Superconductivity: The Meissner Effect, Persistent Currents and the Josephson Effects

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Several phenomena associated with superconductivity are observed in three experiments carried out in a liquid helium cryostat. The transition to the superconducting state of several bulk samples of Type I and II superconductors is observed in measurements of the exclusion of magnetic field (the Meisner effect) as the temperature is gradually reduced by the flow of cold gas from boiling helium. The persistence of a current induced in a superconducting cylinder of lead is demonstrated by measurements of its magnetic field over a period of a day. The tunneling of Cooper pairs through an insulating junction between two superconductors (the DC Josephson effect) is demonstrated, and the magnitude of the fluxoid is measured by observation of the effect of a magnetic field on the Josephson current.

1. PREPARATORY QUESTIONS

Please visit the Superconductivity chapter on the 8.14x website at `mitx.mit.edu` to review the background material for this experiment. Answer all questions found in the chapter. Work out the solutions in your laboratory notebook; submit your answers on the web site.

2. CRYOGENIC ASPECTS AND SAFETY

It is imperative that you read this section on Cryogenic Safety before proceeding with the experiment.

The Dewar flask shown in Figure 7 contains liquid helium in a nearly spherical metal container (34 cm in diameter) which is supported from the top by a long access or neck tube (length about 50-60 cm and diameter about 3 cm) of low conductivity metal. It holds $\sim$25 liters of liquid. The boiling rate of the liquid helium is slowed by a surrounding vacuum which minimizes direct thermal conduction. There are also multiple layers of aluminized mylar which minimize radiative heat transfer. The internal surfaces are carefully polished and silver plated for low emissivity. Measurement shows that helium gas from the boiling liquid in a quiet Dewar is released with a flow rate of gas at STP (standard temperature and pressure = 760 torr and 293K) about 5 $\mathrm{cm^3 s^{-1}}$.

The only access to helium is through the neck of the dewar. Blockage of this neck will result in a build-up of pressure in the vessel and a consequent danger of explosion. The most likely cause of a neck blockage is frozen air (remember everything except helium freezes hard at 4 K) in lower sections of the tube. Thus it is imperative to inhibit the streaming of air down the neck.

In normal quiet storage condition, the top of the neck is closed with a metal plug resting loosely on the top flange. When the pressure in the Dewar rises above $p_0 = W/A$ (where W is the weight of the plug and A is its cross-sectional area) the plug rises and some pressure is released. Thus the pressure in the closed Dewar is regulated at p_0 which has been set at approximately 0.5 inches of Hg. This permits the vaporized helium gas to escape and prevents a counterflow of air into the neck. When the plug is removed, air flows downstream into the neck where it freezes solid. You will have to remove the plug for measurements of the helium level and for inserting probes for the experiment, and **it is important that the duration of this open condition be minimized. Always have the neck plug inserted when the Dewar is not in use.**

In spite of precautionary measures, some frozen air will often be found on the surface of the neck. This can be scraped from the tube surface with the neck reamer, consisting of a thin-wall half-tube of brass. Insertion of the warm tube will liquefy and evaporate the oxygen/nitrogen layer or knock it into the liquid helium where it will be innocuous. **If you feel any resistance while the probe is being inserted in the Dewar, remove the probe immediately and ream the surface (the whole way around) before reinserting the probe.** The penalty for not doing this may be sticking of delicate probe components to the neck surface. Warmed and refrozen air is a strong, quick-drying glue!

In summary:

1. Always have the neck plug on the Dewar when it is not in use.
2. Minimize the time of open-neck condition when inserting things into the Dewar.
3. Ream the neck surface of frozen sludge if the probe doesn't go in easily.

3. THEORETICAL BACKGROUND

In this experiment you will study several of the remarkable phenomena of superconductivity, a property that certain materials (e.g. lead, tin, mercury) exhibit when cooled to very low temperature. As the cooling agent you will use liquid helium which boils at 4.2 K at standard atmospheric pressure. With suitable operation of the equipment you will be able to control the temperatures of samples in the range above this boiling temperature. The liquid helium (liquefied at MIT in the Cryogenic Engineering Laboratory) is stored in a highly insulated Dewar flask.

3.1. Superconductivity

Superconductivity was discovered in 1911 by H. Kamerlingh Onnes in Holland while studying the electrical resistance of a sample of frozen mercury as a function of temperature. Onnes was the first to liquefy helium in 1908. On cooling Hg to the temperature of liquid helium, he found that the resistance vanished abruptly at approximately 4 K. In 1913 he won the Nobel prize for the liquification of helium and the discovery of superconductivity.

