WPI Physics Dept.
Intermediate Lab 2651
Superconducting Transition in YBCO

January 19, 2015

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1 Background Material and Experimental Procedure

1.1 Introduction

In this lab, we will be making a quantitative measurement of the superconducting transition in a bar Yttrium Barium Copper Oxide (YBCO) Superconductivity is a phenomenon occurring in certain materials at low temperatures. Below a transition temperature T_c, superconducting materials suddenly exhibit zero resistance to electric current (R=0) and magnetic fields are completely excluded from the material's interior (the Meissner effect). An excellent chapter on superconductivity can be found in Ref.[1]. The average student would probably also benefit to read the Wikipedia article on superconductivity [2] and in particular the Oak Ridge National Laboratory Website on Superconductivity, especially the discussion of critical magnetic field Hc [3] and the discussion at the Website Ref. [4] There is currently no theory that convincingly explains all aspects of the phenomenon of superconductivity in high temperature type II superconductors such as YBCO, a material which becomes superconducting below about 95K. In the absence of such a theory, many speculate that higher temperature–perhaps room temperature!– superconductors may yet be discovered that will completely revolutionize our world.

At zero applied magnetic field, aType II superconductor such as YBCO loses its resistance below a transition temperature T_c. However, in the presence of an applied external magnetic field, the superconductivity is suppressed: the transition occurs at a temperature below T_c Fig. 1 shows the phase diagram of a "typical " Type II superconductor. As we increase the magnetic field H at a temperature $T < T_c$, for $H < H_{c1}$ we are fully superconducting state where all the magnetic flux is expelled from the interior of the superconductor, for $H_{c1} < H < H_{c2}$, we are in a mixed superconducting state where some of the flux is expelled from the interior but some of it is allowed through, and finally for $H > H_{c2}$ we are in a completely normal state. Evidently H_{c1} and H_{c2} depend on T and in the presence of magnetic fields the temperature for the transition to the superconducting state depends on the applied magnetic field. I our experiments, we will measure the transition both in the presence and absence of a magnetic field in order to ascertain how sensitive the transition is to external magnetic fields.

An additional goal of this lab is to provide an introduction to computerized data acquisition using MATLAB. This will complement your current learning of MATLAB for analyze data analysis.

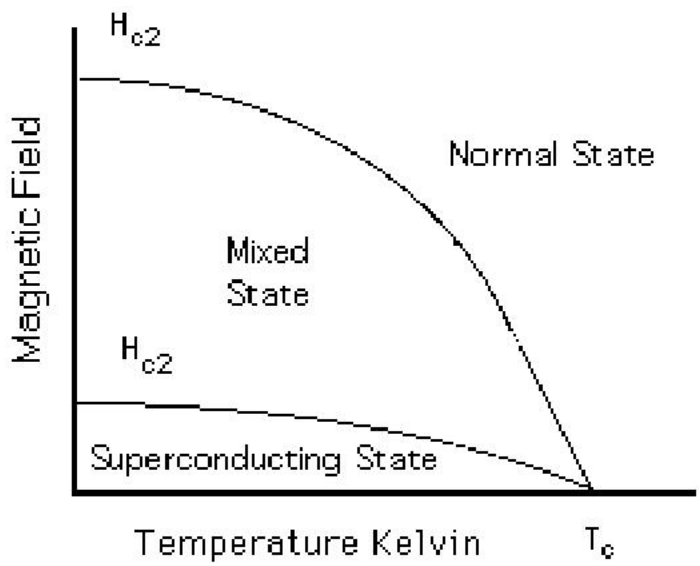

Figure 1: $H - T$ phase diagram for Type II superconductor, showing the critical magnetic fields H_{c1} and H_{c2} as a function of temperature below T_c. Figure borrowed from Ref. [4].

