E-2 Superconductivity

From Physics 191r

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First experiment: II

Contents

Learning Goals

- Understand type I and type II superconductors.
- Measure the susceptibility of several superconducting samples as a function of temperature.

- Determine the critical field and critical temperature of each sample by performing nonlinear curve fits.
- Characterize a superconducting alloy.
- Learn to use a lockin amplifier and AC and DC electromagnets.
- Handle cryogenic liquids safely.

Introduction

Superconductivity was discovered in 1911 by Kamerlingh Onnes (http://en.wikipedia.org/wiki/Kamerlingh_Onnes) in Leiden, for which he received the Nobel Prize in physics in 1913. It took until 1957 to understand superconductivity on a microscopic level, which describes the mechanism of pairing of electrons (formation of Cooper pairs at the Fermi Surface) and condensation of pairs into a macroscopic state. An article by Bardeen, Schrieffer, and Cooper, presented this theory, now known as the BCS (http://en.wikipedia.org/wiki/BCS_theory) theory of superconductivity; earlier in 1948 Fritz London (http://en.wikipedia.org/wiki/Fritz_London) developed a phenomenological theory and derived the "London Equations".

There are two important properties that characterize the transition of a metal from the normal to the superconducting state: zero electrical DC resistance and the Meissner (http://en.wikipedia.org/wiki/Walther_Meissner) effect, or the expulsion of magnetic fields from the interior of a superconducting material. There are two types of superconductors, Type I and Type II. In the first, the magnetic field is completely expelled at temperature T_{c1}, whereas in the latter, above T_{c1} the field begins to penetrate the SC and the penetrating magnetic field lines create vortices of electrical current or quantized flux tubes, while the resistance remains zero; these vortices can be arranged in a vortex lattice. In Type II, above T_{c2}, the field completely penetrates and the sample goes into the normal state. Type II are typically alloys and have important applications such as wire used to wind superconducting magnets.

In this experiment you will investigate several superconducting materials as a function of temperature, both type I and II, distinguished by their magnetic susceptibilities. In addition you will study a lead-tin alloy that we have made, both by its susceptibility and its resistance. This substance is not described in the literature and it will be your challenge to characterize it. You will not study the new high T_c materials.

Some experimental considerations

In this experiment, an ac susceptibility technique is used to determine the differential susceptibility $\chi = dM / dH$ of a superconducting sample as a function of H. From this, the magnetization $M(H)$ can be obtained by integration. The critical field, H_c can be determined from a feature in either $M(H)$ or $dM(H) / dH$.

Differential susceptibility

In elementary discussions of magnetic properties, it is often assumed that M is simply proportional to H: $= \chi H$M . This is oversimplified for a superconductor, since there are critical field values at which properties change. Thus, one must work with the differential susceptibility $\chi = dM / dH$ which in general depends on H. The voltage induced in a pickup coil surrounding the sample is proportional to dB / dt. In gaussian units, $B = H + 4\pi M$, so we can write $dB / dt = (dH / dt)(1 + 4\pi\chi)$. Since dH / dt is taken to be fixed by the drive current in the modulation coils, this voltage effectively measures $(1 + 4\pi\chi)$. One can attempt to cancel the unity term by use of an empty counter-wound coil in series with the coil containing the sample. Or, a "balancing potentiometer" can be used to compensate for inexact geometric balance. It may be more effective to simply subtract out the voltage induced in the pickup coil at a field above the critical field, where the superconductor is normal and shows no important diamagnetic susceptibility. After canceling this background signal, $M(H)$ should be obtainable by integration from the remaining signal.

Possible complication

This method implicitly assumes that a function $M(H)$ exists that has a well-defined derivative dM / dH. This will not be the case if there is any hysteresis, since then $M(H)$ depends on past history, especially sweep direction. This consideration enters both with respect to the slow sweep of the dc bias field and to the rapid sweep due to the field modulation. Hysteresis involves "non-equilibrium currents" in the superconductor, as distinct from the "equilibrium currents" that give the ideal theoretical diamagnetism. These non-equilibrium currents include the current fed into a superconducting magnet, for example, and in the absence of external currents, they are associated with inhomogeneity or "pinning sites" which result in internal currents which keep the flux distribution from relaxing to its equilibrium form. Magnet wire is made from material deliberately disordered to give high pinning and high irreversibility, *i.e.*, high hysteresis. In fact, the critical current in the volume of the wire (as opposed to surface currents) is taken to be proportional to the area of the hysteresis loop of the material. Fortunately for this experiment, the samples used are intended to be homogeneous and well-shaped to reduce these effects, but they cannot be simply assumed negligible. One might imagine a new twist to the experiment to examine these issues by introducing samples with heavy pinning, but let's keep it simple for the present!

