Forecast:
Excitement at low temps

The Relaxation Times

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Condensed-Matter Physics:
Examining Superconductivity – *Three Ways*

If you've been reading our TeachSpin newsletters, you know we've been developing Condensed Matter Physics (CMP) experiments in recent years. You know that we now offer the cryostat, vacuum, and electronic equipment that provides the necessary 'infrastructure' for our existing Electrical-Transport, Specific-Heat, and Magnetic-Susceptibility experiments. Now we've added a fourth set of experiments that is supported by the ***same*** infrastructure: our new **CMP-Superconductivity** experiments that just made their debut at the APS March meeting.

Early in our design process, we decided to minimize the initial, and the operating, costs of our dewar by using liquid nitrogen (LN2) as a coolant. Of course this restricts our experiments to a temperature range above 77 K, but we can fulfill our educational mission by studying phenomena accessible in our temperature range. The discovery of high-temperature superconductivity in the 1980's makes it possible to study many of the properties of superconductivity in the >77 K range accessible with our CMP tools.

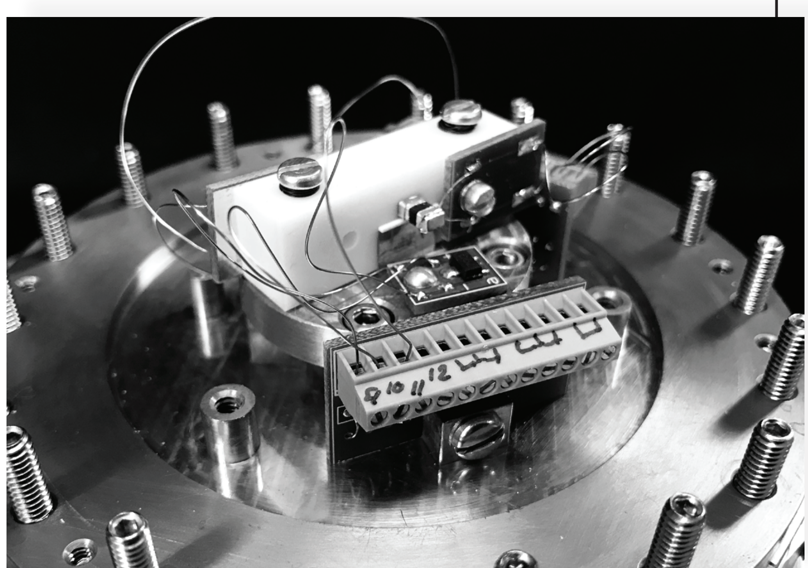
An advanced-lab experiment ought to do more than demonstrate the phenomenon of superconductivity; students ought to be able to detect the superconductive transition in *three independent* ways, and in each case should be able to explore the temperature dependence of the phenomenon under investigation. The three modes we now offer are detection via ***resistivity***, via ***magnetic susceptibility***, and via the creation and maintenance of a ***persistent current*** in a superconductor. This newsletter will show you some results from our new apparatus.

We picked BSSCO, in the form of Bi-2223 or $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ as our material of choice for all three investigations. That's bismuth strontium calcium copper oxide, a material sharing the copper-oxide planes made famous by YBCO. This material is available (in polycrystalline form) in the geometries we need, and displays a transition temperature of about 107 K, giving students access to the study of behavior in adequately-wide regions both above and below the transition temperature.

We know that a reliable supply of robust and affordable samples is critical to our users. We have dealt with these issues both for the BSSCO samples, and for the sample-mountings, in our CMP-Superconductivity offering. Here are some results.

