Superconductivity

PHYS 3606

Lab Report

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1.0 ABSTRACT

This lab report focuses on the superconducting behavior of the cuprate superconductor (Bi-2223-$Bi_{1.8}Pb_{0.26}Sr_2Ca_2Cu_3O_{10+x}$) and the hysteresis curve formed due to the magnetic field applied on it and against the magnetic field that is developed inside of it at 77K temperature. A hall probe inside a current carrying coil was used to take the measurements. Multiple calibration measurements were done before the hysteresis was plotted the celebrative measurements included, the ratio of magnetic field induced inside at the coil center with a 0.5Amp current at room temperature ($0.03 \ +/- \ 0.03$ T/A), the ratio of hall potential and coil current at room temperature (3.51+/- 0.06 V/A) and the ratio of hall potential and coil potential at 77 K (0.212+/- 0.003). For the superconductor part of the experiment a tube shell of the superconductor was insert on top of the hall probe, while the setup was at 77 K and the data was measured that included the range of hall potential and the coil potential. The data measured was then analyzed using the calibration values resulting in a range of intrinsic and applied magnetic field values which were then plotted to provide a hysteresis curve from which the values of trapped (9 +/-2 mT) and shielded magnetic field (9 +/- 1 mT) was extracted. These values should be equal theoretically, an average (9 +/- 1 mT) of the values was then used to calculate the critical current density (1,721,627 +/- 190,000 A/m^2). There were some sources of error that were difficult to account for numerically such as the hall probe was changed during the experiment and was exposed to extremely low temperatures for a long time. A long-time exposure to 77 K temperature leads to issues in the hall probes readings.

2.0 THEORY

Superconducting State

In 1911, Dutch physicist Heike Kamerlingh discovered that the electrical resistance of mercury goes to zero below 4.2 K (-269°C). This was the very first observation of the phenomenon of superconductivity. The majority of chemical elements become superconducting at sufficiently low temperatures. The temperature at which a material starts displaying superconductive properties is called critical temperature. Below this temperature two properties of the material behave in an unexpected manner. Firstly, the electric current offers no resistance and circulates inside the material without any dissipation of energy. Secondly, the external magnetic field does not penetrate the superconductor, but remains on its surface. Figure 1 depicts the various relation between the magnetic field and temperature and the behavior of type 1 and type 2 superconductors in thus situations. In figure 1 when the material in the superconducting region of the plots it depicts the Meissner effect. In Meissner effect the conductor develops surface current that results in cancelling the external magnetic field such that the conductor has no internal magnetic field. Figure 2 depicts the visual representation of the phenomena. For the plot of type 2 superconductor the region that depicts the superconductor to be in mixed behavior depicts the material to have internal flux lines. The material develops internal circular current which allow for some passage of magnetic fields, figure 3 depicts the behavior of a superconductor in mixed region [1] [2] [3].