Simple experiment

If we assume that these irreversibilities can be ignored, so that M(H) does exist, we can try to measure it. The induced voltage in a given loop is actually proportional (in gaussian units) to $dB / dt = dH / dt + 4\pi(dM / dt) = dH / dt(1 + 4\pi\chi)$, not dM / dt itself. It is customary to cancel the separate dH / dt term by using balanced counter-wound coils. If they are exactly balanced, this is fine, but having a balancing potentiometer offers a possible way to compensate for some imbalance. If these procedures fail to give zero induced voltage above H_c, when the material is normal, this non-zero voltage can be simply subtracted out, to leave a voltage proportional to dM / dt itself.

Better balance might be obtained by putting a normal metal (*e.g.*, Cu) sample in the other coil rather than leaving it empty. The reasoning is that even normal metals respond by eddy currents to an ac magnetic field, and balancing this term might lead to a cleaner isolation of the essentially dc magnetization. That is we would like to have a "dummy" sample that behaves like the sample in the normal state. But this is doubtful except possibly very near T_c (where there is still significant "normal" current), since the eddy current is out-of-phase while the diamagnetic current is in-phase with the drive current.

Once the balancing is successfully done, one finds (for a type I superconductor) a peak of positive dM / dH just below Hc and a constant negative value at lower H. This is just what is expected for this simple regime: The type I sample is fully diamagnetic, so dM/dH is a negative constant from $H = 0$ to H_c, and then becomes zero above H_c where the sample becomes normal. This transition at Hc takes the magnetization from a negative value to zero, *i.e.*, dM / dH is positive.

Ideally, for a type I sample, dM / dH should include a delta-function at H_c. Realistically, it will simply be a peak with finite width. Why does this occur? Can one account for the (typically ~10%) width of the transition? Possible causes include the non-zero demagnetizing factor of the sample shape, or other non-idealities of the geometry, or use of excess amplitude for the current in the modulation coils. The latter can be tested easily by varying the amplitude to see if it affects the apparent width of the "spike".

For type II materials, $|dM / dH|$ decreases as H increases, because flux is progressively penetrating above H_{c1}, and there is no discontinuity at H_{c2}.

Possible extension to hysteretic samples

As noted above, interpretation of data is less straightforward if the sample is hysteretic, either because of a non-ideal shape (*e.g.*, a collection of pellets), or because of flux pinning. This could perhaps be illustrated by use of a sample composed of superconducting magnet wire [*e.g.*, NbSn, NbTi, or even Nb (particularly if strained and not annealed).]

Apparatus

The main components of the experiment are

- (1) a liquid helium variable-temperature cryostat
- (2) a temperature controller
- (3) an electromagnet with programmable power supply
- (4) the transducers and electronic instrumentation necessary for the detection and recording of superconductive transitions as a function of applied magnetic field.

Each of these is briefly described below; operation manuals should be consulted for details.

Liquid helium variable-temperature cryostat

The variable-temperature (1.4 to 300 K) research cryostat[1] cools samples by suspending them in temperature controlled flowing helium vapor. A simplified diagram is shown on the next page. Liquid helium is drawn from the 5-liter reservoir via a needle valve and capillary tube to the vaporizer at the bottom of the sample tube. The liquid is vaporized and heated to some specified temperature, and travels upwards to cool the sample. The sample tube itself is isolated from the helium reservoir by a vacuum jacket, which enables the sample temperatures to be varied over a large range while the temperature of the helium in the reservoir remains at about 4.2 K. Temperatures down to about 2 K can be attained in the gas mode. If the flow of liquid out of the capillary is sufficiently low then by pumping, the helium cools and evaporates so the gas is colder than the liquid in the reservoir, with no accumulation of liquid. Alternatively, for operation below 4.2 K, the sample can be completely immersed in liquid helium (this is the typical operation mode). The temperature of the liquid helium and the sample can then be determined from the vapor pressure.

Temperature controller

The vaporizer in the cryostat contains a bifilarly wound heater and calibrated diode control thermometer.[2] The controller is a microprocessor-based instrument, which provides digital set point of the temperature, proportional analog control of the heater, and temperature readout. Another calibrated diode sensor at the sample mount provides for monitoring of the sample's temperature (a second heater at the sample mount is for optional use).

Electromagnet with programmable power supply

The 12-inch diameter poleface Varian electromagnet is a low-impedance type, capable of delivering about 8 kGauss with the present 2-inch pole gap. Power dissipation in the magnet reaches the kWatt range at about 60 Amps, so the magnet must be water-cooled when sweeping to maximum field. For most samples however, smaller currents are adequate to observe the superconducting transitions. The bipolar power supply[3] has a maximum current of 20 A, which produces 2.4 kGauss. No water-cooling is needed when using this supply. In current-programming mode, the gain of the Kepco BOP 20-20M is 2 A/V. If higher fields are desired, consult the faculty or staff for help switching to a supply with greater current capacity.

