Superconductivity

Experiment objectives: study the behavior of a high temperature superconducting material Yttrium-Barium-Copper-Oxide (YBCO, $YBa_2Cu_3O_7$) in magnetic field, measure the critical temperature for a phase transition in a superconductor.

History

Solids can be roughly divided into four classes, according to the way they conduct electricity. They are: Metals, Semiconductors, Insulators and Superconductors. The behavior of these types of materials is explained by quantum mechanics. Basically, when atoms form a solid, the atomic levels of the electrons combine to form bands. That is, over a finite range of energies there are states available to electrons. Since only one electron can occupy a given state, as described by the **Pauli Exclusion Principle**, electrons will fill these states up to some maximum: the Fermi Energy, E_f. A solid is a metal if it has an energy band that is not full. The electrons are then free to move about, making a metal a good conductor of electricity. If the solid has a band that is completely full, with an energy gap to the next band, that solid will not conduct electricity very well, making it an insulator. A semiconductor is between a metal and insulator: while it has a full band (the valence band), the next band (the conduction band) is close enough in energy, and so the electrons can easily reach it. Superconductors are in a class by themselves. They can be metals or insulators at room temperature. Below a certain temperature, called the critical temperature, the electrons "pair" together (in Cooper pairs) and travel through the solid without resistance. Current in a superconductor below the critical temperature will travel indefinitely without dissipation.

Superconductivity was discovered in 1911 by H. Onnes. He discovered that simple metals (Pb, Nb) superconduct when placed in liquid helium (4 K). This was an important discovery, but the real excitement came in 1986 when Swiss scientists discovered that certain ceramics would superconduct at 35 K. Several groups later discovered materials that would superconduct at temperatures up to 125 K. These materials are called high temperature superconductors (HTS). Their discovery was a breakthrough, because it meant that these superconductors will work in liquid nitrogen (at 77 K), which is relatively cheap and abundant.

A fascinating fact about superconductors: they will carry a current nearly indefinitely, without resistance. Superconductors have a critical temperature, above which they lose their superconducting properties.

Another striking demonstration of superconductivity is the **Meissner effect**. Magnetic fields cannot penetrate superconducting surfaces; instead a superconductor attempts to expel all magnetic field lines. It is fairly simple to intuitively understand the Meissner effect if you imagine a perfect conductor of electricity. If a superconductor placed in a magnetic field, Faraday's Law says an induced current that opposes the field would be set up. But unlike in an ordinary metal, this induced current does not dissipate in a perfect conductor. So, this induced current would always be present to produce a field which opposes the external field. In addition, microscopic dipole moments are induced in the superconductor that oppose the applied field. This induced field repels the source of the applied magnetic field, and will consequently repel the magnet associated with this field. Thus, a superconductor will levitate a magnet placed upon it (this is known as magnetic levitation).

Safety

- Wear glasses when pouring liquid nitrogen. Do not get it on your skin or in your eyes!
- Do not touch anything that has been immersed in liquid nitrogen until the item warms up to the room temperature. Use the provided tweezers to remove and place items in the liquid nitrogen.
- Do not touch the superconductor: it contains poisonous materials!
- Beware of the current leads: they are carrying a lethal current!

Experimental procedure

Equipment needed: YBCO disk, tweezers, thermal insulating container, small magnet.

Magnetic Levitation (the Meissner effect)

1. Place one of the small magnets (provided) on top of the superconducting disk at room temperature. Record the behavior of the magnet.
2. Using the tweezers, place the superconducting disk in the thermal insulating container. Attach the thermocouple leads (see diagram) to a multimeter reading on the mV scale. Slowly pour liquid nitrogen over the disk, filling the container as much as you can. The nitrogen will boil, and then settle down. When the multimeter reads about 6.4 mV, you are at liquid nitrogen temperature (77 K).
3. After the disk is completely covered by the liquid nitrogen, use the tweezers to pick up the provided magnet and attempt to balance it on top of the superconductor disk. Record what you observe.
4. Try demonstrating a *frictionless magnetic bearing*: if you carefully set the magnet rotating, you will observe that the magnet continues to rotate for a long time. Also, try moving the magnet across the superconductor. Do you feel any resistance? If you feel resistance, why is this?

