxation is the process that allows the configuration of vortices to relax which leads to a redistribution of current loops in the material. This in turn causes a change in the magnetic moment of the material with time. Magnetic relaxation is most commonly caused by thermal activation or quantum tunneling [17]. The flux tubes as discussed in the previous section, are another source of intrinsic hysteresis. The imperfection in the lattice structure of the material create energy barriers which in turn keep these flux tubes pinned at a specific site. In order for the flux tubes to move, a force must be applied for it to overcome this energy barrier. This would also cause energy dissipation and in turn, a hysteresis effect [13].

The alternate way to define hysteresis is extrinsically. In other words, the hysteresis represents a lag between the input and the output due to its environment. This is the type of hysteresis that will be studied in the magnetometry experiments. In this case, the hysteresis is due to the thermal conductivity (a materials ability to conduct heat) of the copper in the system and the thermal gradient it produces between the sample and the diode.

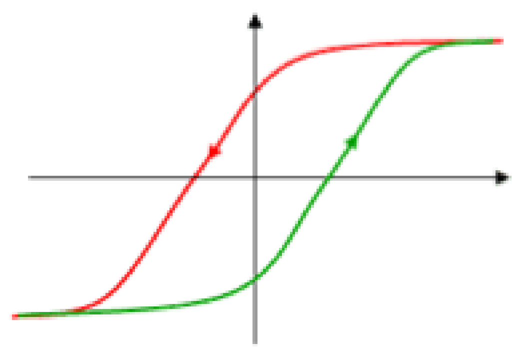

FIG. 6: [8] This is an example of the shape of hysteresis loops.

EXPERIMENTAL SETUP

Magnetometer

The instrument used by the Dessau Lab to measure the T_c of a superconductor is the Magnetometer. The Magnetometer employs the method of mutual inductance. In this method, there are two coils that surround the sample on each side. One is the driver coil, which has an AC current. This AC current produces and AC magnetic field. The other coil is the pick-up coil. This coil generates a current signal when it comes in contact with the AC magnetic field. When the sample that is wedged between these two coils is in the normal state, the magnetic field penetrates the sample. On other words there is magnetic flux through the superconductor. The pick-up coil detects this magnetic coil and produces a signal. When the sample is in the superconducting state the Meissner effect takes over which expels the magnetic field generated by the driver coil from the sample. This shielding prevents the AC field from reaching the pick-up coil and in turn prevents the pick-up coil from producing a signal. In theory, if the sample was infinitely long, the pick-up coil signal would drop to zero. Due to the fact that these samples are of finite size and that often the sample is smaller then the radius of the coils, some of the signal still gets detected by the pick-up coil. Therefore when T_c is reached we see a drop in signal and the size of this drop is proportional to the size of the sample.

There are several advantages to using the method of mutual inductance as opposed to other techniques such as resistivity measurements. Most importantly, it does not damage the sample because there is no direct electrical contact. Another advantage is that it examines the sample more uniformly than other methods. This is because the super-currents that create this shielding effect must flow around a large outer layer in order for the drop in signal to be observed [12].

Figure 7 shows the layout of the magnetometer. Within the removable square piece lies one of the coils while the other lies in the base of rod. The sample gets placed in-between this removable square and the rod. Next to the coils lies the heater and the diode. The heater is used to vary the temperature of the sample at different speeds from both low to high and high to low temperatures. The diode measures the temperature on the copper base of the magnetometer. The diode used is a semiconductor junction that can be used to sense temperature due to a change in voltage along the forward direction of the diode. One advantage to using diodes to measure temperature is that they have a nearly linear relationship between temperature and voltage applied [7]. Originally, it was assumed that the temperature that the diode measures from the copper is equivalent to the temperature of the sample (which is located 15mm below the diode). As we will see later in the discussion of the hysteresis, open-holes, and no-holes data, this assumption is incorrect. Therefore the diode is not measuring the correct T_c value. At the other end of the magnetometer there is a wire heatsink which heats the wires so that there is not a large thermal gradient along each wire.