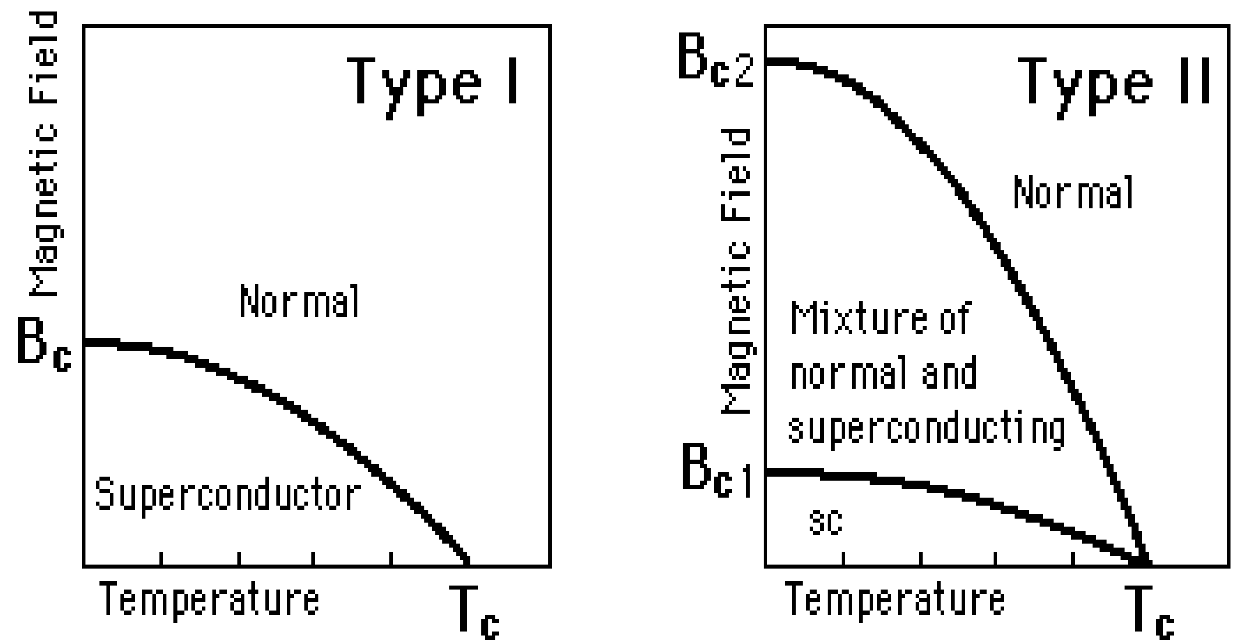
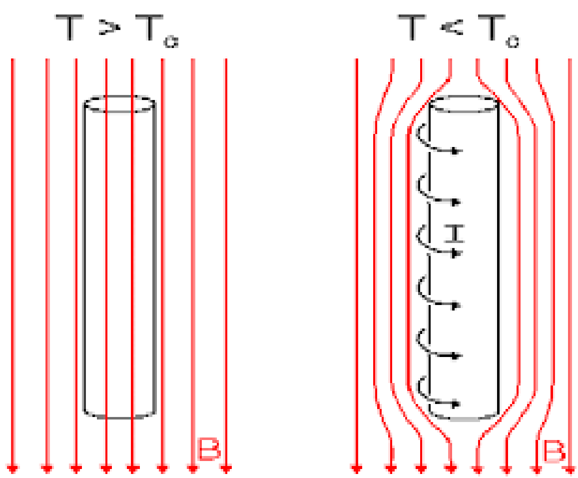


Figure 1: Superconductivity behavior with respect to Temperature and Magnetic Field



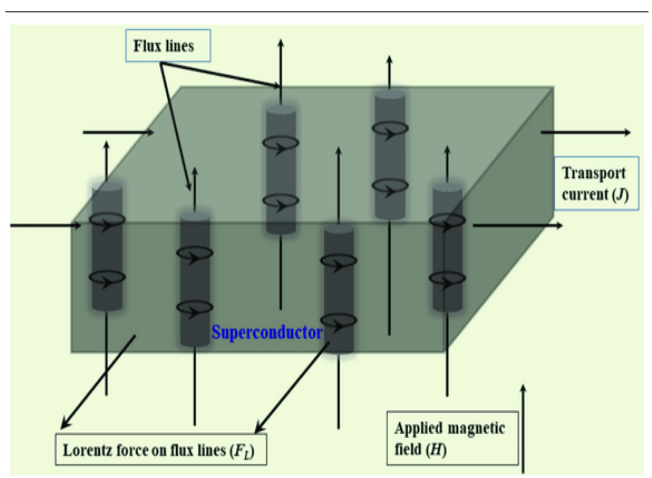


Figure 2: Meissner Effect

Figure 3: Flux Lines in Type 2 Semiconductor

Cooper Pairs

In 1957, John Bardeen, Leon Cooper and John Schrieffer established microscopic theory of superconductivity (BCS Theory). According to this theory electrons group into pairs, "Cooper Pairs" which move around inside the crystal lattice without friction. The solid can be seen as a lattice of positive ions immersed in a cloud of electrons. As an electron passes through this lattice, the ions move slightly, attracted by the electron's negative charge. This movement generates an electrically positive area which, in turn, attracts another electron. The energy of the electron interaction is quite weak, and the pairs can be easily broken up by thermal energy – this is why superconductivity usually occurs at very low temperatures. However, the BCS theory offers no explanation for the existence of "high-temperature" superconductors around 80 K (-193°C) and above. Figure 4 depicts the behavior of the superconductor lattice forming cooper pairs. [1] [4] [5].