1.2 Apparatus

To measure the T_c of the YBCO bar, we will measure the resistance of the YBCO bar as a function temperature. We will take data using a microcomputer that is interfaced via MATLAB to a Lakeshore temperature controller and an HP Voltmeter. The first order of business is to familiarize yourself with the parts of the apparatus. The YBCO bar is mounted on a round aluminum disk which is in turn mounted on a printed circuit board. The circuit board is wrapped in transparent cling wrap to minimize the amount of water that condenses on the YBCO every time we dip it in liquid nitrogen. There are six wires coming from the printed circuit board. Two of the wires go to a silicon diode thermometer that is embedded into the aluminum disk and is used to monitor the temperature of the YBCO. The voltage-temperature characteristic of a silicon diode is shown in Fig. 2. You will use the Lakeshore temperature controller to monitor the voltage and convert this voltage using a standard curve to temperature in Kelvins. The other four of the wires on the printed circuit board go to the YBCO bar; they are used to make a four wire measurement of the YBCO resistance. Two of the wires are current leads and two of the wires are voltage leads. The HP Power supply (located underneath the HP voltmeter) will be used to supply a constant current through the current leads located on opposite sides of the YBCO bar. The HP voltmeter will be used to measure the voltage across the YBCO bar. The resistance of the YBCO bar is then calculated using Ohm's law.

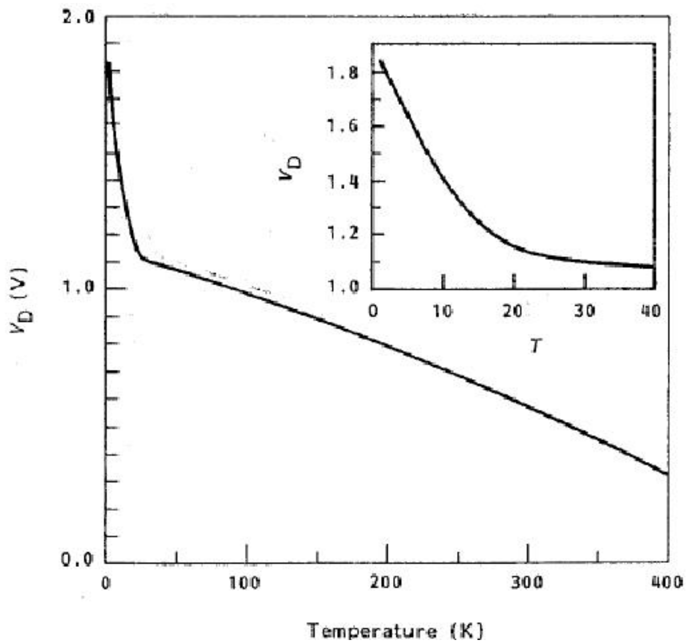

Figure 2: Silicon Diode voltage-temperature characteristic curve. Obtained from http://www.bipm.fr/utils/common/pdf/its-90/TECChapter14.pdf

In your report, you will want to report the resistivity of the YBCO bar as a function of temperature. You should measure the width and height of the YBCO bar as well as the distance between the two voltage leads, as you will need these data to calculate the resistivity.

1.3 Introduction to MATLAB Data Acquisition

NOTE: If the file is not in the folder, please download from the website provided on Canvas. Also, you may use your own laptop for data acquisition. To do that, you need to download and install the driver software for the GPIB USB interface.

Log into the computer, and locate the folder C : MATLAB/Superconductivity. You will find a MATLAB program called data_logger.m, which collects data at regular, 1 second, intervals. Although the program is read-only and therefore protected from changes, please do not try to make any changes.

N.b. if you want to make changes follow the standard procedure: re-save the source code using a new filename (preferably by appending your initials). Run the program, and a graphics figure opens with two time-trace graphs of the temperature and multimeter meter. The upper plot shows the entire run, and the lower shows the last 40 seconds of the collected data. The file is stored in the data directory, and is entitled something like "26Jan1237.mat", which is the date and time when you started the data logger. Note that this program is running in the background, and that you can seamlessly use MATLAB in the foreground. For example try running the program called "analyze_data.m". This program takes the most recent data file (i.e. 26Jan1237.mat), and makes plots. You will need to use a similar program to analyze your data. Remember before changing the analyzer program to rename it first!

I recommend that you start data_logger.m at the beginning of class and let it run as long as you are in the lab. You will need to record time-stamps in your lab books whenever there is something noteworthy occurring in the experiment. For example when the current is changed, or the sample put into liquid nitrogen, note the time.