Figure 8 shows a zoomed in view of the coils. On each solenoid there are eight coils with current going in a clockwise direction and eight in a counter-clockwise direction. This setup allows external fields such as earths magnetic field to have less of an effect on the measurement.

The maximum B-field produced is approximately 0.002 T. Note, this was calculated assuming that all the coils along each solenoid were carrying current in the same direction. The fact that half of them were in opposite directions means that the actual field produced is less than the value calculated.

Before the sample is placed in the magnetometer, it is

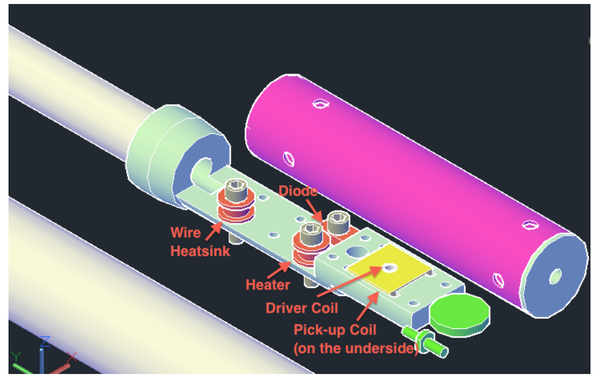

FIG. 7: Figure made by Justin Griffiths. The position of the driver coil and pick-up coil are not necessarily in this order. The rod that holds the these elements is made out of copper (used for its high thermal conductivity at cold temperatures).

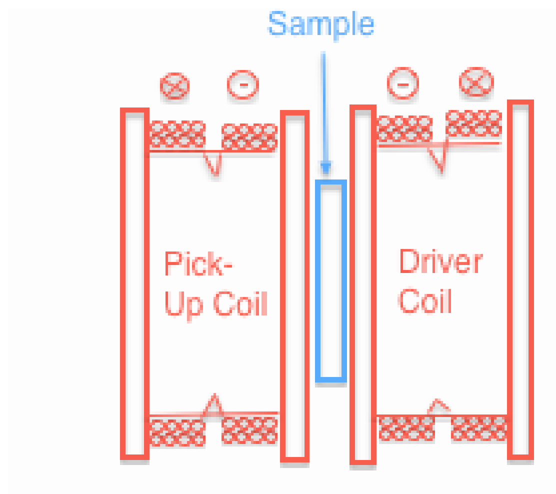

FIG. 8: This image is not to scale. The clockwise/counterclockwise direction of the coils is not necessarily set up in this order.

first put in a magnetometer packet. The magnetometer packet is composed of lens tissue that is folded into a pocket which is then sealed by tape. This packet acts as protection from dirt and other surface damages that might otherwise occur.

Lock-In Amplifier

Due to the very small magnetic field used, the signal generated by the pick-up coil is also very small and is overpowered by noise such as Johnson noise (from thermal fluctuations in the electron density in the resistors), shot noise (from non-uniformity in the electron flow in the current), 1/f noise (from fluctuations in resistance due to the current flowing through the resistor), and external noise [3] . In order to eliminate noise and amplify the signal, a lock-in amplifier is used. A lock-in amplifier is a device that amplifies the incoming signal and them multiplies it by a lock-in reference signal using a phase-sensitive detector (PSD). The PSD singles out the component of the incoming signal that is at a specific reference frequency and phase. The PSD operates by multiplying two signals-input(actual signal plus noise) and reference-together to yield the output signal [1].

$$V_{psd} = V_{in}V_{ref}sin([\omega_{in}t + \theta_{in})sin([\omega_{ref})]t + \theta_{ref}) \quad (1)$$

$$V_{psd} = \frac{1}{2}V_{in}V_{ref}cos([\omega_{in} - \omega_{ref})]t + \theta_{in} - \theta_{ref})$$
$$-\frac{1}{2}V_{in}V_{ref}cos([\omega_{in} + \omega_{ref})]t + \theta_{in} + \theta_{ref})$$

