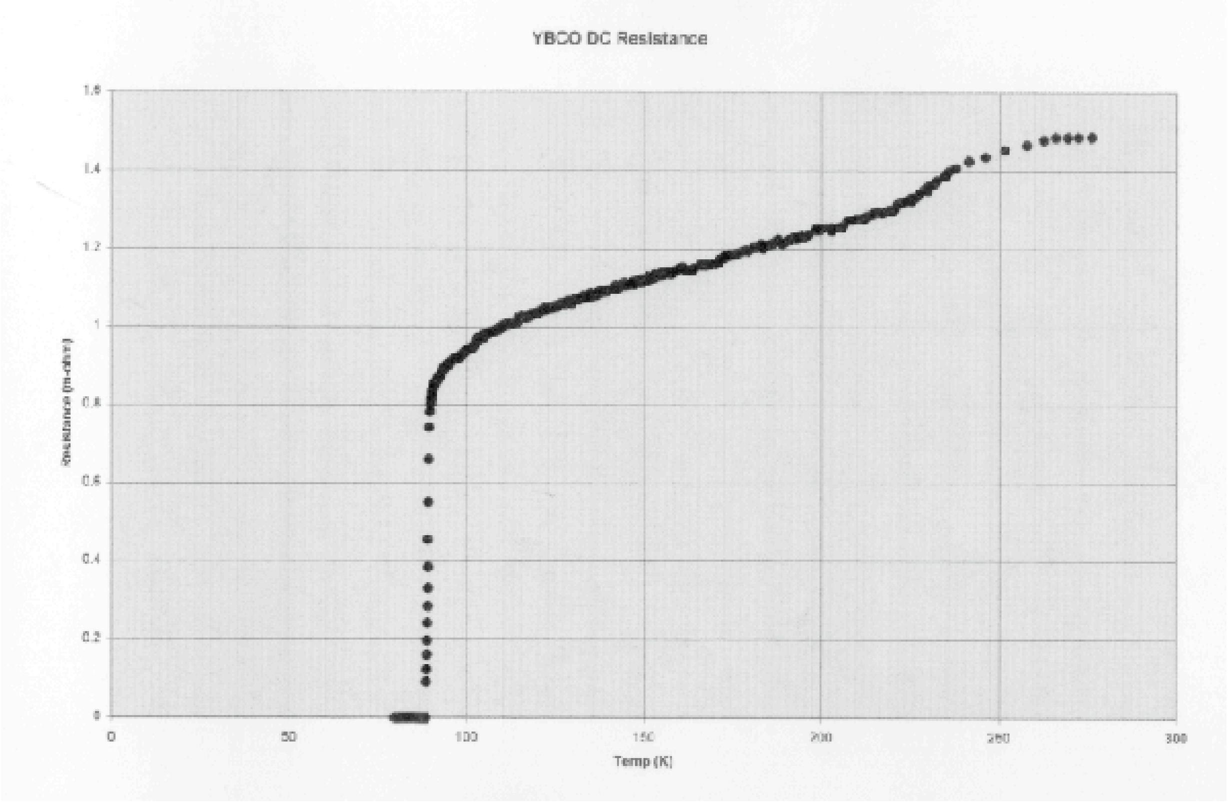
YBCO HIGH TC SUPERCONDUCTOR

The graph shows the resistance vs. temperature results for the high Tc superconductor Yitrium(1)Barium(2)Copper(3)Oxygen(6.95). .

Unlike Copper, the YBCO pellet experiences a phase change on the quantum mechanical level at approximately 90 Kelvin. At this temperature the electrons begin to form pairs due to a weak attraction. The attraction between the electrons is a rather amazing feat considering the fact that the particles involved have like charges. The attraction is actually a result of the electrons' interaction with the crystal lattice of the YBCO atoms. As a result of the pairing, the electrons share the same quantum mechanical wave function. Now if one electron runs into an impurity in the sample it will only stop if all of the paired electrons come to a stop. Since a single impurity is incapable of stopping all of the electrons, the electron in question will pass the impurity without being scattered. The ramification of this purely quantum mechanical phenominon is that the sample will have absolutely ZERO resistance - a perfect conductor. This can be clearly seen on the graph where the resistance dives downward as the sample is cooled to below its transition temperature.