After the experiment, stop the data_logger program by closing the figure window. You will need to copy the analysis program and the data file. The data file is stored in binary format, and will be a mess if you chose to "look" at it. It is a MATLAB native format, and can only be decoded by MATLAB.

1.4 Superconducting Transition at zero Field

At atmospheric pressure, the temperature of liquid nitrogen is 77K (-200°C). Because this is cold enough to deep freeze your skin, you need to be especially careful to not be frostbitten by the liquid nitrogen. Another danger from the use of the liquid nitrogen is that the coldness will cause water to condense on the YBCO bar; repeated freezing and unfreezing of the condensed water will cause the YBCO to slowly deteriorate and crumble. Thus precautions to minimize the exposure of the YBCO to air while it is cooling or warming are necessary. Please make sure the entire sample is inside a plastic wrapping before cooling it.

Before lowering the printed circuit board holder with YBCO into the container holding the liquid nitrogen, make sure the data_logger is runnging. You should set the current coursing through the current leads at about 1A and verify that the voltage being measured and saved by the computer is reasonable. Now you can start slowly cooling the YBCO sample by lowering it slowly into the liquid nitrogen. (Record a time stamp!) As you approach

95K, you will also want to slow down the rate of cooling and/or warming to reduce the thermal lag between the different parts of the YBCO and the thermocouple inside the aluminum block.

When taking your data, you will want to measure the superconducting transition both going up and down in temperature. You will observe that the transition to the zero resistance state is not infinitely abrupt but occurs over a range of temperature. You may want to consider recording several temperatures: the temperature at which the resistance starts to fall, the temperature at which it falls to half its value and the first temperature at which the resistance is observably not zero. Which one is the best measure of the T_c of the superconductor?

1.4.1 Observing the Meissner Effect

While you are slowly cooling down the YBCO bar, or perhaps while you are working on your program, you might want to experiment with observing the Meissner effect. To do this, place the small rare-earth magnet on the YBCO disk mounted on the Cu piece located in the small styrofoam plate. Now pour liquid nitrogen into the styrofoam. When the YBCO becomes superconducting, it will expel the flux from the magnet causing it to levitate. This is the Meissner effect. An important thing to observe is that the levitated magnet does not up and fall off of the YBCO, even if you push it with your finger. In fact, if you push the magnet just right, you can get it to spin in place above the YBCO sample. Because H_{c1} for YBCO is less that 200 G and the field at the surface of the magnet is about 600 G, the sample is in mixed superconducting/normal state while you are performing the Meissner demonstration. As a result, some of the field lines of the magnet have penetrated the sample. These field lines are trapped in defects and grain boundaries in the crystals, a phenomenon known as flux pinning. The flux pinning "locks" the magnet to a region above the pellet and keeps it from falling off to the side.

1.5 Superconducting Transition between the Poles of a Permanent Magnet

According to the generic phase diagram (Fig. 1) a small magnetic field of about 700G ($< H_{c2}$) should decrease the temperature of the observed transition to superconductivity for YBCO. In this part of the lab, you will determine what effect such a small field has. The first order of business is to measure the magnetic field between the poles of the permanent magnet using the Hall probe and the HP 7010 Gaussmeter. By moving around the Hall probe inside the magnet cavity, determine the uniformity of the field or lack thereof.

*********************CAUTION**************************

The Hall probes are delicate—handle with care. Be careful not to bend it. Ask your instructor for help.

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Next, carefully do the measurement of R vs. T between the poles of the permanent magnet. To do this measurement, place two styrofoam cups, one within the other, between the poles of the magnet and fill the inner one part way with liquid nitrogen. Then lower the circuit board with YBCO bar mounted on it slowly into the nitrogen, so that in the final position it is near the center between the magnet poles Practice this measurement a number of times, both going up and down in temperature, until you can do it in such a manner that you can determine the T_c within a fraction of 1K. Later when interpreting your data you may have to be careful about what you call T_c.

After doing the measurement between the magnet poles, you should try doing it in just the same manner but with the magnet removed far away from the YBCO. Is there a significant change in the T_c? What if anything changes?