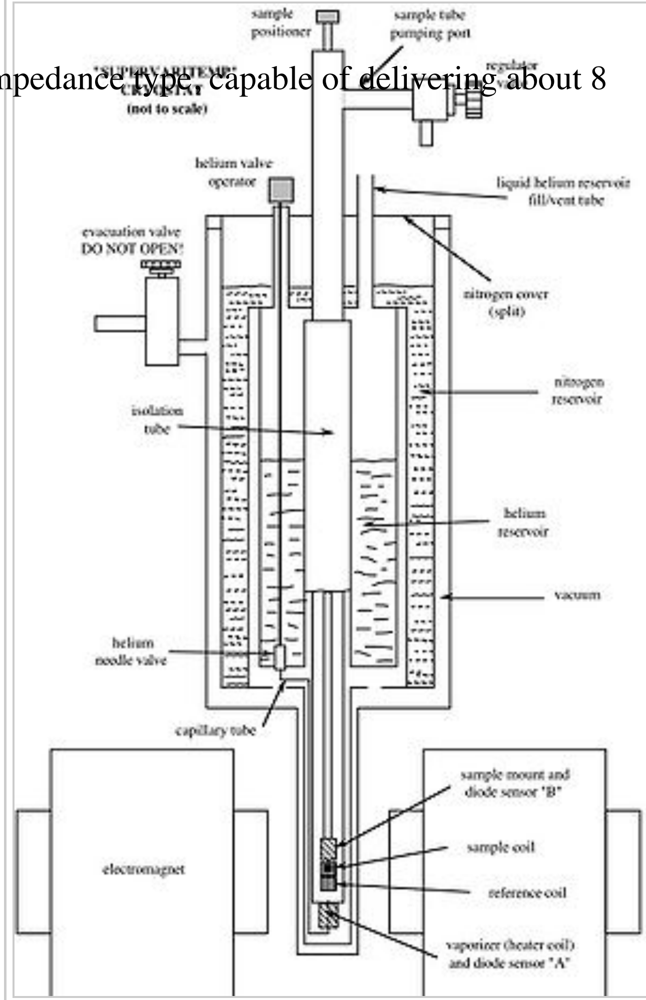
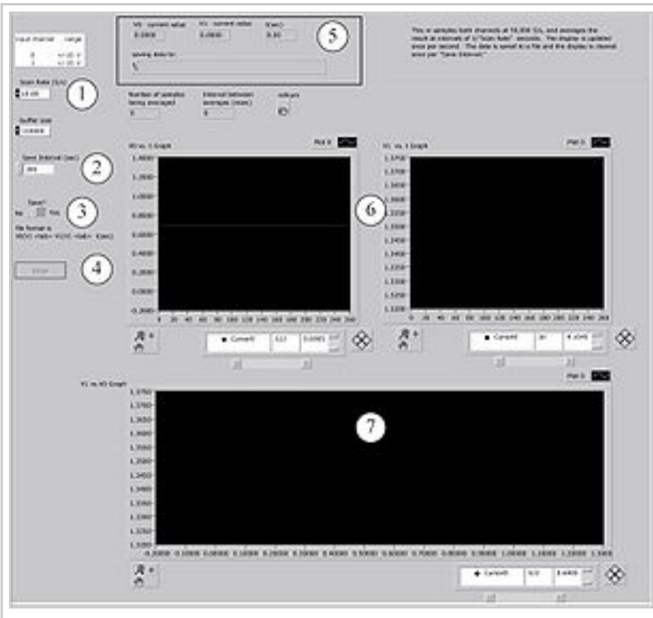


Figure 1. Janis 8DT cryostat

The magnetic field is detected with a Hall probe[4] and gaussmeter[5] whose analog output drives the x-input of a computerized X-Y recorder. The analog output of the Bell 615 gaussmeter has a 10 kΩ output impedance and gives only 100 mV for a full-scale reading. A dc amplifier with gain of 20 is provided to amplify the magnetic field signal and buffer it for connection to the interface box. Low-pass filtering is also needed for the magnetic field signal - more below. The analog to digital converter is a National Instruments PCI-6035E interface card. Use the LabVIEW program called "xyt_mx.vi" to record the output of the lock-in amplifier and the gaussmeter as functions of time.