Since that time, many other materials have been found to exhibit this phenomenon. Today over a thousand materials, including some thirty of the pure chemical elements, are known to become superconductors at various temperatures ranging up to about 20 K.

Within the last several years a new family of ceramic compounds has been discovered which are insulators at room temperature and superconductors at temperatures of liquid nitrogen. Thus, far from being a rare physical phenomenon, superconductivity is a fairly common property of materials.

Superconductivity is of great importance for applications such as Magnetic Resonance Imaging (MRI) and the bending magnets of particle accelerators such as the Tevatron and the LHC.

Zero resistivity is, of course, an essential characteristic of a superconductor. However superconductors exhibit other properties that distinguish them from what one might imagine to be simply a perfect conductor, i.e. an ideal substance whose only peculiar property is zero resistivity.

The temperature below which a sample is superconducting in the absence of a magnetic field is called the critical temperature, T_c. At any given temperature, $T < T_c$, there is a certain minimum field $B_c(T)$, called the critical field, which will kill superconductivity. It is found (experimentally and theoretically) that B_c is related to T by the equation

$$B_c = B_0 \left[1 - \left(\frac{T}{T_c} \right)^2 \right], \tag{1}$$

where B_0 is the asymptotic value of the critical field as $T \to 0$ K. Figure 1 shows this dependence for various materials including those you will be studying in this experiment.

Note the extreme range of the critical field values. These diagrams can be thought of as phase diagrams: below its curve, a material is in the superconducting phase; above its curve the material is in the nonsuperconducting phase.

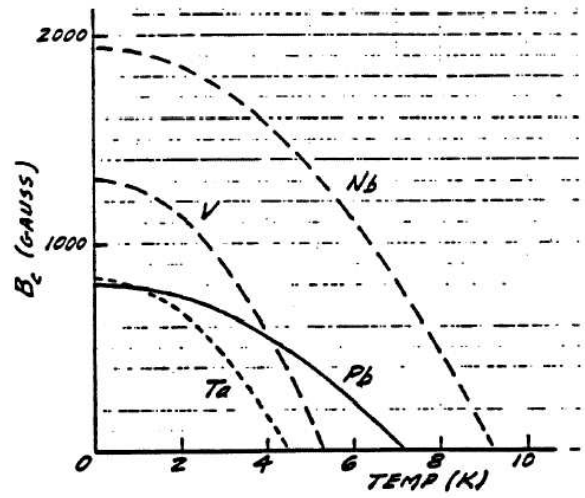

FIG. 1: Critical field plotted against temperature for various superconductors.

3.2. Meissner Effect and the Distinction Between a Perfect Conductor and a Super Conductor

An electric field $\vec{E}$ in a normal conductor causes a current density $\vec{J}$ which, in a steady state, is related to the electric field by the equation $\vec{J} = \sigma\vec{E}$ where σ is called the electrical conductivity. In a metal the charge carriers are electrons, and at a constant temperature, σ is a constant characteristic of the metal. In these common circumstances the relation between $\vec{E}$ and $\vec{J}$ is called "Ohm's law". A material in which σ is constant is called an ohmic conductor.

Electrical resistance in an ohmic conductor is caused by scattering of conduction electrons by impurities, dislocations and the displacements of atoms from their equilibrium positions due to thermal motion. In principle, if there were no such defects, the conductivity of a metal would be infinite. Although no such substance exists, it is interesting to work out the theoretical consequences of perfect conductivity according to the classical laws of electromagnetism and mechanics. Consider a perfect conductor in the presence of a changing magnetic field. According to Newton's second law, an electron inside the conductor must obey the equation $e\vec{E} = m\dot{\vec{v}}$, where $\dot{\vec{v}}$ represents the time derivative of the velocity vector. By definition $\vec{J} = ne\vec{v}$ where n is the conduction electron number density. It follows that $\vec{E} = m\dot{\vec{J}}/ne^2$. For later convenience, we rewrite this as $\vec{E} = 4\pi\lambda^2\dot{\vec{J}}/c^2$, where

$$\lambda^2 = \frac{mc^2}{4\pi ne^2}. \tag{2}$$

From the Maxwell equation $\nabla \times \vec{E} = -\dot{\vec{B}}/c$, we get

$$\frac{4\pi\lambda^2}{c} \nabla \times \dot{\vec{J}} = -\dot{\vec{B}}. \tag{3}$$

