Magnetic Susceptibility of $YBa_2Cu_3O_7$

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Meissner Effect reviewed for high temperature superconductors. Experimental setup described. Results given, showing the superconducting critical temperature to be in agreement with previous experiments. Improvements suggested for future experiments.

I. INTRODUCTION

Superconductivity was first observed by Kamerlingh Onnes in 1911 when he discovered that for many metals and alloys, the electrical resistivity drops suddenly to zero when the sample is cooled to a low enough temperature.[1] Most metals and alloys have a critical temperature (T_c) around 10 K, which makes their use impractical. In recent years, however, other materials (ceramics) were discovered to exhibit superconducting properties at much higher temperatures. One of these materials is $YBa_2Cu_3O_7$ (YBCO), which has been shown to have a critical temperature of 91 K.

One of the superconducting effects that can be seen on a macroscopic level is the Meissner Effect. Meissner and Ochsenfeld in 1933 discovered that if a superconductor is cooled in a magnetic field to below the transition temperature (T_c), the magnetic field is effectively pushed out of the material. The Meissner effect shows that a bulk superconductor behaves as if inside the sample B=0 (see Fig.1).

The theoretical explanation for the Meissner effect follows from a postulate that the current density inside the superconductor is proportional to the vector potential $\mathbf{j} = -\kappa\mathbf{A}$. This is called the London Equation. Taking the curl of both sides yields a form describing the magnetic field: $\nabla \times \mathbf{j} = -\kappa\mathbf{B}$. From Maxwell's equations, we know that $\nabla \times \mathbf{B} = \mu_0\mathbf{j}$ under static conditions. Combining these two and using the fact that $\nabla \cdot \mathbf{B} = 0$, yields the equation $-\nabla^2\mathbf{B} = \mu_0\nabla \times \mathbf{j}$. Substituting in the equation relating B and j, we see that:

$$\nabla^2\mathbf{B} = \mu_0\kappa\mathbf{B}.$$

This equation accounts for the Meissner effect because it does not allow for a solution uniform in space (inside the superconductor). That is, $\mathbf{B} = \mathbf{B_0}$=constant is not a solution unless $\mathbf{B}$=0.[2]

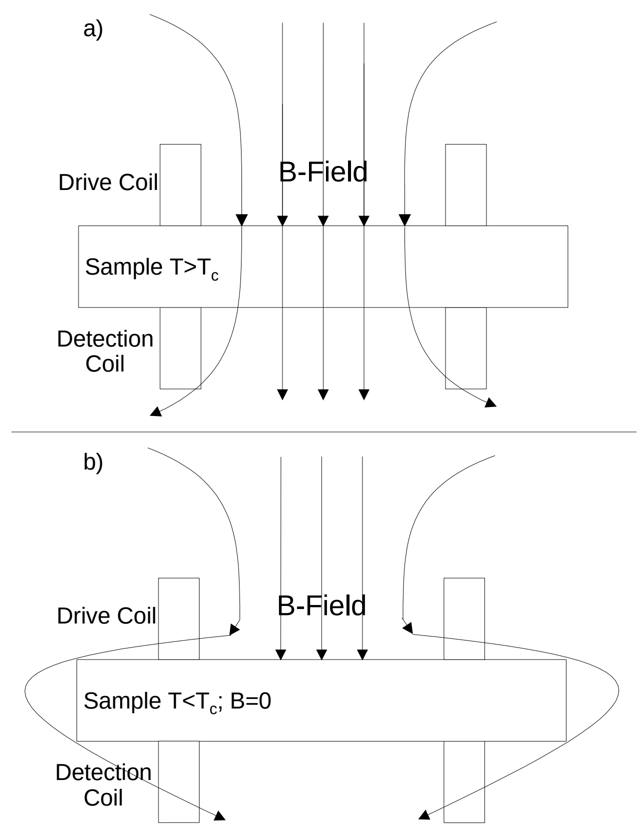

FIG. 1: The Meissner effect in a bulk superconductor. a)Temperature of sample is greater then T_c, magnetic field penetrates sample b)Temperature of sample is cooled to below T_c, B=0 inside sample