LabVIEW

In the Meissner effect measurement, we wish to measure the EMF across a sample coil as a function of applied magnetic field. To this end, a LabVIEW program called xyt_mx.vi records the analog outputs from the SR530 lockin amplifier and the Bell 615 Gaussmeter (after amplification and filtering) at a rate specified by the user. See the figure below for details.



- (Figure 2-1). Rather than simply sampling the A/D converter at fixed intervals, this program samples both channels continuously at 50 kS/s and averages blocks of data at a rate determined by control #1. For example, if the SCAN RATE is set to 10 S/s, the program averages approximately 5000 samples every 100 msec.
- (Figure 2-2). Control #2 sets the time interval at

which the display is cleared and data written to file (if the SAVE? switch is set to Yes).

- (Figure 2-3). The SAVE? switch MUST be switched to Yes BEFORE running the vi if you want to save data.
- (Figure 2-4). Use this STOP button to end execution of the program.
- (Figure 2-5). Indicators #5 give the current values of V0 and V1, the time since the program started, and the path of the data file.
- (Figure 2-6). Graphs of V0 and V1 as functions of time.
- (Figure 2-7). Graph of V1 as a function of V0.

Figure 2. LabVIEW virtual instrument

Inductive detection

Coils are used to detect the superconductive transition, as described by F. Behroozi (1983) and W. Fietz (1965). The sample under investigation forms the core of the sample coil. A coil containing copper, which is not a superconductor or teflon, which is not even a conductor, is used as a reference. The samples have their axes aligned with the field of the electromagnet. In the normal regime, any change in applied field results in an induced emf in the coils. Below the superconducting transition, the sample exhibits perfect diamagnetism and reduces the magnetic flux passing through the coil around it.

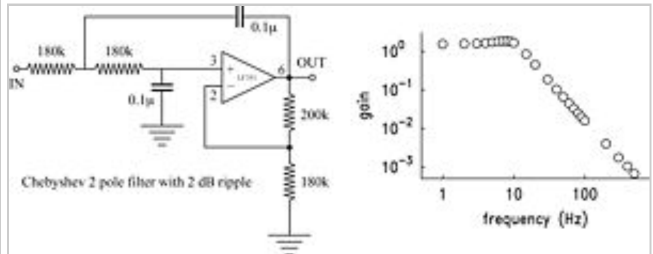


Figure 3. Chebyshev filter

Cylindrical samples (16mm long x 1mm diameter) of tin, lead, a tin-lead alloy (tin/40% lead), indium, and two indium-bismuth alloys (indium/2% bismuth and indium/4% bismuth) are loaded in a single sample holder, along with the reference samples. The pickup coils wound on the samples all contain 240 turns of #40 varnished magnet wire in two layers. A duplicate lead sample (labeled Pb1) with 120 turns of wire in a single layer is included for investigation of geometric effects. The finite thickness of the wire from which the coil is wound manifests as a non-zero flux in the superconducting regime.

Figure 4. Panel view of filter/amplifier box

Modulation coils on the magnet's pole pieces are driven with a sinusoidal current from a function generator[6] and amplifier[7]. The modulation is picked up by the Gaussmeter and thus its analog output has an AC component in addition to the DC component of interest. Use the low-pass filter (Figure 4-1) to attenuate this AC signal as it is not desired in the data record. A second filter is available for faster fall-off in the attenuation band. The filters have gain of about 2 in the pass band. Since the analog output of the Gaussmeter is limited to 100 mV full scale, an amplifier with gain 20 is also provided (Figure 4-2). The amplifier is constructed using both halves of an LF 412 op amp configured as


Figure 5. Circuit view of filter/amplifier box

noninverting amplifiers. The input impedance is 10 kΩ. Since the output impedance of the Gaussmeter is also 10 kΩ, use the filter(s) to buffer it before amplification. Calibrate the output of the filter(s)/amp in terms of the dc Gaussmeter reading. After observing a superconducting transition in lead, measure this signal for various modulation amplitudes and frequencies. The signal should not depend on these parameters.

Resistivity

A separate resistivity sample is mounted above the Meissner effect samples. The material is the same lead-tin alloy as used for the susceptibility measurement, but it is in the form of a long bifilar wound ribbon with four contacts at the ends – two for voltage and two for current. The dimensions are roughly 1 m x 2 mm x 0.1 mm and it is wound non-inductively. Make a constant AC current source with a function generator and a series resistor and perform a 4-probe resistance measurement as a function of temperature. Typical currents are on the order of 100 μA (your result should be independent of current). The lock-in amplifier is used as the voltmeter.

If you choose to measure the sample's normal resistivity at high temperature, the analog output of the Lakeshore 805 might be useful for temperature measurements above 15 K. Take care to buffer it properly rather than connecting it directly to the National Instruments card which has low input impedance.