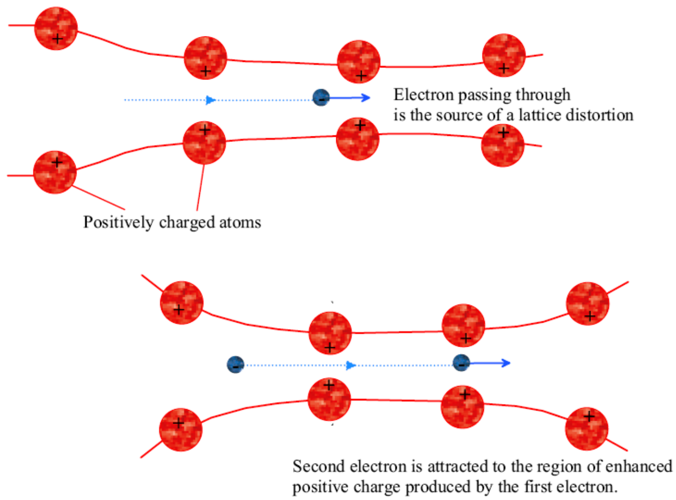


Figure 4: Cooper Pair Formation

Cuprate Superconductors

Cuprate superconductors are quasi-two-dimensional materials with their superconducting behavior determined by electrons moving within weakly coupled copper-oxide (CuO2) layers. Neighboring layers containing ions or dopants such as lanthanum, barium, strontium, or other atoms act to stabilize the structure and dope electrons or holes onto the copper-oxide layers. The pure compound is a Mott insulator with long-range antiferromagnetic order at low temperature. Single band models are generally considered to be sufficient to describe the electronic properties [6].

Analysis Applied

Multiple calibrations were done with the end purpose of being able to calculate the trapped magnetic field and shielded magnetic field for the superconductor. The expected values for the magnetic fields should be equal. Calibration is used to calculate a range of applied and internal magnetic fields using equations 1 and 2.

$$B_{internal} = V_H \cdot \frac{V_c}{V_H} \cdot \frac{I_c}{V_c} \cdot \frac{B}{I_c} \tag{1}$$

$$B_{applied} = V_c \cdot \frac{I_c}{V_c} \cdot \frac{B}{I_c} \tag{2}$$

The plot is used to get the value of shielded and trapped magnetic field using the x-intercept and y-intercept of the plot. Both values should be the same. An average of the values is taken to calculate the critical current density using equation 3.

$$j_c = \frac{BL}{\mu_0} \cdot \frac{1}{Lt} = \frac{B}{\mu_0 t} \quad (3).$$

3.0 APPARATUS

This section lists the apparatus used for collecting data for superconductivity experiments along with the basic apparatus setup that was used for the experiment as is depicted in figure 5. Further figure 6 depicts the Hall probe setup used.