//www.physics.ubc.ca/~outreach/phys420/p420_96/bruce/ybco.html



THE MEASUREMENT OF TEMPERATURE

Temperature can be accurately measured with thermometers designed and calibrated for use in the temperature range of interest. For all experiments in this manual using Colorado Superconductor's family of superconductor kits, a range from room temperature to that of liquid nitrogen is of interest. Highly accurate thermometers typically do not operate over such a wide range. Thermocouple thermometers however are fairly accurate over this large temperature variance.

A thermocouple consists of a mechanical junction of two dissimilar metals. This junction generates a small electrical potential (voltage), the value of which depends upon the temperature of the junction. Thus with calibration, and an appropriate choice of metals, one can obtain a thermometer for the desired temperature range. For our range (300 Kelvin to 77 Kelvin), a type T, or Copper-Constantan thermocouple is used. A -0.16mV reading indicates room temperature (298K), and +6.43mV is 77K.

The thermocouple junction has been carefully attached to the superconductors in our kits, and thermally balanced and calibrated to be used with the table below at 70°F. A simple digital millivoltmeter attached to the leads can be used to determine the voltage of this junction. Note that thermocouple leads must be connected to the voltmeter via wires of the same material and the junction to the thermocouple leads must be at room temperature. This voltage can be converted to the equivalent temperature with the help of the conversion chart below.

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

See the appendix for a more detailed explanation of how thermocouples operate, and how to use a reverence junction to make extremely accurate temperature measurements

MEASURING THE CRITICAL TEMPERATURE USING THE MEISSNER EFFECT

We have discussed the concept of Critical Temperature on page 7. There are several ways that it can be measured. One effective and elegant way is to use the Meissner Effect. The superconducting devices with attached thermocouple probes in both the *Critical Temperature Kit* and the *Critical Temperature Comparison Kit* are designed for this purpose.

The superconductor and thermocouple device are encapsulated in a metal casing. We have designed this casing to impart greater thermal and mechanical stability to the device. The top of the device is the brass portion that shows a flat surface of the black superconductor disk. See figure 1 on the following page for details.

The procedure below will guide you through the measurement of the Critical Temperature of the superconductor step by step.

Procedure

1. ACTION: Carefully straighten the thermocouple leads and attach them to a voltmeter that can measure and display in the 0.01 milliVolt range.

2. ACTION: Immerse the device completely in liquid nitrogen. Allow the boiling of the liquid to subside. The thermocouple should read about +6.43 milliVolts, corresponding to the liquid nitrogen temperature of 77K.

3. ACTION: Remove the device from the liquid nitrogen and place it flat on a non-conducting surface with the black superconductor exposed on the top surface.

4. ACTION: Carefully balance the small cubical magnet so that it 'floats' via the Meissner Effect over the center of the disk.

5. ACTION: Keep the magnet under careful observation while recording the voltmeter reading at 5-second intervals. This part is best performed with the aid of a lab partner. You may have to center the magnet periodically with the tweezers.

   RESULT: For several minutes the magnet stays levitated. During this time the voltmeter reading begins to show a gradual increase in temperature. After a while, the magnet begins to drop, and finally comes to rest on the surface of the superconductor. The temperature as measured by the voltmeter at the time when the magnet has just come to a complete rest on the surface of the superconducting device, is the Critical Temperature, T_c, of the superconductor.

One of the mysteries of these new superconductors is that they do not have sharply defined Critical Temperatures. Typically, the transition from normal to superconducting state takes place over a range of about 5 Kelvin. The 'Critical Temperature' that you measure falls in this range, with a reading of about 95 Kelvin for $YBa_2Cu_3O_7$, and about 110 Kelvin for $Bi_2Sr_2Ca_2Cu_3O_9$.

We suggest that you use clean alligator clips to attach the thermocouple leads to the voltmeter leads. These connection points should be kept dry and at room temperature. The thermocouple has been carefully attached and packed inside the metal device casing. Please do not attempt to open the casing, or else the thermocouple junction will no longer be in good thermal contact with the superconductor.

Precautions.