II. EXPERIMENTAL SETUP

The YBCO superconductor achieves its optimum transition temperature $T_c = 91$ K right at the stoichiometric

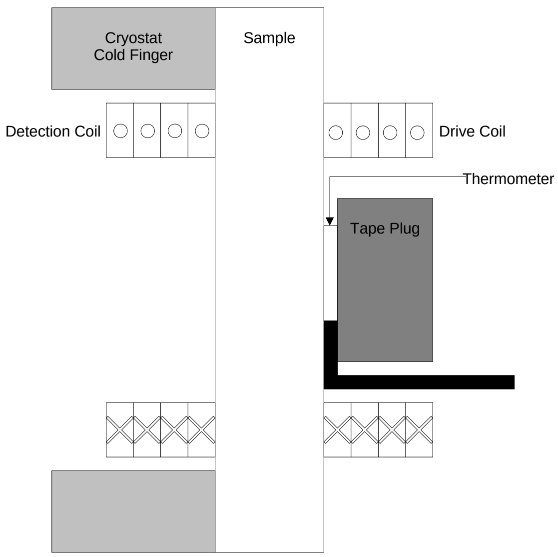

FIG. 2: A drawing of the sample, the coils used to produce a magnetic field (drive coil) and to detect an induced EMF (detection coil).

composition.[3,4] We modified the established procedure for mixing the component powders and baking times to produce a 9.0 g pellet. After the process, we measured the pellet and found that we had a cylindrical pellet, radius r=1.25 cm, thickness w=0.4 cm and weight 7.97 g.

We made two wire coils of 50 turns, each with a radius R=0.6 cm. Because of the size of the wire we used (30 gauge), the coils were about l=0.4 cm wide. The coils were glued to the outside of the sample in order to get them as close to the sample as possible. The sample was then mounted onto the cryostat cold finger using vacuum grease and tape. A thermometer was mounted onto the center of the sample, on the side of the drive coil, using vacuum grease and a non-conducting plug to hold it in place.(see Fig. 2) In order to measure the Meissner effect, we sent a sinusoidal signal current through the drive coil. This created a magnetic field which also varies sinusoidally. The current was generated by putting a voltage through a 5Ω resistor. We measured the current through an ammeter. The varying magnetic field then passed through the sample and induces an EMF in the detection coil, which we measured with a voltmeter. The oscilloscopes shown in the setup were used to verify that the measurements made on the meters were correct.(see Fig.3)

III. EXPERIMENTAL RESULTS

In order to understand the magnitude of the signal detected by the detection coils, as well as the magnitude of the applied magnetic field, several simple calculations can

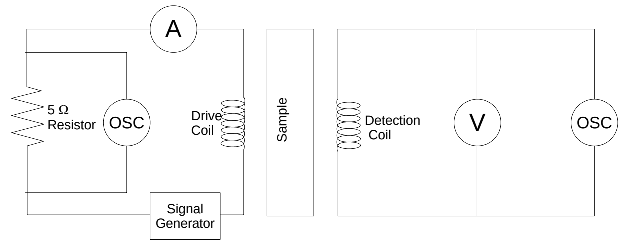

FIG. 3: The wiring diagram, showing the configuration of meters, coils and resistor with respect to the sample.

be made. If we assume that the coils are long solenoids, with the number of turns N in a length l, and an applied current I, then the magnetic field can be solved for exactly: $\mathbf{B} = \mu_0 \mathrm{IN/l}$. Our initial conditions were that I=0.012 A, N=50 turns and l=0.4 cm. This leads to a magnetic field of **B**=2 Gauss. The actual magnetic field that is at the detection coil is going to be less then the magnetic field in the center of the drive coil because of the distance separating the coils. If we were to estimate the magnetic field at the detection coil by approximating the drive coil as one loop of wire with N times the current passing through it, the problem can also be solved exactly:

$$\mathbf{B} = \frac{\mu_0 \mathrm{NIR}^2}{2(\mathrm{R}^2 + \mathrm{z}^2)^{3/2}}$$