Liquid Helium Level Gauge

A capacitance level gauge (https://coursewikis.fas.harvard.edu/phys191r/How_to_Transfer_Liquid_Helium#Capacitance_level_gauge) in the helium can measures the level of helium during and after transfer. The capacitance increases by 1 pF for each 6 cm of helium. For work above 4.2 K, transfer 2 pF of helium. For colder temperatures, transfer 3 pF of helium. An LCR meter[8] can measure this with a precision of 0.1 pF. The capacitance when empty is about 166 pF.

Liquid helium transfer

Appendix 4 (https://coursewikis.fas.harvard.edu/phys191r/How_to_Transfer_Liquid_Helium) explains the procedure for transferring liquid helium in detail. Read Appendix 4 carefully before you transfer helium for the first time. The procedure is summarized below. At the beginning of the lab, you should find the cryostat temperature to be between 100 K and 130 K. If so, it's ready for liquid helium transfer.

- Begin by checking the level of liquid helium in the storage Dewar. This is performed with the thermal-acoustic oscillation indicator, which is more commonly called the "thumper" in the lab. The change in frequency of the oscillations has to do with the resonant frequency of an open versus a closed tube. The reason why the oscillations occur in the first place is more complex and has been described in the literature.[9] In any case, measure the liquid helium level in the storage Dewar before, as well as after, you transfer and record your measurements on the clipboard. This way you will know how efficient your transfer was and the staff can tell (at a glance) if and when it's time to order more helium.

- Close the needle valve lightly. Close the balloon toggle valve on the cryostat and remove the two rubber stoppers (from the fill and vent tubes). While precooling, the He reservoir is slightly pressurized with He gas in the balloon to prevent condensation of air or water vapor that can clog or block the needle valve.

- Insert the transfer tube into the storage Dewar and into the fill-tube on the cryostat. The ends of the transfer tube should be just above the bottom of the storage Dewar and the bottom of the cryostat.

- Transfer slowly using about 0.25 psi pushing pressure on the storage Dewar. The economical transfer of liquid helium is particularly dependent upon good technique. After a minute or so, a flame-shaped white plume will appear at the cryostat vent tube. This indicates that liquid has started collecting in the helium can. Increase to 0.75 psi pushing pressure and transfer until the cryostat is full monitoring the capacitance helium level gauge (see below). During the transfer you should periodically (every minute or so) check that the needle valve has not seized up - open it (CCW) about one turn and then lightly close the valve again. Do not over tighten or the valve may seize shut due to the contraction of the dissimilar materials used in the valve body and needle assembly. If it's seized, stop the transfer procedure and consult a staff member.

- Release the driving pressure and remove the transfer tube.

- Install the two rubber stoppers in the fill and vent tubes. Replace the balloon with a vent tube and open the balloon toggle valve. The system is now ready to operate and cool the sample space.

Cryostat operation with temperature controller: You have four parameters to vary to achieve the desired temperature: (1) needle valve opening, (2) heater power, (3) sample-space pressure (controlled with a vacuum pump), and (4) liquid helium reservoir pressure. Adjust and try to find the optimal balance in these variables so as to minimize liquid helium consumption. For temperatures in the 4.2 K to 10 K range, we have found that 1/4 turn open on the needle valve, medium heater power, sample-space regulator valve less than or equal to 1/4 turn open and atmospheric pressure in the liquid helium reservoir works quite well.

An important warning: The vaporizer heater must not be energized when there is no helium flow. The extreme thermal isolation will allow the vaporizer to quickly reach destructive temperatures and either burn out the heater or melt the soft solder joint at the bottom of the assembly.

The temperature controller is equipped with two diode sensors[10] and two heaters. Their locations are designated as "A" (vaporizer assembly) and "B" (sample holder). One can read the temperature at either A or B, but we've set up the controller to use the A reading to determine how to drive the heater (at A) - so "A" is the control sensor and heater, but the sample temperature is given by sensor B. Sensor B does not have the best thermal contact with the sample and, once you see the temperature fluctuations at A during operation, you'll appreciate why we don't use B as our control sensor (and heater).

With the sample tube pumped down to 5-10 Torr, one can operate down to about 2K. Here we have to rely on the calibration of the sensor diode to monitor the temperature. However the diode calibration is sensitive to magnetic field. An alternative approach is to allow the sample to be immersed in liquid helium. The temperature of liquid He is 4.2 K at atmospheric pressure (760 mm Hg = 760 Torr). Pumping on the liquid He to reduce the vapor pressure, and hence cooling by evaporation lowers the temperature. You will have to allow liquid helium to accumulate in the sample space by opening the needle valve 2 to 3 turns and removing heater power. The level of liquid helium is monitored by a superconducting indicator[11] - a piece of wire (typically a niobium alloy) with a superconducting transition temperature above 4.2 K. The portion of the wire in the liquid helium is superconducting (zero resistance) and the portion above the liquid is normal. The total resistance is related to the proportion of normal wire; a four-lead resistance measurement is necessary. Additionally, there is a heater resistor built into the probe to ensure that the wire above the liquid is warmed above the transition temperature. Therefore don't leave the level indicator on, after you check the level, as this will boil away your helium! Note that the bottom of the sensor is actually 5 inches above the sample. Thus a 0% level indication does not necessarily mean that the sample is not immersed in liquid helium.