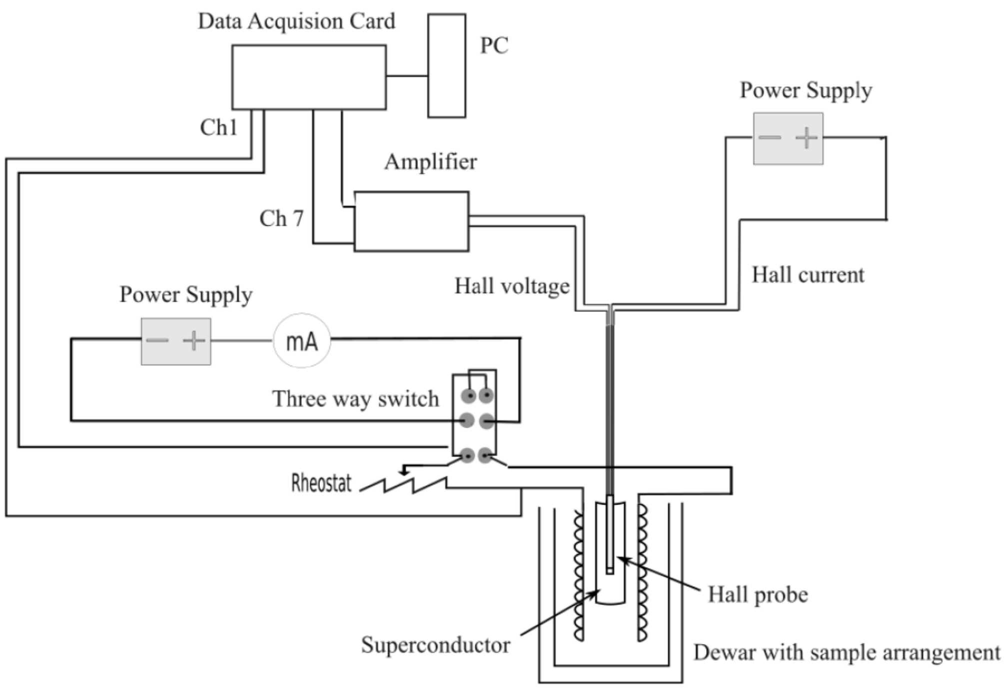


Figure 5: Setup for Superconductivity measurements

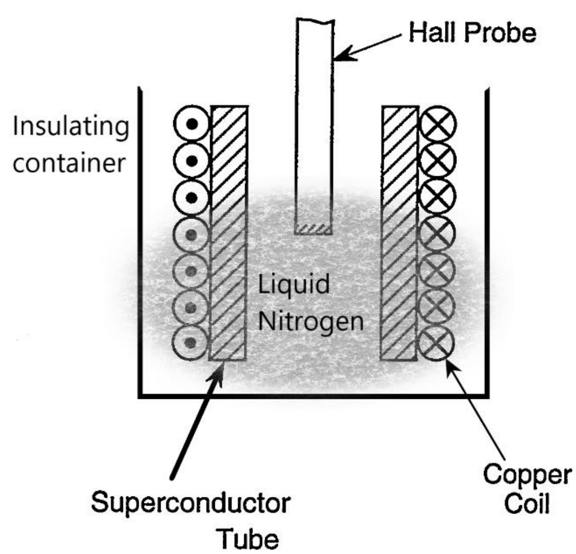


Figure 6: Hall Probe Setup with Superconductor

List of apparatus

- Hall probe
- Super conductor (Bi-2223- $Bi_{1.8}Pb_{0.26}Sr_2Ca_2Cu_3O_{10+x}$)
- Dewar with sample arrangement
- Three-way switch
- Power supply
- Amplifier
- Data Acquisition Card
- Computer
- Gaussmeter

4.0 PROCEDURE

This section discusses the procedure followed to collect the data for three calibration parts of the experiment and the experiment itself. Calibration 1 and 2 were performed at room temperature and calibration3 and the superconductivity part of the experiment were performed at 77 K. Liquid nitrogen was used to cool the temperature of the setup to 77 K.

Calibration 1

The magnetic field present in the center of the coil was measured while the coil carries a 0.5 Amp current. This is done while the system was at room temperature. For this the hall probe was lowered into the center of the coil. The eight readings were taken for the magnetic field with alternating the direction of current every time and the results were averaged.

Calibration 2

The hall probe was still set up at the center of the coil for this part of the experiment one side of the three-way switch was chosen and the current was incremented from the power supply in steps of 0.2A up until 1.35 A. This is then repeated for the other side. The coil current and potential were measured using this method.

Calibration 3

For this part of the experiment the setup was cooled down to 77K using liquid nitrogen. The hall probe was then inserted in the setup. With the coil current being varied from zero to maximum in each direction. Thus, the hall potential and the coil current were recorded, resulting in the formation of a hysteresis curve.

Superconductivity

For this part of the experiment hall potential and the coil potential was recorded with a superconductor tube inserted on top of the hall probe with the setup at 77K. The sample rate was 5 per second with 500 samples for each side.