with z=0.4 cm, the distance separating the coils, and R=0.6 cm, the radius of the coil. The calculation in this case gives **B**=0.4 Gauss. The actually magnetic field is in between the two values. From Faraday's law, we know that $\mathcal{E} = V = \frac{\mathrm{d}(\mathrm{N}\Phi_B)}{\mathrm{dt}}$, where Φ_B is the magnetic flux through the detection coil, and N is the number of turns in the coil. Given a sinusoidally varying magnetic field $\mathbf{B} = \mathbf{B}_0 sin(\omega \mathrm{t})$, and using the solenoid approximation for the magnetic field, then

$$V = \frac{\mathrm{N}^2 \mu_0 \pi \mathrm{R}^2 \mathrm{I}\omega}{\mathrm{l}}(cos\omega \mathrm{t}).$$

The magnitude of the voltage is approximately V=0.533 V. The voltage we detected across the coil, using the voltmeter, was 0.266 V. The approximation is higher by about a factor of two. This leads us to conclude that the magnetic field actually penetrating the sample is closer to 1 Gauss, which as mentioned before, is between the two given approximations. Due to the difficulty in controlling the rate at which the cryostat cooled down, we discovered that it was more accurate to take data with the cryostat turned off. The cryostat was cooled to a temperature well below the transition temperature, then turned off, and a heater in the thermometer attached to the sample was turned on. This led to a ramp rate of 1 degree per minute, versus a rate of 10 degrees per minute

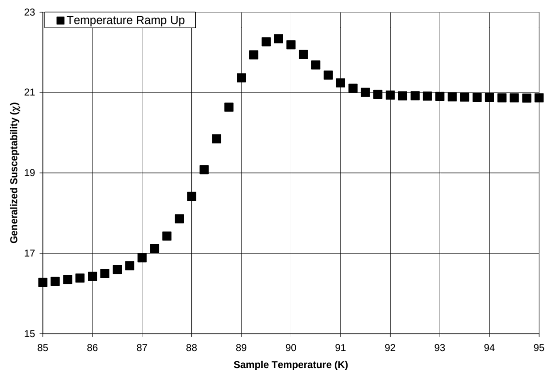

FIG. 4: Generalized Magnetic Susceptibility, as found through the expulsion of the magnetic field in the Meissner Effect. $T_c = 91K$

for the ramp down temperature rate. For the data shown (see Fig.4) the cryostat temperature was, on average, 0.58 degrees K cooler then the sample temperature. The transition temperature appears to be around $T_c = 90 \pm 0.5$ K, which is within experimental uncertainty of previous measurements taken on YBCO material.[5] The dependent variable in the graph is related to the susceptibility, but only indirectly. It is the induced voltage from the detection coil, normalized against changes in the voltage due to the drop in temperature of the coil itself. Because the drop in the magnetic flux lines going through the coil causes a reduction in voltage induced in the coil, the voltage drop is related to the Meissner effect. An actual plot of the susceptibility would show that at T_c, the value would be -1, which means that $\mathbf{B}$=0.

IV. EXPERIMENTAL ERROR

If the experimental setup were ideal, i.e. if our sample were an infinite plane compared to the coil radius, we would expect that no magnetic flux lines would work around the sample below the superconducting transition temperature. This would lead to a zero voltage reading in the detection coils. Our signal was not zero below T_c. There are a number of possible explanations for this. First of all, YBCO material is known as a Type II superconductor. There is a critical magnetic field strength, H_{c1} above which there is an incomplete Meissner effect; in other words, magnetic flux lines begin to penetrate the sample. For bulk YBCO material, $H_{c1} = 750$G. As noted previously, our field strength is on the order of 1 G, so this is not an issue. Another possible reason is that, due to the geometry of the setup, magnetic flux lines can wrap around the bulk sample close enough to the surface in order to still be able to penetrate part of the detection coil, inducing a voltage in the coil(see Fig.1 part b). Because we saw a definite drop in the induced voltage, we are sure that we are seeing a Meissner effect, but somehow flux lines are still penetrating the detection coil. One possible improvement in this experiment would be to make the coils even smaller then their current radius of 0.6 cm in order to effectively increase the relative size of the sample in comparison to the coils.

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