Superconductivity, via resistance

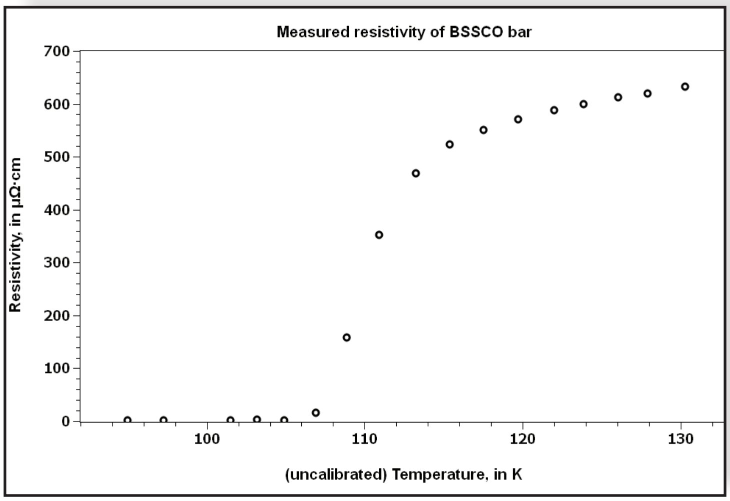
We supply a sample of BSSCO with permanent silver ohmic contacts on a bar-shaped sample suitable for four-wire resistance measurements. That bar comes mounted in a well-designed holder, using copper and alumina to provide good thermal contact with, and good electrical isolation from, the 'cold plate' of our dewar. The mount also provides permanent, and strain-relieved, electrical connections to the contacts on the bar of BSSCO.



At center: one end of a 4-wire BSSCO sample, emerging from its copper-and-plastic holder, showing voltage and current leads and their interface to our dewar's experimental stage.

Electrical wiring to these connections, and also to the mount's temperature transducer, are all made via the screw-terminal contacts provided on our dewar's cold plate – *no soldering required.*

The electrical resistance of such a sample can be measured by ordinary d.c. methods, using sample currents as large as 100 mA, and detecting voltage drops along the sample as small as 1 μV. The BSSCO material, despite being an oxide, displays metallic conductivity at ordinary temperatures, although at room temperature its resistivity is 700-fold larger than that of copper. BSSCO's resistivity drops, approximately linearly, with temperature, until a faster-than-linear decrease sets in at about 120 K. Further cooling shows a precipitous drop in resistivity, to values indistinguishable from zero below about 107 K.



Electrical resistivity of a BSSCO sample, measured in the temperature range around its superconductive transition.

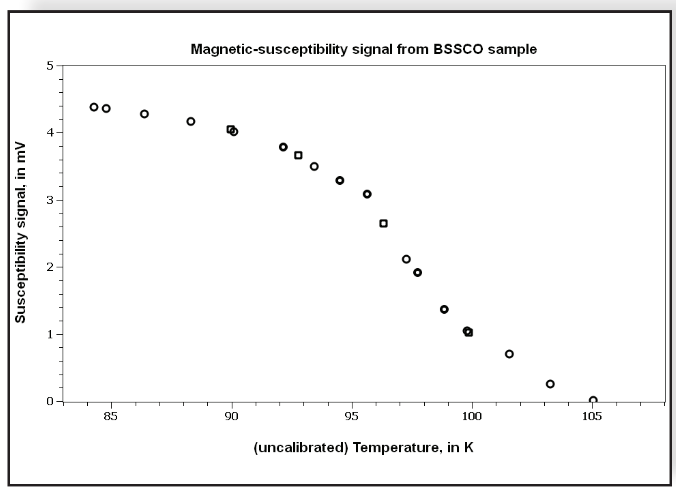
For reference, at 100 K the resistivity of pure copper is $\approx 4\times10^{-8}\ \Omega\cdot$m, and our sample displays resistivity at least as small as this. Use of our SIM (small instrument module) called the High-Gain Utility Amplifier (HGUA1-A) might provide still-higher sensitivity via d.c. methods. Astute students might note that an a.c. method of measurement, using lock-in detection, might be used to establish an even smaller upper limit to the resistivity.

Superconductivity, via magnetic susceptibility

Students who have seen a superconductive-levitation demonstration will have heard about the Meissner effect, or flux exclusion. From the fundamental relation $\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M})$ and the definition of magnetic susceptibility χ via $\boldsymbol{M} = \chi\,\boldsymbol{H}$, it follows that $\boldsymbol{B} = \mu_0(1 + \chi)\boldsymbol{H}$. Hence the case of 'perfect diamagnetism', or $\chi = -1$, entails $\boldsymbol{B} = 0$, i.e. the complete exclusion of magnetic flux from a sample.