Although the two temperature-sensing diodes have been calibrated down to 1.2 K, we have found them not to be reliable below about 3 K. Consequently we have added a mechanical manometer, which operates over a pressure range of 1 to 760 Torr.[12] Using the "1958 He4 Scale of Temperatures" (found in the Bench Notes), you can convert the pressure readings to temperature. However, because of the location of the manometers, be aware of uncertainties; the relation between vapor pressure and temperature may not be accurate because of density stratification caused by cycling the pressure.

Before leaving the lab at the end of the day, please:

- Make sure that the rubber stoppers are in the fill and vent tubes of the liquid helium reservoir. This prevents water vapor (in the air) from condensing inside and clogging the valve and capillary tube with ice.
- The liquid nitrogen reservoir cover should also be in place. This will limit water buildup inside.
- Make sure that the toggle valve is open for venting the helium can.
- Turn off all electronic instruments.

Experimental procedure

Before cooling the cryostat, familiarize yourself with the magnet power supply and the inductive detection system. Test the magnet current sweep and gaussmeter and record magnetic field as a function of time with the LabVIEW program. Measure magnetic pickup from each sample coil using the lock-in amplifier. Think carefully about how to choose the lock-in phase. Discuss the cryostat operation with faculty or staff. When ready to cool down, find a superconducting transition signal in lead, and check that your modulation parameters are reasonable. Then measure the critical field as a function of temperature for each sample.

Lastly measure the resistivity of the lead-tin sample to determine the superconducting transition. The only sample which has not been studied in the literature is the lead-tin sample. You should carefully determine its transition temperature and the type of superconductor (I or II) from its measured properties.

References and Notes

1. ↑ Janis model 8DT "SuperVaritemp" Cryostat with 2.00-inch outer tail diameter and 1.00-inch sample tube
2. ↑ Lake Shore Cryotronics model 805 with two calibrated GaAlAs diode sensors (model TG-120P).
3. ↑ Kepco BOP 20-20M.
4. ↑ Bell model HTB1-0608 transverse probe.
5. ↑ Bell model 615 gaussmeter.
6. ↑ Wavetek model 21.
7. ↑ Kepco BOP 20-5M.
8. ↑ Electro Scientific Industries 252
9. ↑ *Experimental Cryophysics*, Hoare, Jackson, and Kurti (eds), (Butterworths, London, 1961): Chapter 7 by A. Wexler, entitled "Transfer of liquefied gases"
10. ↑ These are model TG-120P calibrated GaAlAs diodes; the controller has been programmed with the particular response curves (curve #6 and #7 for sensor A and B, respectively) which are switch-selected on the rear of the instrument.
11. ↑ American Magnetics model 110 Liquid Helium Level Meter; the sensor is 20 inches long.
12. ↑ Leybold model DIAVAC N - notice that the scale is logarithmic.

Additional reading

Resource letters:

D.M. Ginsberg, Am J Phys 32, 85 (1964), and Am J Phys 38, 949 (1970). "Resource Letters Scy-1 (http://www.fas.harvard.edu/~phys191r/References/e2/ginsberg1964.pdf) and Scy-2 (http://www.fas.harvard.edu/~phys191r/References/e2/ginsberg1970.pdf) on Superconductivity."

C.T. Lane, Am J Phys 35, 367 (1967). "Resource Letter LH-1 on Liquid Helium (http://www.fas.harvard.edu/~phys191r/References/e1/lane1967.pdf) ."

R.B. Hallock, Am J Phys 50, 202 (1982). "Resource Letter SH-1 on Superfluid Helium (http://www.fas.harvard.edu/~phys191r/References/e1/hallock1982.pdf) ."

Papers: The following references are included in the Bench Notes. Note that our present setup uses the scheme described by Behroozi (1983) and W. Fietz (1965). R. Dalven, Am J Phys 52, 1043-1049 (1984). "Physics of the critical magnetic field in type-II superconductors."

F. Behroozi, Am J Phys 51, 28 (1983). "Magnetic behavior of superconductors: An experiment for the advanced laboratory (http://www.fas.harvard.edu/~phys191r/References/e2/behroozi1983.pdf) ."