Each of the terms in this output voltage is an AC signal. The output signal is then transferred through a low pass filter. The low pass filter removes all non-DC signal. When the input signal and reference signal are at the same frequency ($\omega_{in} = \omega_{ref}$),

$$V_{psd} = \frac{1}{2}V_{in}V_{ref}cos(\theta_{in} - \theta_{ref}) \quad (2)$$

This output is a DC signal (because the voltage output is no longer dependent on time) which will not be filtered by the low pass filter. At all other frequencies ($\omega_{in} \neq \omega_{ref}$) there is an AC signal which gets filtered out by the low pass filter. The noise from the experiment only contributes to the AC component (assuming that the $\omega_{noise} \neq \omega_{ref}$) and therefore gets filtered out, leaving just the actual amplified signal to be read. When, the reference and input signals are 90 degrees out of phase, the output voltage is reduced to zero. To fix this, the lock-in amplifier has a second PSD which multiplies the input signal with the reference signal shifted 90 degrees.

$$V_{psd2} = \frac{1}{2}V_{in}V_{ref}sin(\theta_{in} - \theta_{ref}) \quad (3)$$

Now we have two output signals, one which is proportional to cosine and one proportional to sine:

$$V_{psd1} = V_{in}cos(\theta_{in} - \theta_{ref}) \quad (4)$$

This is called the in-phase component, because when$\theta_{in}-\theta_{ref}$=0 then only V_{psd} will be measured.

$$V_{psd2} = V_{in}sin(\theta_{in} - \theta_{ref}) \quad (5)$$

This is called the quadrature component [2].

The magnitude of the signal is therefore,

$$R = (V_{psd1}^2 + V_{psd2}^2)^{1/2} = V_{in} \quad (6)$$

Note: Because of the second PSD, the magnitude of the output is no longer dependent on the phase between the input and reference signal. In this magnetometer experiment the lock-in amplifier is set up to produce a 1 V sine wave output. The phase-locked-loop voltage controlled oscillator is set to the highest setting, 10 kHz, in order to reduce the 1/f noise.

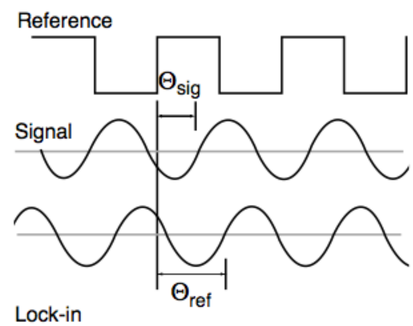

FIG. 9: [?] This image shows the input signal, reference signal, and the signal produced when the two are multiplied by a phase sensitive detector.

Reproducibility

In order to trust the measurements made with the magnetometer we need to be sure that the data is reproducible. To test this, a multitude of situations were experimented with. The most straightforward test was taking one sample and measuring the T_c twice (both measurements were done in the same way: load, cool, warm, unload). Other tests that were run were rotating the sample 180 degrees, measuring the T_c three days later, using liquid helium to cool the sample instead of liquid nitrogen, cutting the sample in half, and placing the sample not at the center of the coils.

Figure 10 shows that most disparity from the original measurement (repeat 1) occurs in the off-centered and the halved measurements. The other measurements fell within 0.17K of the original measurement. This was calculated at a amplitude of 0.5 microV and excludes the off-centered and halved measurements. If these two traces are not excluded, the measurements fall within 0.44K of each other. It should be noted that all of this reproducibility data was collected before the hysteresis was understood. Therefore this data is not as accurate as it now can be.