5.0 RESULTS

Calibration 1

Coil Current (I) = (0.499 +/- 0.004) A

Average Magnetic field (B) = (0.0173 +/- 0.0001) Tesla

$\frac{B}{I} = 0.03 +/- 0.03$ T/A

Calibration 2

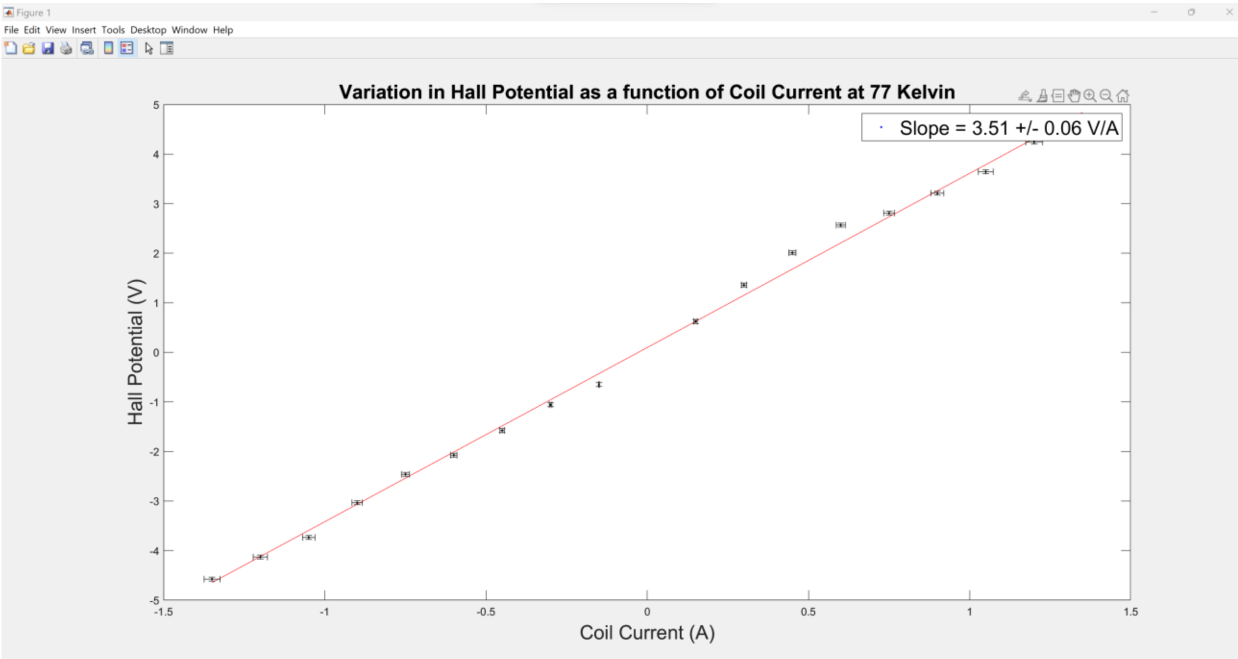


Figure 7: Calibration plot of Hall Potential at Coil Current 77 Kelvin

As seen in figure 7 the slope of variation in hall potential and coil current in 3.51+/- 0.06 V/A. The corresponding MATLAB code can be found in the appendix. The variation in the error bars of the plot is due to the error on the ammeter being dependent on the current itself.

Calibration 3

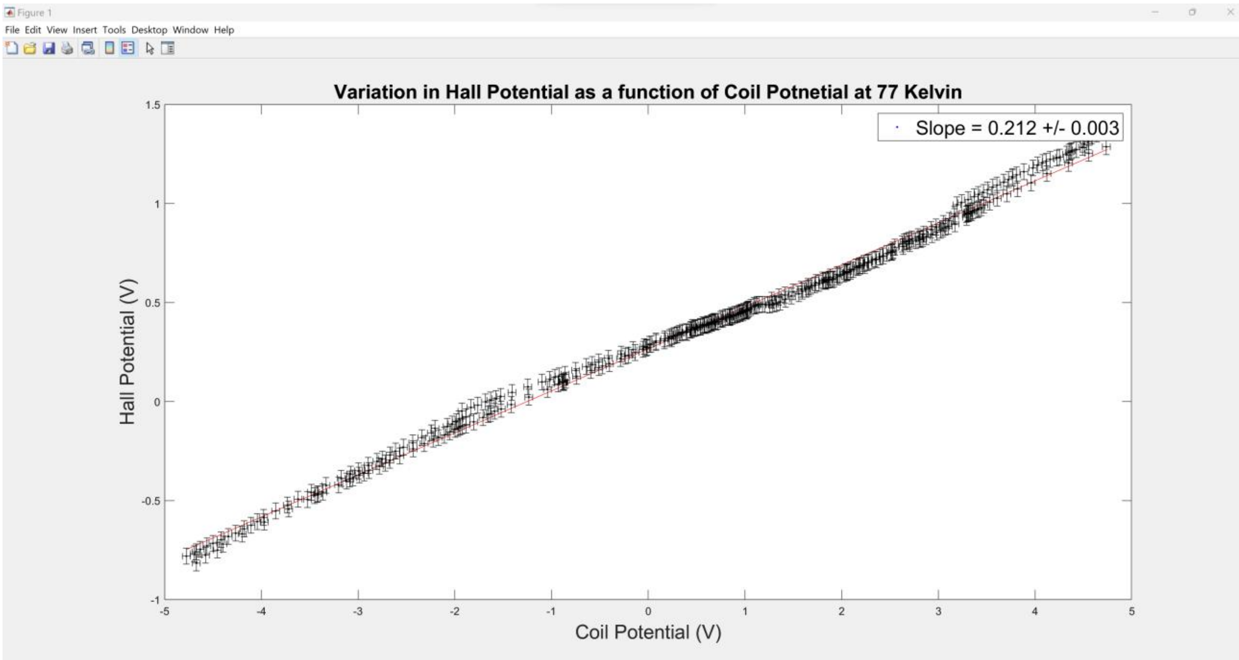


Figure 8: Calibration plot of Hall Potential at Coil Potential 77 Kelvin

As seen in figure 8 the slope of variation in hall potential and coil current in 0.212+/- 0.003. The corresponding MATLAB code can be found in the appendix.