1. Be careful not to let the liquid nitrogen splash or spill when you pour it. Read the handling guidelines (page 14) before using liquid nitrogen.
2. Use the provided non-magnetic tweezers when handling the device or magnet.
3. The electrical leads of the thermometer are delicate. Do not pull them, or twist or bend them unnecessarily. Bend the wires only before the device is cooled in the liquid nitrogen. Remember to keep the thermocouple-to-voltmeter lead connection at room temperature.

It appears that in ceramic superconductors, the Meissner Effect is a bulk phenomenon. Consequently, if any portion of the superconductor is below its Critical Temperature, the resultant Meissner Effect for that portion of the material will repel the magnet. The top surface of the superconductor disk warms first and looses its superconductivity as the liquid nitrogen evaporates. Other parts of the superconductor disk are still below the Critical Temperature, and thus continue to repel the magnet. However, since these parts are further from the magnet, it is levitated less. As the disk warms further, the magnet floats lower and lower, until the bottom of the disk is finally warmer than the Critical Temperature, at this point the magnet finally comes to rest on the top surface of the disk. Therefore, when the magnet comes to a complete rest on the surface of the superconductor, the bottom part of the disk, which is thermally attached to the thermocouple, is at the Critical Temperature.

Some Questions.

- Under some circumstances, the magnet will abruptly scoot to one side of the device as it warms. Can you think of an explanation for this?
- The device develops a layer of frost only after the liquid nitrogen has all boiled away. Why is this?
- Try the experiment by first placing the magnet on the superconducting device, and then cooling it down in liquid nitrogen. Do you observe any differences in the Critical Temperature? If so, why?
- The application of the Meissner Effect to measure the Critical Temperature was just one possible application of this effect. Can you think of other, elegant applications of this unique Effect?

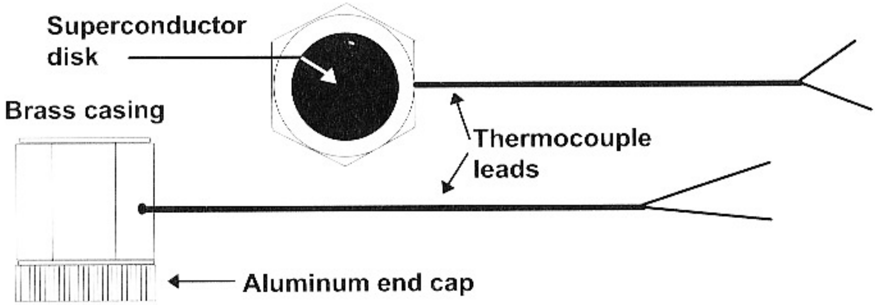


Figure 1: **The Superconducting Thermocouple Device**

THE FOUR POINT ELECTRICAL PROBE

The four point electrical probe is a very versatile device used widely in physics for the investigation of electrical phenomena. Colorado Superconductor Inc. has especially designed two four point superconducting devices from the $YBa_2Cu_3O_7$ and the $Bi_2Sr_2Ca_2Cu_3O_9$ materials for such investigations. The **Complete Exploration Kit** and the **Super Exploration** Kit contain four point electrical probes.

When a simple measurement of the electrical resistance of a test sample is performed by attaching two wires to it, one inadvertently also measures the resistance of the contact point of the wires to the sample. Typically the resistance of the point of contact (called contact resistance) is far smaller than the resistance of the sample, and can thus be ignored. However, when one is measuring a very small sample resistance, especially under variable temperature conditions, the contact resistance can dominate and completely obscure changes in the resistance of the sample itself. This is the situation that exists for superconductors.

The effects of contact resistance can be eliminated with the use of a four point probe. A schematic of a four point probe is shown in figure 2. In this diagram, four wires (or probes) have been attached to the test sample. A constant current is made to flow the length of the sample through probes labeled 1 and 4 in the figure. This can be done using a current source or a power supply as shown. Many power supplies have a current output readout built into them. If not, an ammeter in series with this circuit can be used to obtain the value of the current. A 5-Watt power supply capable of producing about ½ Amp is required for the experiments described for our superconducting devices.