The large difference in the off-centered measurement can be explained by the fact that when the sample is not in the center of the coil, then the magnetic field only goes through part of the sample. Therefore the measurement is only the T_c of that section that is between the coils. This is very possible considering the inhomogeneities within the superconductor. Also, the magnitude of the amplitude decreased a significant amount as seen before the curves were normalized. The curves were normalized in order to put all the traces on the same scale so that comparisons can be done between the curves. All the curves in these graphs have been normalized by dividing each trace by its maximum height. The magnitude of the amplitude decreased because the surface area between the coils (i.e. the area that gives a signal) was reduced, causing less screening currents to be produced and in turn a smaller signal.

The halved measurements can be explained in a similar way to the off-centered measurements. When a sample is cut in half, it should not be assumed that both halves have the same T_c. Due to inhomogeneity in the sample, one half can have a different T_c value than the other half. This also explains why some T_c curves have two or more different slopes and/or bumps along the trace. Logically, the T_c of the original whole sample should be a weighted superposition of the two halved curves. This trend was noticed in further measurements of halved samples, although it was not thoroughly explored nor was it measured accurately (in other words the hysteresis effect was not taken into account). Also, like the off-centered measurement, the magnitude of the amplitude drop was decreased due to less screening currents and more magnetic field reaching the pick-up coil.

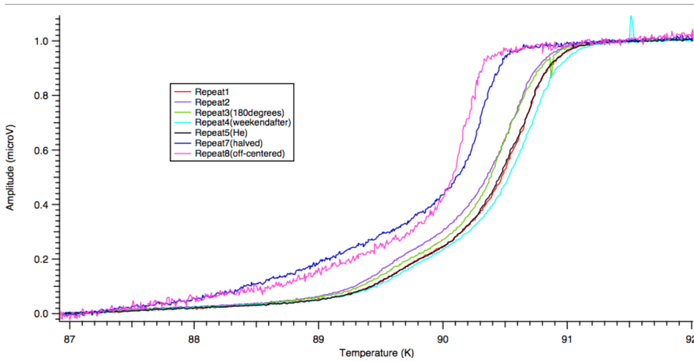

FIG. 10: Data obtained from the reproducibility testing of the magnetometer. The data was collected from various situations such as rotating the sample 180 degrees, measuring the T_c several days after the first measurements, using liquid helium to cool the sample instead of liquid nitrogen, cutting the sample in half, and placing the sample off-centered between the coils.

RESULTS

Hysteresis

The results from the hysteresis all conclude that ramping the temperature of the system at a slower rate decreases the hysteresis. In Figure 11 the hysteresis size drops from 0.27 K to 0.03 K (this was calculated at a amplitude of 0.5 microV) when the ramping drops from 1 K/min to 0.1 K/min. This greatly increases the accuracy of measuring the true value of T_c (which lies in-between the hysteresis curves).

The direction of the arrows indicate the direction of the ramping. This also shows that the sample lags behind the diode as explained in the next section.

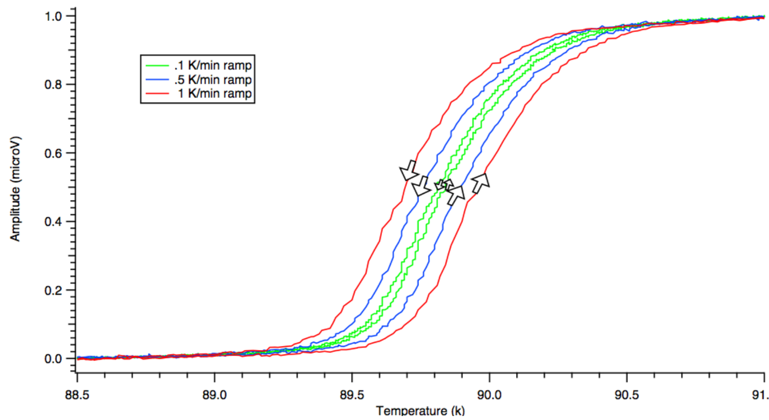

FIG. 11: This is the data collected when ramping one sample at several different rates: 1K/min, 0.5K/min, and 0.1K/min. The arrows indicate the direction of the ramping.