Superconductivity

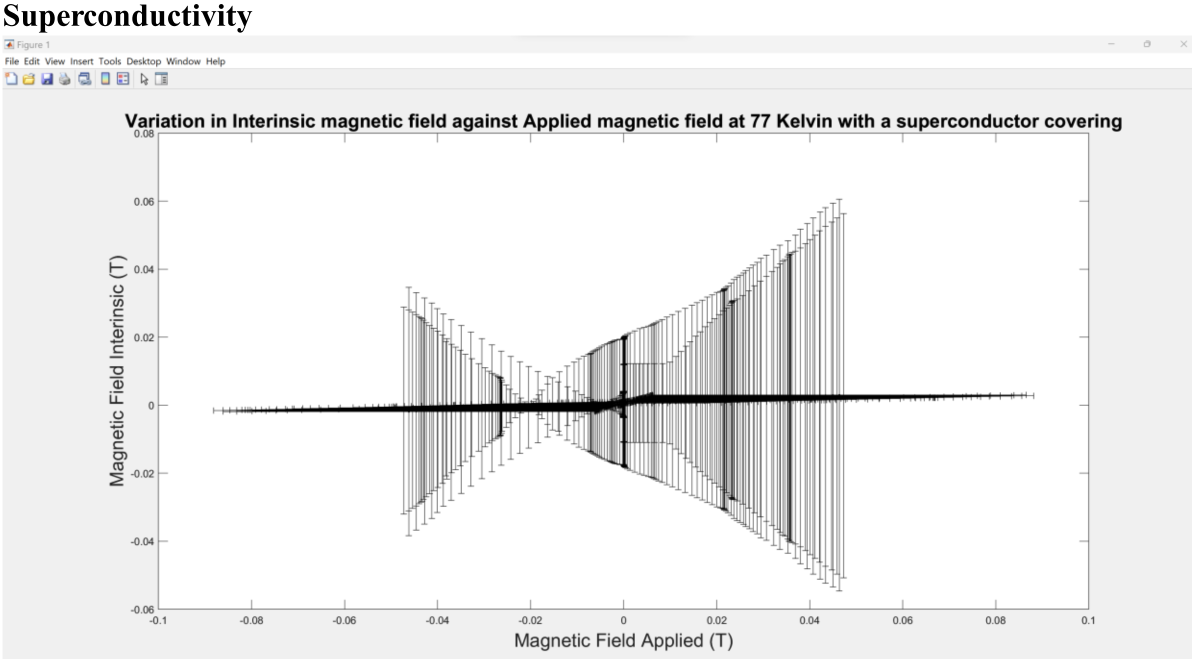


Figure 9: Hysteresis Curve for magnetic field observed inside the superconductor due to the external magnetic field applied, with error bars

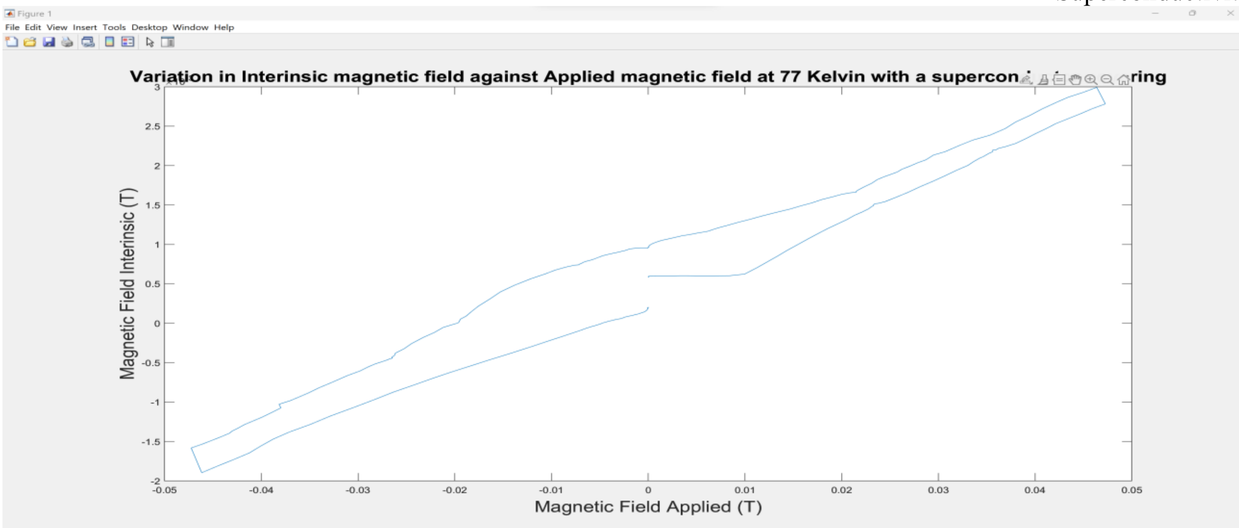


Figure 10: Hysteresis Curve for magnetic field observed inside the superconductor due to the external magnetic field applied