Users of TeachSpin's dewar who have the CMP-Magnetic Susceptibility apparatus already have all that's required to measure the susceptibility χ for a BSSCO sample. As part of the CMP-Superconductivity offering, we include a 'chip' of polycrystalline Bi-2223 material of known mass (about 100 mg), epoxy-encapsulated into a sample of standard shape. Another sample containing a known mass of a paramagnetic salt, Gd_2O_3, permits a comparison measurement that makes possible an absolute measurement of susceptibility χ.

Our magnetic-susceptibility method uses an a.c. technique, in which an audio-frequency alternating ***H***-field is applied continuously to a sample as it's cooled. A lock-in detection method is sensitive enough to detect the diamagnetism of the epoxy encapsulant ($\chi \approx -10^{-5}$) even at room temperature, so the onset of perfect diamagnetism ($\chi = -1$) will give an enormous contrast. What we find is that the susceptibility is diamagnetic, but starts to grow very rapidly when cooling below 107 K. For further decreases in temperature, the susceptibility continues to grow in magnitude, but shows signs of saturating at the lowest temperatures we can reach. That 'saturation value' is qualitatively consistent with the full-flux-exclusion value, $\chi = -1$.



Magnetic susceptibility of a BSSCO sample, measured from its superconducting transition to lower temperatures.

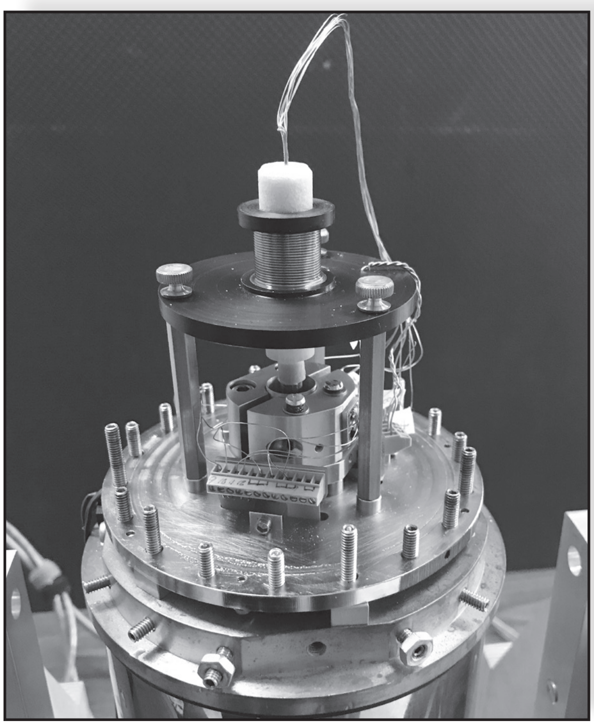
Note that whereas in resistivity methods, it's the above-transition region which has the interesting data, here it's the below-transition region that reveals the interesting physics. Note also that our lock-in method for detection of χ also offers a contact-free way of measuring the electrical conductivity of the material (data not shown).