Hoare, Jackson, and Kurti "Experimental Cryophysics, sections 7.8 and 7.9: Liquid Level Indicators and Thermal Oscillations (http://www.fas.harvard.edu/~phys191r/References/thumper.pdf) ."

R.J. Soulen Jr., Journal de Physique 39, C6-1166 (1978). "A Superconductive Device to Provide Reference Temperatures below 0.5 K."

J.F. Schooley, Journal de Physique 39, C6-1169 (1978). "Superconductive Fixed Points for Temperatures Above 0.5 K (http://www.fas.harvard.edu/~phys191r/References/e2/Schooley.pdf) ."

R.J. Soulen Jr., J.F. Schooley, and G.A. Evans Jr., Rev Sci Instr 44, 1537 (1973). "Simple Instrumentation for the Inductive Detection of Superconductivity (http://www.fas.harvard.edu/~phys191r/References/e2/Soulen.pdf) ."

W.A. Fietz, Rev Sci Instr 36, 1621 (1965). "Electronic Integration Technique for Measuring Magnetization of Hysteretic Superconducting Materials (http://www.fas.harvard.edu/~phys191r/References/e2/Fietz.pdf) ."

F.G. Brickwedde, H. Van Dijk, M. Durieux, J.R. Clement and J.K. Logan, The "1958 He 4 Scale of Temperatures", (NBS Monograph 10, US Govt. Print. Office, Washington DC, 1960). This should be with the Bench Notes (and remain there).

Books: These references should help you in your background preparation.

McClintok, Meredith, Wigmore, Matter at Low Temperatures, (Wiley, N.Y., 1984). Cabot QC278.M35

M. Tinkham, Introduction to Superconductivity, Second Ed. (McGraw-Hill, N.Y., 1996). Cabot QC611.92.T56 1996

Guy K. White, Experimental Techniques in Low Temperature Physics, (Oxford Univ. Press, N.Y., 1979). Physics Research QC278.W45

R.D. Parks, Ed. Superconductivity, (Dekker, N.Y., 1969). Physics Research QC612.S8 P2

P.G. De Gennes, Superconductivity of Metals and Alloys, (Benjamin, N.Y., 1966). Cabot QC612.S8 G4

J.A. Strosio and W.J. Kaiser eds, Scanning Tunneling Microscopy (http://www.fas.harvard.edu/~phys191r/References/e2/Stm.pdf) , Methods of Experimental Physics v. 27, (Academic Press 1993).

Bench Notes

- Liquid Helium: Pressure (mTorr) vs. Temperature (K) (http://www.fas.harvard.edu/~phys191r/Bench_Notes/pt.txt)
- The 1958 Helium-4 Scale of Temperatures (P vs. T for lHe4) (http://www.fas.harvard.edu/~phys191r/Bench_Notes/HeScale.pdf)
- Liquid Helium Transfer Video (http://stream.fas.harvard.edu/ramgen/permanent/physics190r/LiquidHeliumTransfer.rm)
- Appendix 4: How to Transfer Liquid Helium (http://www.fas.harvard.edu/~phys191r/pdf/ap4_09.pdf)
-
- **Helium Transfer Quick Checklist**
- 1. Measure level in storage dewar
- 2. Precool transfer tube
- 3. Transfer helium into cryostat
- 4. Remeasure level in storage dewar
-
- Janis 8DT Cryostat (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E2/Cryostat.pdf)
- Sample Map (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E2/sample_map11.pdf)
- Pinout of Sample Connector (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E2/sc_pinout11.pdf)
- Bell 615 Gaussmeter (http://www.fas.harvard.edu/~phys191r/Bench_Notes/bell615.pdf)
- Helium Level Detector (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E2/HeDetector.pdf)
- He Scale of Temperatures (http://www.fas.harvard.edu/~phys191r/Bench_Notes/HeScale.pdf)
- Kepco BOP Specifications (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E2/bopspecs.pdf)
- Kepco BOP 20-5M and BOP20-20M Bipolar Amplifier (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E2/bopfull.pdf)
- Superconductor Properties (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E2/Props.pdf)
- Rectifier and Filter Notes (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E2/Rectifier.pdf)
- Lakeshore 805 Temperature Controller (http://www.fas.harvard.edu/~phys191r/Bench_Notes/Tempcontroller.pdf)
- Leybold Diavac N Pressure Gauge (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E2/diavacn.pdf)
- Stanford Research Systems SR530 Lockin Amplifier (http://www.fas.harvard.edu/~phys191r/Bench_Notes/E2/SR530.pdf)
- National Instruments PCI-6023e Multifuction DAQ card (http://www.fas.harvard.edu/~phys191r/Bench_Notes/A10/ni6023e.pdf)
- Dell Optiplex 980 Technical Guide (http://www.fas.harvard.edu/~phys191r/Bench_Notes/optiplex-980-tech-guide.pdf)

Photos

Appendix: Notes on Skin Effect

Cryostat.