If the sample has any resistance to the flow of electrical current, then there will be a drop of potential (or voltage) as the current flows along the sample, as for example between the two wires (or probes) labeled 2 and 3 in the figure. The voltage drop between probes 2 and 3 can be measured by a digital voltmeter. The resistance of the sample between probes 2 and 3 is the ratio of the voltage registering on the digital voltmeter to the value of the output current of the power supply. The high impedance of the digital voltmeter minimizes the current flow through the portion of the circuit comprising the voltmeter and probes 2 & 3. Thus, since there is no potential drop across the contact resistance associated with probes 2 and 3, the resistance associated with only the superconductor between probes 2 and 3 is measured.

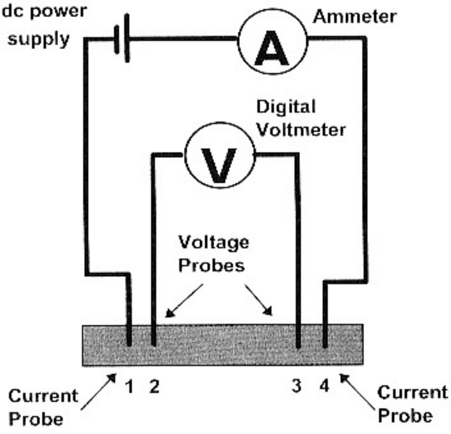


Figure 2: **Schematic of Four Point Probe**

The four point probe devices in the Complete *Exploration Kit* and the *Super Exploration Kit* are both encapsulated in rugged brass casings. On one side of the casing, the superconductor disk is visible. An aluminum end cap has been *inserted into the backside of the brass casing to seal and to protect* the probe connections with the superconductor. Please do not attempt to remove the end cap. A matched thermocouple has also been attached to the superconductor in this casing. This thermocouple is a *type 'T', and has been* described in detail on page 11 and in the appendix (page 42).

The $Bi_2Sr_2Ca_2Cu_3O_9$ superconductor *four point electrical probe casing is larger* than the $YBa_2Cu_3O_7$ casing. The former has BSCCO printed on the aluminum cap, and the latter with YBCO for further identification.

The illustration in figure 3 below shows the salient features of the four point probe devices. The pair of black wires are current leads for the *input* of current from the power supply, and have been labeled probes 1 and 4 in figure 2. The pair of yellow wires are the voltage measurement probes for measuring the voltage drop across the superconductor with the help of a digital voltmeter, and have been *labeled probes 2 and 3 in figure* 2. The red and blue wires are leads for the thermocouple.

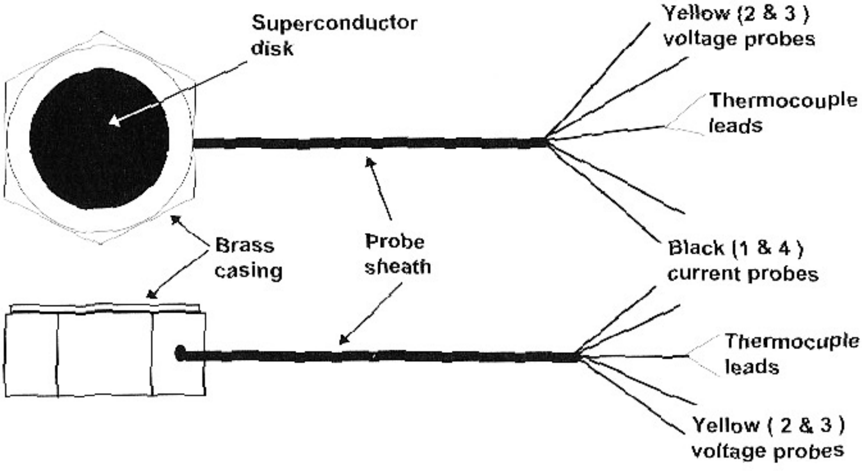


Figure 3: The Superconducting Four Point Probe

Measuring Resistance versus Temperature and Critical Temperature

The measurement of electrical Resistance as a function of the superconductor's Temperature yields fundamental insights into its properties. The Critical Temperature, Critical Current Density, and the Critical Magnetic Field, can all be obtained through variations of this basic experiment.