The intrinsic and applied magnetic field are calculated using the measured data and the calibrations calculated in previous parts as per the equations given below. Thus, the magnetic fields were plotted to obtain a hysteresis curve in figure 10. The error bars on the plot are so large as they depend on the varying coil and hall potential and thus increase and decrease with it, which can be seen in figure 9.

$$B_{internal} = V_H \cdot \frac{V_c}{V_H} \cdot \frac{I_c}{V_c} \cdot \frac{B}{I_c}$$

$$B_{applied} = V_c \cdot \frac{I_c}{V_c} \cdot \frac{B}{I_c}$$

From the plots the Trapped and shielded magnetic field was measured. The values obtained were as following:

$B_{trapped}$ = 9 +/-2 mT & $B_{shielded}$ = 9 +/- 1 mT

Using these values, the critical current density was calculated.

$B_{average}$ = 9 +/- 1 mT

t = 4.16 +/- 0.01 mm

$\mu = 4\pi * 10^{-7}$ m Kg /(sA)^2

$$J = \frac{B}{t\mu}$$

Critical Current Density (J) = 1,721,627 +/- 190,000 A/m^2

6.0 DISCUSSION

This experiment studied the superconductive nature of a cuprate superconductor (Bi-2223-$Bi_{1.8}Pb_{0.26}Sr_2Ca_2Cu_3O_{10+x}$). For the experiment the dimensions of the superconductor tube used were; thickness (4.16 +/- 0.01 mm) and length (14.94 +/- 0.01 mm). The uncertainty of the voltmeter used in the experiment was 1600uV and that of the ammeter was 2.5% + 3mA. A higher value of the potential uncertainty was used at certain points in the analysis, specifically during the calibration parts to account for changing the hall probe mid experiment and prolonged exposure of the hall probe to extremely low temperatures. As seen in figure 5 a rheostat was used to account for extremely low resistance provided to the current at 77K and thus to avoid blowing up the setup with high current. A potential amplifier was used in the setup after the rehosts to compensate for the loss of potential at the rheostat.

The end purpose of the whole analysis concluded by calculating the critical current density (1,721,627 +/- 190,000 A/m^2) of a superconductor shielded hall probe at 77K. Multiple calibration steps were completed to get there. These steps included calculating the magnetic field per unit current ($0.03 \ +/- \ 0.03$ T/A) at the center of the coil at room temperature along with the hall potential to coil current ratio (3.51+/- 0.06 V/A) at 77K. Further hall potential to coil potential ratio (0.212+/- 0.003) was calculated at 77K. All these calibrations were then applied to a hall potential against coil potential hysteresis curve using a superconductor to form an intrinsic magnetic field to applied magnetic field curve, from this curve the trapped (9 +/-2 mT) and shielded (9 +/- 1 mT) magnetic field for the superconductor were measured and an average (9 +/- 1 mT) of them was used to calculate the critical current density.

Superconductors have many applications in modern technology including and not limited to Magnetic Resonance Imaging (MRI) and magnetic levitation trains (Maglev). Maglev uses cuperate superconductors to get strong magnetic field which allow for the trains to levitate and thus reducing friction largely. They have been implemented in several countries, including Japan, China, and South Korea. For MRIs the strong magnetic fields are required and are generated by superconducting coils, which allow for high-quality images to be produced. There are also many fields in which the application of superconductors, though not yet in practice, is being studied, one of them being quantum computing. The zero resistance and high energy efficiency of superconductors make them ideal for use in quantum computing. In conclusion, superconductors have a wide range of applications in many different fields, and their unique properties make them invaluable for many technological advancements. As research and development in this area continues, it is likely that even more innovative applications of superconductors will be discovered [7].

Bibliography

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[7] "The Electrochemical Society," [Online]. Available: https://www.electrochem.org/superconductors. [Accessed 11 April 2023].

APPENDIX I: CALIBRATION II

```
I = Lab2DataS1(:,1); % Coil current (A)
I = table2array(I);
err_I = (0.02*I) + 0.002;
V = Lab2DataS1(:,2); % Hall Pontetial (V)
V = table2array(V);
err_V = 0.04*ones(size(V));
[F, gof, F_output] = fit(I, V, '(m*x)+b');

% Extract weighted jacobian
    J_F = F_output.Jacobian;

    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_F = J_F'*J_F;
    covariance_matrix_F = inv(curvature_matrix_F);

    % Calculate CHI_squared
    min_chi2_F = gof.sse;
    dof_F = gof.dfe;

    reduced_chi2_F = min_chi2_F/dof_F;

    err_F_m = covariance_matrix_F(1,1);

figure(1)
plot(F,I,V)
hold on;
errorbar(I, V, err_I,'horizontal',"k.",'HandleVisibility','off')
errorbar(I, V, err_V,'vertical',"k.",'HandleVisibility','off')
xlabel('Coil Current (A)','FontSize',18);
ylabel('Hall Potential (V)','FontSize',18);
legend('Slope = 3.51 +/- 0.06 V/A','FontSize',18)
title ('Variation in Hall Potential as a function of Coil Current at 77
Kelvin','FontSize',18);
```