Open Versus Closed Holes

The outer barrel of the magnetometer has several holes in it. The holes were added in order for the nitrogen gas to flow through the barrel and in turn cool the diode and sample at the same rate. This is not the result that is produced from measurements that are taken with open holes and closed holes. In Figures 12 and 13, the curves measured with no holes in the barrel are at lower temperatures that the curves measured with holes. Another interesting feature is that the distance between the two curves is approximately halved for the sample that is about double the mass: the temperature difference between holes and no-holes for Half1 is 0.3577 for Half2 is 0.411 and for Half3 is 0.1436 (this was measured at an amplitude of 0.5 microV).

In order to see which of these T_c curves is more accurate, an additional copper plate was added to the system in order to increase the thermal syncing of the sample to the rest of the copper rod. With this new piece, the sample is placed directly on the copper plate and held in place by silver paint instead of it being placed in a thermally isolated tape packet. This copper plate is then placed into the magnetometer as per usual, making good contact with the copper in the rod. The results from the measurements with the copper are seen in Figure 14.

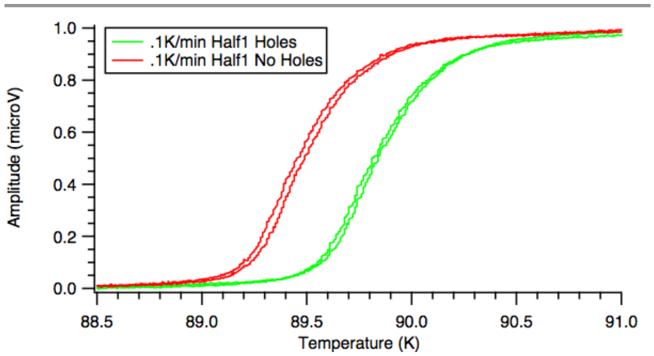

FIG. 12: This is the hysteresis and T_c data collected from sample "Half1" ramped at 0.1K/min with closed and open holes. This sample was split from the same sample as "Half3"

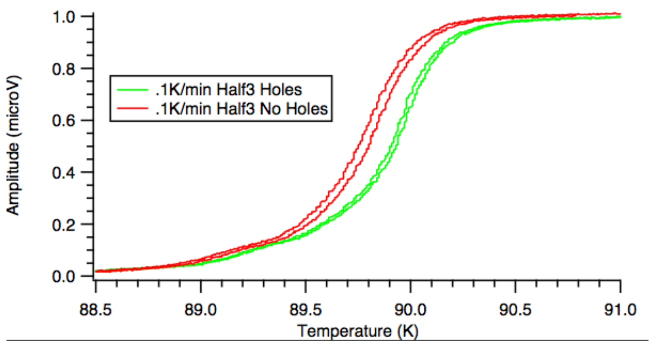

FIG. 13: This is the hysteresis and T_c data collected from sample "Half3" ramped at 0.1K/min with closed and open holes. This sample was split from the same sample as "Half1"

Figure 14 shows that adding the copper plate slightly increased the measured T_c value for both the open and closed holes situations. Inserting the copper plate increased the hysteresis in the open holes measurement and decreased the hysteresis in the closed holes measurement.

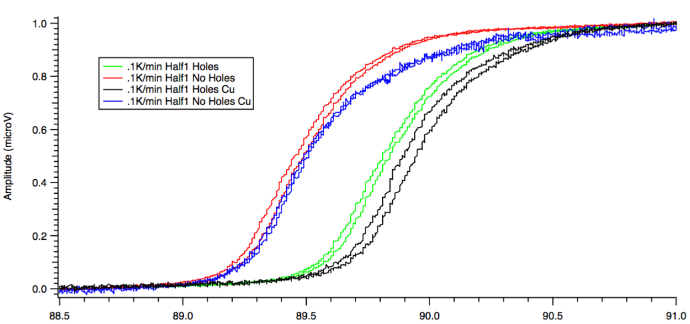

FIG. 14: This is the hysteresis and T_c data collected from sample "Half1" ramped at 0.1K/min with closed and open holes and with or without the sample being silver painted to a copper plate.