Superconductivity, via persistent currents

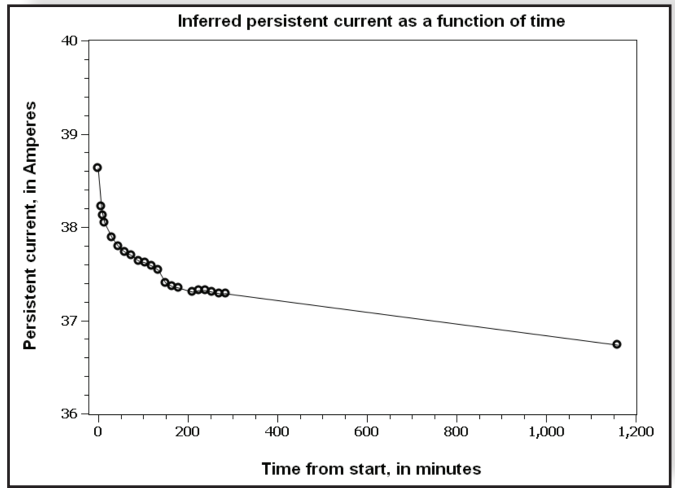
Some students are content to show that, below 107 K, their sample is of lower resistivity than (say) copper would be, but others will want to know if the resistivity is merely small, or is 'really zero'. Perhaps the best way to get extremely tight upper limits on the resistivity is to set up a 'persistent current', an electric current that will flow around a superconducting loop *forever* (if the resistance is truly zero).

Hence our new CMP-Superconductivity offering also includes another apparatus to mount onto the temperature-controlled cold plate of our dewar. Inside this mount is held an annulus, or thin-walled tube, of Bi-2223 material. This tube has no electrical contacts, but we provide a contact-free way to set up a supercurrent, and another contact-free way to measure the strength, and infer the spatial distribution, of that current once it is induced.

We cool this ceramic annulus while a long-enough permanent-magnet bar is held in place inside it, so that a non-zero magnetic flux is threaded through the still-resistive annulus. Now when the material becomes superconducting, that flux becomes 'trapped' within the annulus. Then upon withdrawing the permanent magnet, an electrical current starts flowing in the annulus to preserve the value of the magnetic flux. We measure that (super)current via the magnetic field it creates. Our rig includes a (temperature-stabilized) Hall-effect probe to measure the field inside the annulus. The mount includes a copper-wire solenoid of the same dimensions as the ceramic annulus, enabling the calibration of the Hall probe. With a calibrated probe measuring magnetic field over many hours (or days!) of time, we can set tight upper bounds to the decay rate (if any) of the magnetic field.



The holder for a BSSCO annulus (hidden inside its copper 'doughnut') and the calibration coil above it, with the Hall-probe magnetic-field sensor shown in position on axis.



The size of the persistent current, inferred from the magnetic field it sets up, plotted over the course of 20 hours' operation.

We already can say the decay rate of the field is smaller than 0.1% per hour, ie. that the time constant for decay is >1000 hours. If there were any resistance R to the flow of that supercurrent, we'd expect a decay time constant $\tau = L/R$, where L is the inductance of the annulus as a one-turn coil. We estimate $L \approx 10$ nH, and knowing $\tau > 10^6$ s gives us $R < 3 \times 10^{-15}\ \Omega$. Given the dimensions of the annulus, this limits the resistivity to $\rho < 2 \times 10^{-18}\ \Omega\cdot\text{m}$; this bound for the resistivity of BSSCO is about 10^{10}-fold better than the one we've established by direct measurement of resistivity.

Conclusion

We offer to users of our CMP infrastructure a well-thought-out and engaging package of superconductivity experiments, in which students can see three dramatic manifestations of the transition to superconductive behavior, and can explore these behaviors quantitatively and as a function of temperature.

Expect to see more details in a future Newsletter about rich physics that can be studied just in the persistent-current experiments.

TEACH SPIN

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Inside:

Our newest condensed-matter physics (CMP) experiment is now available –
See how to examine, systematically, the phenomenon of ***superconductivity*** in *three distinct ways.*

From our 'spring tour':

The TeachSpin 'Food Truck for the Physics Mind' made its way back from exhibiting at the March APS meeting by an outreach tour of the north-east USA, making day-long visits to physics departments at 17 colleges and universities. At our visit to Syracuse University, our founder Jonathan Reichert was surprised by a formal lunch and the award of a plaque recognizing his creation of both TeachSpin and the J. F. Reichert Foundation. He accepted this plaque on behalf of all the TeachSpin family that has kept their focus, stayed true to our mission, and worked hard over the past 25 years to make this dream a reality.

Reminder:

There's still time to sign up for a summer-2019 ALPhA Immersion!