APPENDIX Ii: CALIBRATION III

```
%Superconductivity Caliberation PArt 3
%Importing values

coil_V = Lab2DataS2(:,1); % Coil current (A)
coil_V = table2array(coil_V);
hall_V = Lab2DataS2(:,2); % Hall Pontetial (V)
hall_V = table2array(hall_V);

a = 0;
for i = 1:589
    if ((-0.01 > coil_V(i)) &&(coil_V(i) > -4.8))
        a = a+1;
        V_coil(a) = coil_V(i);
        V_hall(a) = hall_V(i);
    else if((0.01 < coil_V(i))&&( coil_V(i) < 4.8))
            a = a+1;
            V_coil(a) = coil_V(i);
            V_hall(a) = hall_V(i);
        end
    end
end
V_coil = transpose(V_coil);
%V_hall = transpose(V_hall);
err_V = 0.04*ones(size(V_hall));
[F,gof,fit_F] = fit( V_coil, V_hall, '(m*x)+b');

% Extract weighted jacobian
    J_F = fit_F.Jacobian;

    %Get the covariance and curvature matrix and extract the errors on F
    %parameters from there.
    curvature_matrix_F = J_F'*J_F;
    covariance_matrix_F = inv(curvature_matrix_F);

    % Calculate CHI_squared
    min_chi2_F = gof.sse;
    dof_F = gof.dfe;

    reduced_chi2_F = min_chi2_F/dof_F;

    err_F_m = covariance_matrix_F(1,1);

plot (F,V_coil, V_hall)
hold on;
errorbar(V_coil, V_hall, err_V,'horizontal',"k.",'HandleVisibility','off')
errorbar(V_coil, V_hall, err_V,'vertical',"k.",'HandleVisibility','off')
xlabel('Coil Potential (V)','FontSize',18);
ylabel('Hall Potential (V)','FontSize',18);
legend('Slope = 0.212 +/- 0.003 ','FontSize',18)
title ('Variation in Hall Potential as a function of Coil Potnetial at 77
Kelvin','FontSize',18)
```

APPENDIX III: SUPERCONDUCTIVITY

```
%Superconductivity
%Importing values

coil_V = Lab2DataS3(:,2); % Coil current (A)
coil_V = table2array(coil_V);
hall_V = Lab2DataS3(:,3); % Hall Pontetial (V)
hall_V = table2array(hall_V);
Vch = 0.2121; % Vc/Vh for caliberation 3
err_Vch = 0;
figure (1)
plot (coil_V, hall_V)

mcal2 = 3.5141; % Vc/Ic for caliberation 2
err_mcal2 = 0.06;
mcal1 = 0.034669339; % B/I for caliberation 1
err_mcal1 = 0.03;
mcal3 = 0.212;
err_mcal3 = 0.003;

Bint = hall_V*Vch*mcal1/mcal2;
Bapp = coil_V*mcal1/mcal2;

err_int =
sqrt(((0.0016.*mcal1./(mcal2.*mcal3)).^2)+((hall_V.*err_mcal1./(mcal2.*mcal3)).^2)+
...

((hall_V.*mcal1.*err_mcal2./(mcal2.*mcal2.*mcal3)).^2)+((hall_V.*mcal1.*err_mcal3./(m
cal2.*mcal3.*mcal3)).^2));
err_app =
sqrt(((0.0016.*mcal1./mcal2).^2)+((coil_V.*err_mcal1./mcal2).^2)+((coil_V.*mcal1.*err
_mcal2./(mcal2.*mcal2)).^2));

figure (2)
plot (Bapp, Bint)
hold on
errorbar(Bapp, Bint, err_app,'horizontal',"k.",'HandleVisibility','off')
hold on
errorbar(Bapp, Bint, err_int,'vertical',"k.",'HandleVisibility','off')
hold on
xlabel('Magnetic Field Applied (T)','FontSize',18);
ylabel('Magnetic Field Interinsic (T)','FontSize',18);
title ('Variation in Interinsic magnetic field against Applied magnetic field at 77
Kelvin with a superconductor covering','FontSize',18)
```