This experiment requires the following pieces of equipment:

1. A constant current source, or a power supply operating in the current limited mode. The output should not exceed 0.5 Amp. This is connected between the black current probes (probes 1 and 4). An ammeter placed in series with this circuit will measure the current. This current will be referred to as I_{14}.

2. A digital voltmeter with a 0.01-millivolt resolution to measure the voltage drop across the yellow voltage probes (probes 2 and 3). This voltage will be referred to as V_{23}.

3. Use of a **CSI Sand Cryostat (see appendix, page 38)** is suggested for optimal results. Alternatively, a container of liquid nitrogen deep enough to completely immerse the four point probe device may be used.

The voltmeters should be connected as shown in figure 2. Alternatively, a strip chart recorder with a 10-milliVolt full-scale range and a resolution of 10-microvolt may be connected between probes 2 & 3. This will provide a continuous record of the voltage drop. If a two-channel recorder or x-y plotter is used, then the thermocouple reading can also be measured simultaneously. The output from the voltmeters connected to probes 2 & 3, and to the thermocouple, may be sent directly to a computer to store and further analyze the data. The following is a step-by-step guide for measuring the device's Resistance versus its Temperature:

Procedure.

1. ACTION: Set up the measurement equipment as described above, but do not as yet immerse the device (four point probe) in liquid nitrogen.

2. ACTION: Insert the device into the CSI Sand Cryostat or other certified container and carefully fill it with liquid nitrogen. Ensure that the current (I_{14}) remains constant at less than 0.5 Amp.

   RESULT: The nitrogen boils furiously. Wait until the boiling subsides.

3. ACTION: Record the voltage V_{23}, and across the thermocouple junction.

   RESULT: V_{23} should equal zero. The thermocouple temperature reading should be 77 K.

4. ACTION: If you are not using the CSI Sand Cryostat, remove the device from the liquid nitrogen. As the device warms, continuously monitor the value of V_{23}. Record the thermocouple temperature each time V_{23} is recorded.

   RESULT: Initially, V_{23} remains constant even as the thermocouple temperature increases. The the voltage between the probes (V_{23}) abruptly increases, the thermocouple readin corresponding to this jump in voltage is the Critical Temperature, or T_c of th superconductor. The ratio of the voltage between probes 2 & 3 (V_{23}) to current flowin between probes 1 & 4 (I_{14}) is the instantaneous resistance of the superconduct between probes 2 & 3. The probe voltage, and the thermocouple reading could b input directly into a computer or chart recorder for more accurate results. This latt approach also provides a permanent record of the data. This result is shown in figur 4 on page 24.

Precautions.

1. When pouring liquid nitrogen be careful to prevent any splashing. Read the section on safety & handling starting page 13 before beginning this experiment.
2. Be careful not to touch the device or wires when they are cold. Follow the safety directions.
3. No more than 0.5 Amp of current should pass through the device or wires at any time.
4. If using a cryostat, slowly pour the sand out first, then remove the probe. Do not try to pull the probe out by the wires
5. Use a hair dryer to carefully dry the Four Point Probe device after use. Store it with a desiccant.
6. The probe and thermocouple wires are very brittle when cold. Please handle them with care.

Some Questions.

1. What effect would one expect if the Critical Temperature is measured with the device placed inside a functioning electromagnet?
2. Why is the transition in resistance gradual at the Critical Temperature?
3. A simple two-probe measurement of device resistance below its Critical Temperature exhibits a non-zero value. Why?

Determination of the Critical Temperature

The Critical Temperature, T_c is obtained during the measurement of the electrical Resistance as function of the Temperature of the superconductor on the previous page. The Critical Temperature of the $Bi_2Sr_2Ca_2Cu_3O_9$ superconductor is about 110 Kelvin versus about 92 Kelvin for the $YBa_2Cu_3O_7$ material. These results are shown below in figure 4.