References

[1] Charles Kittel, Introduction to Solid State Physics (ISBN 0-471-87474-4).

[2] See for example, http://en.wikipedia.org/wiki/Superconductivity.

[3] See for example, http://www.ornl.gov/info/reports/m/ornlm3063r1/pt3.html.

[4] See for example, http://www.cartage.org.lb/en/themes/Sciences/Physics /SolidStatePhysics/Superconductivity/Fundamentals/fundamentals.htm

[5] See for example, http://www-ee.eng.buffalo.edu/faculty/paololiu/edtech/ roaldi/tutorials/labview.htm

[6] See for example, http://www.upscale.utoronto.ca/GeneralInterest/LabView.html

2 Pre-lab Exercises

1. What is the purpose of liquid nitrogen in this experiment? Why is it potentially dangerous?

2. Why is it that Cooper pairs are essential to superconductivity? Can you think of why magnetic fields might be inimical to superconductivity, given that superconductivity is due to Cooper pairs of electrons?

3. What are contact resistance and lead resistance and how do they affect your measurements?

4. Why is the heat capacity of the YBCO and aluminum block a potential source of error in your determination of the temperature for the superconducting transition?

5. How does a four-wire measurement of resistance avoid the error due to measuring resistance of the electrical leads making contact with the YBCO sample?

3 Experimental Checklist

1. Roughly determine the location of the sensitive region of the transverse Hall probe to within 3 mm. Track the behavior of the Hall probe (using the older of the two Gaussmeters) between the poles of the permanent magnet. Be sure to adjust the Gaussmeter zero for equal positive/negative maximum values. Measuring every 10°, cover a range of at least 200° that includes two peak B-field values.

2. Use the micrometer to make detailed measurements of the YBCO sample: width, height and length, as well as the distance between the contacts for the voltage and current leads.

3. Observe the Meissner effect. Place the small magnet on the sample of YBCO that is glued to a copper block in small circular Styrofoam cup, and pour enough liquid nitrogen into the side of the cup that if fills to above where the dark foam sits. Watch what happens and observe. Bump the magnet to test how stable it is above the superconducting YBCO. Can you make it spin in place?

4. Use the data_logger program to monitor the resistance of YBCO bar as you cool the sample by slowly lowering it into a dewar containing liquid nitrogen. Set the current through the current leads to be about 0.10A.

5. Make the modifications to the MATLAB program, analyze_data.m, and view the data as you are measuring. Be sure to save different versions of this program whenever you have produced a good plot.

   **********You should get this far by the end of Day 1 **************

6. You want to make the best, most precise observation of T_c possible. To do this you want to cool the sample slowly. You may want to repeat your measurements several times until you get the hang of it. Make sure to record time stamps.

7. Repeat the measurements but for the YBCO placed between the poles of the permanent magnet. You will have to use a Styrofoam cup to hold the liquid nitrogen. Be careful to place the YBCO in the middle between the pole pieces.

8. Repeat the above measurements and look for the effect of different currents and different rates of cooling on the transition temperature.

4 Report Checklist

1. Hall probe measurement as a function of angle.
   In addition to providing a plot of B vs. θ, also graph the data in such a way so as to expect a straight-line relationship. One possibility is $\frac{B_{\text{measured}}}{B_{\text{max}}}$ vs. $\sin(\theta - \theta_0)$. To do this, you will need to determine θ_0, which is the angle at which the B field is maximal.

2. Superconducting transition in YBCO.
   One or two figures of your paper should present your resistance data for YBCO. One figure may represent the data going up in temperature and one going down. You may want to discuss the discrepancy between the two data. What role does I^2R heating play? If there is hysteresis in your data, is it consistent with the effect expected due to the heat capacity of the aluminum and YBCO bar? A table showing a representative subset of points (maybe 10-20 points?) near T_c should be included in your report, along with the calculations you made for those points.

3. Superconducting transition in the presence of a B field.
   At least one figure should show your results for the transition in the presence of the B field. You should try to keep your conditions as similar as possible for the measurements in the presence and in the absence of B field. In the text, you should describe your methods and observations. Discuss whether a significant difference in the transition temperature was caused by the presence of a B field.