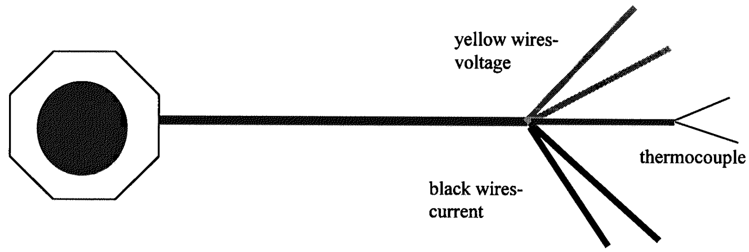

Figure 1: The superconducting disk with leads.

5. Using tweezers, take the disk (with the magnet on it) out of the nitrogen and place it beside the container, allowing it to warm. Watch the thermocouple reading carefully, and take a reading when the magnet fails to levitate any longer. This is a rough estimate of the critical temperature. Make sure you record it!
6. Repeat the experiment by starting with the magnet on top of the superconductor disk and observe if the magnet starts levitating when the disk's temperature falls below critical.

Measuring resistance and critical temperature

We will measure the resistance by a **four probe method**, as a function of temperature (see Fig. **??**). Using four probes (two for current and two for voltage) eliminates the contribution of resistance due to the contacts, and is good to use for samples with small resistances. Connect a voltmeter (with 0.01 mV resolution) to the **inner** black and red wires. Connect a current source through an ammeter to the **outer** black and red wires. Place a current of about 0.2 Amps (200 mA) through the black leads. Note: **DO NOT EXCEED 0.5 AMP!!!!** At room temperature, you should be reading a non-zero voltage reading. The **yellow** leads are for measuring the temperature with the thermocouple (see table below for mV-to-Kelvin conversion).

1. With the voltage, current and thermocouple leads attached, carefully place the disk in the container. Pour liquid nitrogen into the container. Wait until the temperature reaches 77 K.
2. With tweezers, take the disk out of nitrogen and place it outside of the container. **Start quickly recording the current, voltage and thermocouple readings as the disk warms up.** When superconducting, the disk should have V=0 (R=0). At a critical temperature, you will see a voltage (resistance) appear.
3. Repeat this measurement several times to acquire a significant number of data points near the critical temperature (6.4-4.5 mV). Make a plot of resistance versus temperature, and make an estimate of the critical temperature based on this plot.

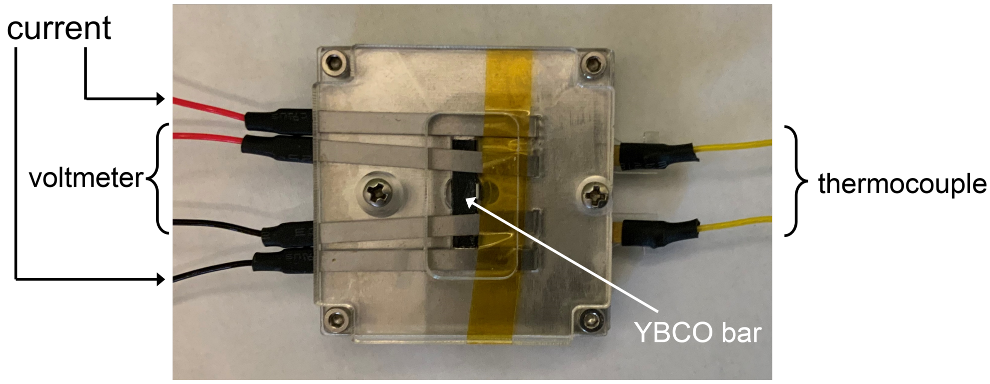

Figure 2: 4-point measurement setup for measuring the resistance of the bar of YBCO superconductor. The setup requires a current source, Ammeter, and two voltmeters (4-point voltage, thermocouple).