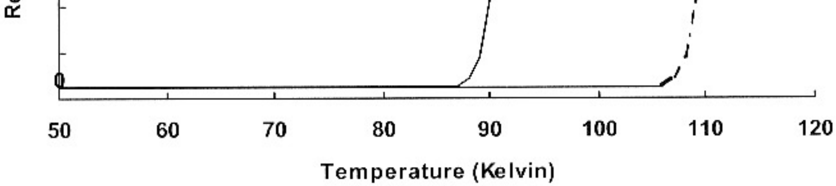


Figure 4: **Resistance versus Temperature**

Determining the Critical Current Density

The four point probe device can be used to measure the Critical Current Density, J_c, of the superconductor materials in your kit. Theoretically, one could measure J_c of the probe immersed in liquid nitrogen, by boosting the applied current I_{14} until a transition to non-superconducting state occurs. Practically, this procedure would damage the probe permanently. The following procedure will help preserve the integrity of your superconducting four point probe device. This procedure also has the added advantage of obtaining Critical Current values at different operating temperatures.

For this experiment, a power supply capable of up to 0.5 Amp output is required. Connect the device to the digital voltmeters and power supply as explained on page 22 of this Instruction Manual (describing the measurement of the device's Critical Temperature, T_c). A constant current source that can be set to output a range of current values up to 0.5 Amp will make the execution of this experiment considerably easier. Proceed with the following directions:

1. ACTION: Set the current through probes 1 and 4 at 0.1 Amp, and measure the Critical Temperature as described on page 23 of the Instruction Manual. Record the measured T_c versus the value of current used.

2. ACTION: Now increase the set current to 0.2 Amp, and repeat the process in action Item 1, above. Keep repeating the process with 0.1 Amp increments in current, taking care not to exceed a maximum of 0.5 Amp.

   RESULT: Five data points will be obtained, each at a Critical Temperature, T_c, versus the set current, I_{14}. An appropriate extrapolation (curve fit) to 77 Kelvin will result in the Critical Current for the superconductor. The Critical Current Density, J_c, can then be estimated from the probe geometry listed in the table below. Figure 5, below shows an example of the result with a $Bi_2Sr_2Ca_2Cu_3O_9$ based four point probe.

This is a difficult experiment. The data is electrically `noisy'. Some improvement in the signal-to-noise ratio may be achieved by making several independent measurements at each current setting.

Material	Diameter	Thickness	probe 1&4 spacing	probe 2&3 spacing	probe depth
$Yba_2Cu_3O_7$	24 mm	4 mm	17.5 mm	11 mm	Surface contact
$Bi_2Sr_2Ca_2Cu_3O_9$	30 mm	5 mm	17.5 mm	11 mm	1.75 mm

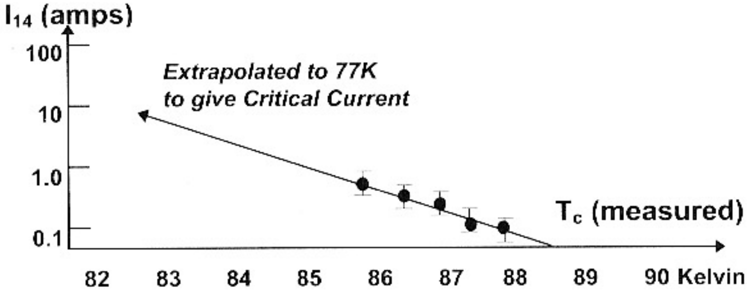


Figure 5: **The evaluation of Critical Current**

Determining the Critical Magnetic Field

This experiment measures the Critical Magnetic Field, Hc_2 of a ceramic superconductor using the four point probe device. Equipment to measure Hc_1, the lower Critical Field is beyond the scope of our approach.

For this experiment you will need an electromagnetic coil and associated power supply. The value of the field can be obtained using the geometry of the coil and a knowledge of the current flowing through it. The cavity in the middle of the coil needs to be large enough to accommodate the four point probe device and the liquid nitrogen container in which it is immersed. The four point probe device has been designed without any ferromagnetic parts to eliminate any potential interference.

Assemble the experiment as on page 25 in preparation of the measurement of Critical Current Density. However, this time place the four point device and its container of liquid nitrogen inside the cavity of the electromagnet. Gradually increase the current flowing through the electromagnet thus increasing the magnetic field strength through the superconductor. The value of V_{23} will show an abrupt increase at some value of applied magnetic field strength. This value of magnetic field is the upper Critical Magnetic Field, Hc_2 for the superconductor sample at the temperature of liquid nitrogen, 77 Kelvin.