Aluminum radiation shield, bolted to nitrogen can. Tail cap has been removed.

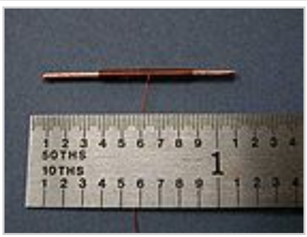
Sample can. Radiation shield has been removed.

Detail of sample can showing capillary, heater and diode.

End view of sample can.

Bottom view of cryostat body with sample can removed.

Current sample holder.



Copper sample in preparation.

M. Tinkham 3/17/04

The diamagnetic response of a classic type I superconductor ("Meissner effect") is limited by the "London penetration depth" λ_L, named after the London brothers, Heinz and Fritz. That is, a weak magnetic field penetrates only to a depth λ_L, and for usual superconductors λ_L is very small (about 500Å). For a type II superconductor, there is a range of stronger fields, between H_{c1} and H_{c2} in which flux partially penetrates the material in the form of quantized flux tubes, each carrying a flux quantum $hc/2e$ (gaussian units) $\approx 2 \times 10^{-7}$ gauss-cm^2. This regime is an important part of this experiment.

With a **normal** metal like Cu (or a superconductor above T_c), the DC diamagnetism is very weak, so the magnetization is very small compared to the full Meissner effect (flux exclusion) of a bulk superconductor. However, if the experiment is performed by exposing the sample to an ac magnetic field, currents are induced in the normal metal which limit the penetration of the field to a "skin depth δ" which characterizes the exponential decay of the penetrating applied ac field. This penetration depth is approximately given by $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$, where σ is the electrical conductivity of the metal, ω is the angular frequency, and μ is the dc susceptibility of the metal, which can normally be approximated by μ_0, the susceptibility of free space $4\pi \times 10^{-7}$ in SI units. Plugging in a typical metallic conductivity and a measuring frequency of a few hundred Hertz, the order of magnitude of δ is a millimeter. Thus, for samples of the size used in this experiment, the fractional ac magnetization will be of the same order of magnitude as that of a type II superconductor, *not* zero.

The skin effect response of a normal metal is treated in most E & M texts, with varying degrees of rigor and detail. Here I will give a short version, based directly on Maxwell's Equations:

In SI units, a Maxwell equation gives

$$\vec{\nabla} \times \vec{H} = \vec{J} = \sigma \vec{E}\cdot$$

Taking the curl of both sides, and applying another Maxwell equation:

$$\vec{\nabla} \times \vec{\nabla} \times \vec{H} = \sigma \vec{\nabla} \times \vec{E} = -\sigma \partial \vec{B} / \partial t\cdot$$

Using a vector calculus identity, the left member can be replaced by $-\nabla^2 \vec{H}$. Assuming an $e^{i\omega t}$ time dependence, and setting $B = \mu H$ in a normal metal, we have

$$-\nabla^2 \vec{H} = -i\omega\mu\sigma H\cdot$$

This has a solution that decays exponentially with the penetration depth δ mentioned above, thanks to an induced current, which is 45° out of phase with the drive field.

You may want to check this sketchy derivation (which assumes that displacement currents are negligible compared to conduction currents in the metal), and also think about checking it qualitatively against experimental observations. For example, how do your measurements vary with the frequency used? Does the relative phase of the magnetization differ from that of superconductors in the Meissner state by something like the 45 degrees that comes from the square root of *i*?

Appendix (Staff Notes): Superconductivity cryostat precool procedure

- One day in advance of cooldown, with the cryostat at room temperature, pump the vacuum jacket.
- Flush with nitrogen gas. (Helium can and sample can MUST be at atmospheric pressure.)
- Pump the vacuum jacket for a few hours.
- Valve off the vacuum jacket.
- Pump the sample can and helium can. Use two hands to open the gate valve since it has no mechanical support. (Vacuum jacket MUST be at vacuum.)
- Fill Mr. Smiley Face balloon with helium from liquid helium boil-off.
- Valve off sample can and helium can and backfill from the balloon.
- Refill Mr. Smiley Face and reconnect to the helium can.
- Make sure that the liquid nitrogen can is dry. If any water is visible, remove it with a sponge and/or warm air from an airtrack blower.
- Fill the liquid nitrogen can with liquid nitrogen.
- Top off the liquid nitrogen periodically until the experiment runs.