Conversion from mV to Kelvin

°K	0	1	2	3	4	5	6	7	8	9	10	°K
60	7.60	7.53	7.46	7.40	7.33	7.26	7.19	7.12	7.05	6.99	6.92	60
70	6.92	6.85	6.78	6.71	6.64	6.56	6.49	6.42	6.37	6.33	6.29	70
80	6.29	6.25	6.21	6.17	6.13	6.09	6.05	6.01	5.97	5.93	5.90	80
90	5.90	5.86	5.83	5.79	5.75	5.72	5.68	5.64	5.60	5.56	5.52	90
100	5.52	5.48	5.44	5.41	5.37	5.34	5.30	5.27	5.23	5.20	5.16	100
110	5.16	5.13	5.09	5.06	5.02	4.99	4.95	4.91	4.88	4.84	4.81	110
120	4.81	4.77	4.74	4.70	4.67	4.63	4.60	4.56	4.53	4.49	4.46	120
130	4.46	4.42	4.39	4.35	4.32	4.28	4.25	4.21	4.18	4.14	4.11	130
140	4.11	4.07	4.04	4.00	3.97	3.93	3.90	3.86	3.83	3.79	3.76	140
150	3.76	3.73	3.69	3.66	3.63	3.60	3.56	3.53	3.50	3.47	3.43	150
160	3.43	3.40	3.37	3.34	3.30	3.27	3.24	3.21	3.18	3.15	3.12	160
170	3.12	3.09	3.06	3.03	3.00	2.97	2.94	2.91	2.88	2.85	2.82	170
180	2.82	2.79	2.76	2.73	2.70	2.67	2.64	2.61	2.58	2.53	2.52	180
190	2.52	2.49	2.46	2.43	2.40	2.37	2.34	2.31	2.29	2.26	2.23	190
200	2.23	2.20	2.17	2.14	2.11	2.08	2.05	2.02	1.99	1.96	1.93	200
210	1.93	1.90	1.87	1.84	1.81	1.78	1.75	1.72	1.69	1.66	1.64	210
220	1.64	1.61	1.59	1.56	1.54	1.51	1.49	1.46	1.44	1.41	1.39	220
230	1.39	1.36	1.34	1.31	1.29	1.26	1.24	1.21	1.19	1.16	1.14	230
240	1.14	1.11	1.09	1.07	1.04	1.02	0.99	0.97	0.94	0.92	0.89	240
250	0.89	0.87	0.84	0.82	0.79	0.77	0.74	0.72	0.69	0.67	0.65	250
260	0.65	0.62	0.60	0.58	0.55	0.53	0.50	0.48	0.45	0.42	0.40	260
270	0.40	0.38	0.36	0.34	0.32	0.30	0.28	0.26	0.24	0.22	0.20	270
280	0.20	0.18	0.16	0.14	0.12	0.10	0.08	0.06	0.04	0.02	0.00	280
290	0.00	-0.02	-0.04	-0.06	-0.08	-0.10	-0.12	-0.14	0.16	-0.18	-0.20	290
300	-0.20	-0.22	-0.24	-0.26	-0.28	-0.30	-0.32	-0.34	-0.36	-0.38	-0.40	300

Lab Report Guidelines

Address the following points

Diagram the experimental setup, including the current source, the superconductor and its wires, and the DMMs.

Thermocouple Explain in your own words what a thermocouple is and how it works (i.e., the physics). No more than a paragraph is needed.

Resistance In the Meissner effect demonstration, when moving the magnets around, did you feel resistance? Why or why not? Explain in terms of physics concepts and principles that you learned in PHYS 102.

Tabulate your data, including columns for voltage, current, resistance, thermocouple voltage, and temperature.

Uncertainties Estimate them and state them.

Temperature Explain how you got the temperature from the thermocouple voltage. What was your procedure? No more than a couple of sentences are needed.

Plot the resistance (y-axis) vs temperature (x-axis). Based on the plot, what is the critical temperature for YBCO?

Fit the R vs T plot. What function? You tell me. Based on the fitted function, can you estimate the critical temperature? Parameterizing a dataset and then using it to characterize the data, perhaps with a single number, is a common laboratory task.