DISCUSSION

Hysteresis

Due to the fact that the magnetic field induced from the coils is only 0.002 T, which is much smaller than H_{c1} (approximately 0.02 T for cuprates [5]), no vortices are produced. Therefore all of the hysteresis in this system is due to thermal effects. Since the sample is in a thermally isolated packet, the thermal syncing between the sample and diode is decreased. So as the sample becomes superconducting, there is a difference in the actual temperature that the sample is experiencing and the temperature that the diode is reading. When the sample is being ramped down, the diode reads a temperature that is colder than the actual T_c value. When the sample is being ramped up, the diode reads a temperature that is warmer than the actual T_c value. We see that the sample lags behind the heater/diode because the heater and diode are thermally connected (on the same copper rod) as compared to their connection to the sample. In other words, this lag occurs because the sample is not thermally sunk to the copper rod.

The faster the ramping done by the heater, the larger the hysteresis effect. Since the hysteresis is set by the thermal conductivity of the copper rod, when you ramp the system faster, a larger thermal gradient gets built up between the copper and the thermally isolated sample. This in turn creates a large hysteresis effect. As the ramping slows down, the thermal gradient gets smaller and the hysteresis decreases. The relationship between ramping speed and hysteresis size is shown in Figure 15, which uses a linear fit for lack of a better model.

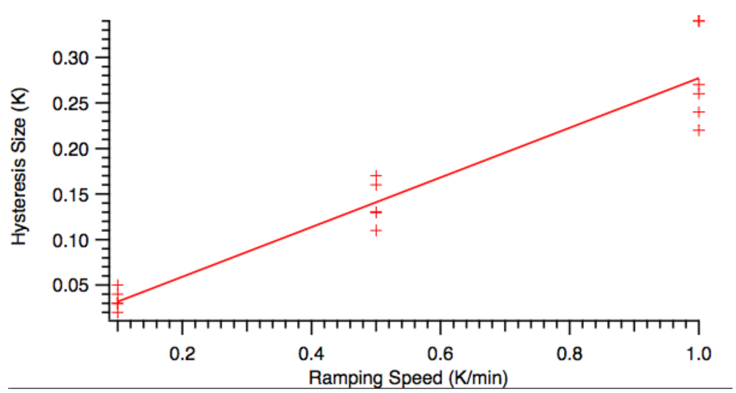

FIG. 15: This is a graph of the width of the hysteresis curves plot against its ramping speed. This data was then fit to a linear model

The real value of T_c can lies inside the hysteresis curves. If the average of the two curves for all ramping rates is taken, you can see the real value of T_c (see Figure 16). The average of these curves was not taken along the x or y axis. Instead, the curves were averaged along each interpolation point. Due to the fact that the curves do not have the same amount of points at the same spacing, there were some areas where the average curve was not a good fit to the actual average. This occurred at the upper and lower ends of the curve for the faster ramped (1 K/min) traces because it contained less points to be interpolated with larger spaces in-between each point.

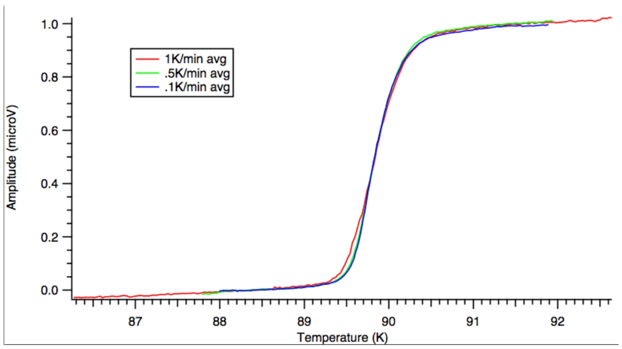

FIG. 16: This is the average taken along the interpolation points of each hysteresis curve at each ramping: 1K/min, 0.5k/min, and 0.1K/min