The value of the Critical Field, Hc_2 can be obtained at other temperatures by either placing the device in a cryostat while performing this experiment, or by removing the device from the liquid nitrogen container and monitoring the output of the thermocouple thermometer while measuring Hc_2.

Another interesting experiment is the measurement of the Critical Temperature at different applied magnetic field strengths. The result of such an experiment for $YBa_2Cu_3O_7$ is shown schematically in figure 6. The value of Hc_2 has been extrapolated to 0 Kelvin. It is very instructive to perform a subset of this experiment using the square neodymium magnet provided with your kit instead of an electromagnet. As the magnet is brought close to the surface of the superconductor device (which has been prepared as on page 25), the value of V_{23} will slowly increase for a given value of I_{14}. This phenomenon could potentially be used to construct a superconductor-based magnetic field detector.

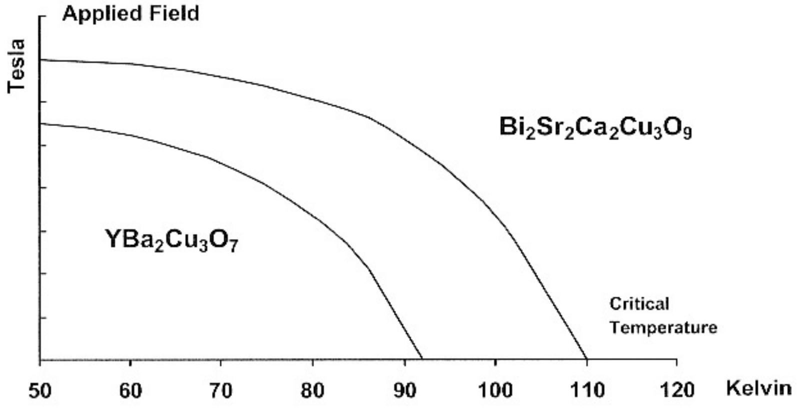


Figure 6: **Effect of Applied Magnetic Field on Critical Temperature**

THE SUPERCONDUCTING SUSPENSION EFFECT

The levitation of a magnet above a superconductor, the Meissner Effect, is well known. In October 1988, Huang and Peters of Lockheed and NASA respectively announced a startling and almost accidental discovery that they had made while investigating high temperature ceramic superconductors. This suspension phenomenon can be demonstrated with the help of the *Suspension & Levitation Kit* from Colorado Superconductor Inc.

The Kit contains a special superconductor disk which we shall call the Enhanced Flux Pinning (EFP) disk. A large, powerful neodymium rare earth magnet has been provided to suspend the EFP disk. A parallel set of materials has also been provided with the Kit to demonstrate the Meissner Effect described on page 16, for comparison. The experimenter requires only a source of liquid nitrogen for this experiment.

Procedure

1. ACTION: Completely immerse the EFP disk in a flat dish containing liquid nitrogen.

   RESULT: The liquid nitrogen boils around the EFP disk. When the boiling subsides, proceed.

2. ACTION: Examine the large neodymium magnet, and find the face through which the magnetic axis passes (the magnet has the strongest attraction on this face).

3. ACTION: Holding the magnet with the provided non-magnetic tweezers such that the magnetic axis is vertical, slowly lower the magnet so that it just touches the top of the immersed EFP disk.

   RESULT: As the magnet approaches the EFP disk, there will be a momentary resistance to its continued downward motion. This will cease when the magnet is in contact with the EFP disk. This resistance is a manifestation of the well-known Meissner Effect.

4. ACTION: Gradually withdraw the magnet upwards out of the liquid nitrogen.

   RESULT: The EFP disk should follow the magnet as it moves upwards and out of the liquid nitrogen. Observe that there is a gap between the EFP disk and the magnet. This is a gap that one would not observe in normal magnetic attraction.

   RESULT: As the EFP disk warms, it will lose its superconductivity, and can no longer be suspended under the magnet. It will drop.

This was a demonstration of the Suspension Effect in the new high temperature ceramic superconductors. Figure 8 on the following page illustrates the salient features of this demonstration. A picture of the Suspension Effect is also shown on the cover of this Instruction Manual.