Open Versus Closed Holes

In order to understand whether the open or closed holes trace is more accurate, several theories explaining the accuracy of both traces have been discussed. If it is assumed that the no holes trace (red curve) is the correct T_c of the sample that means that when the open holes trace (green curve) is measured, the diode is warmer than the sample. This makes sense because the cold gas flowing through the holes is cooling the sample faster than it is cooling the copper. This theory is also consistent with result for the larger mass sample. In the larger mass measurement (Half3) the sample is still cooling faster than the copper but it is cooling at a slower rate due to the fact that it has more mass to cool. Because it has approximately twice the mass to cool, then it has half the amount of disparity between the diode and sample temperature. From this we should expect that when the copper plate is added, the hysteresis should decrease due to the increase in thermal syncing. This is not the result seen from this data and should be further explored.

If it is assumed that the open holes trace (green curve) is the correct T_c of the sample that means that when the no holes trace (red curve) is measured, the diode is colder than the sample. This makes sense because there is not enough conduction to the sample and there is not enough exchange gas in order the the sample to be colder than the diode. Therefore, the sample is warmer than the diode specifically because the sample is thermally isolated in the tape packet and because of the thermal gradient existing between the sample and the diode. From this, we should expect that when the copper plate is added, which decreases the thermal isolation of the sample from the rod, that the hysteresis should decrease (for closed holes), which is consistent with our results. Unfortunately this explanation is not able to incorporate the effect seen with the larger mass sample.

Adding the copper plate was inconclusive in determining whether the closed or open holes trace was more accurate. Therefore more tests are in the process of being measured. One such test is to make a measurement without using the heater. Instead of a heater, the sample is slowly being lowed/raised by hand in order to change the temperature of the sample. Although this does not produce a steady or precise ramping speed, which means that the hysteresis of these measurements should into be taken into account, it should be able to show which T_c value is more accurate due to the fact that there is less of a thermal gradient between the diode/heater and the sample. More tests regarding the effect of larger mass on the distance between the open and closed holes traces are also being conducted.

FUTURE WORK

There are many extensions to this project that should be experimented with in order to better understand the instrument. One such project is doing a more in-depth study of the T_c of halved samples and their relationship to the original whole sample. Another aspect is studying the effects of using liquid nitrogen versus liquid helium on the T_c value and on the size of the hysteresis. This is especially interesting when looking at the relative distances of the T_cs calculated in the open versus closed holes measurements and with the copper plate measurements. It would also be interesting to study isotope samples now that the measurements are more accurate. Due to the fact that isotope samples have a 0.5 K change in the value of T_c as compared to its non-isotope counterpart, measuring this new value was difficult when the error in the measurement was between 2-3 K, larger than the change itself. Now that the hysteresis effect in this system is understood and the measurement is accurate to within 0.03 K, isotope samples can be studied with this instrument.

Other advances can be made in order for the magnetometer to be a more accurate device. This includes creating a tube filled with helium that surrounds the barrel that holds this sample. This technique will work through a series of conduction and convection to cool the sample instead of the nitrogen gas flowing through the sample itself. The exchange gas in this system will be the helium in the tube. This eliminates any error or ambiguities caused by using the gases in the air as the exchange gas. In order for this to work though, the entire magnetometer rod must be vacuum sealed. This is necessary so that the helium does not escape and that gases in the air do not get in. It is also important for controlling the pressure inside the system. Finally, it would be convenient to have a way to measure the T_c of a sample when it is already mounted on a copper disk and ready to be loaded into the ARPES (angle-resolved photoemission spectroscopy). Due to the lack of signal experienced with the thin copper plate (when it was solid and no holes were drilled around the sample), it can be implied that the copper disks will have a similar problem. In order to accomplish this, there must be new design for the magnetometer setup.

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