From the Maxwell equation $\nabla \times \vec{B} = (4\pi\vec{J}/c + \dot{\vec{E}}/c)$, it follows that $\lambda^2 \nabla \times (\nabla \times \dot{\vec{B}}) = -\dot{\vec{B}}$, where we assume the low frequency of the action permits us to drop the displacement term $\dot{\vec{E}}$. The latter equation can then be expressed as $\nabla^2 \dot{\vec{B}} = \dot{\vec{B}}$. The solution of this equation is $\dot{\vec{B}}(z) = \dot{\vec{B}}(0)e^{-z/\lambda}$ where z is the distance below the surface.

Thus $\dot{\vec{B}}$ decreases exponentially with depth leaving $\vec{B}$ essentially constant below a characteristic penetration depth λ. If a field is present when the medium attains perfect conductivity, that field is retained (frozen-in) irrespective of what happens at the surface. If we attempted to change the magnetic field inside a perfect conductor by changing an externally-applied field, currents would be generated in such a way as to keep the internal field constant at depths beyond λ. This may be thought of as an extreme case of Lenz's law. If a perfect conductor had a density of conduction electrons like that of copper (approximately one conduction electron per atom), the penetration depth would be of order 100 Å. A magnetic field can exist in a medium of perfect conductivity providing it was already there when the medium attained its perfect conductivity, after which it cannot be changed.

It came as quite a surprise when Meissner and Ochsenfeld in 1933 showed by experiment that this was not true for the case of superconductors. They found instead that the magnetic field inside a superconductor is always zero, that is $\vec{B} = 0$, rather than the less stringent requirement $\dot{\vec{B}} = 0$. This phenomenon is now referred to as the *Meissner Effect*.

Shortly after its discovery, F. and H. London [1] gave a phenomenological explanation of the Meissner effect. They suggested that in the case of a superconductor, Eq.(3) above should be replaced by

$$\frac{4\pi\lambda}{c} \nabla \times \vec{J} = -\vec{B}. \tag{4}$$

This is called the London equation. Continuing as before, one obtains

$$\vec{B} = \vec{B}_0 e^{-z/\lambda_L}, \tag{5}$$

which implies that $\vec{B} \approx 0$ for depths appreciably beyond λ_L, in agreement with the Meissner Effect.

Thus, we can think of a superconductor as being a perfectly diamagnetic material. Turning on a magnetic field generates internal currents which flow without resistance and completely cancel the field inside.

The constant λ_L, called the London penetration depth. Experiments have demonstrated the universal validity of Eq.(5) The magnitude of λ_L may well differ from that of λ since the density of superconducting electrons is not necessarily the same as that of conduction electrons in a normal metal. It varies from material to material and is a function of temperature.

3.3. Implications of the Meissner effect

The Meissner Effect has remarkable implications. Consider a cylinder of material which is superconducting below T_c. If the temperature is initially above T_c, application of a steady magnetic field $\vec{B}$ will result in full penetration of the field into the material. If the temperature is now reduced below T_c, the internal field must disappear. This implies the presence of a surface current around the cylinder such that the resulting solenoidal field exactly cancels the applied field throughout the volume of the rod. A current in a long solenoid produces a uniform field inside the solenoid parallel to the axis with a magnitude determined by the surface current density (current per unit length along the solenoid axis), and no field outside the solenoid. In the case of the superconducting cylinder in a magnetic field, the surface current is in a surface layer with a thickness of the order of λ_L. Any change of the externally applied field will cause a change of the surface current that maintains zero field inside the cylinder. The difference between this behavior and that of a perfectly conducting cylinder is striking. As mentioned previously, if such a cylinder underwent a transition to a state of perfect conductivity in the presence of a magnetic field, the internal field would remain unchanged and no surface current would appear. If the field were then reduced, a surface current would be induced according to Faraday's law with the result that the flux of the internal field would remain constant.

Next we consider the case of a hollow cylinder of material which is superconducting below T_c. Just as in the solid rod case, application of a field above T_c will result in full penetration both within the material of the tube and in the open volume within the inner surface. Reducing the temperature below T_c with the field still on gives rise to a surface current on the outside of the cylinder which results in zero field in the cylinder material. By itself, this outside-surface current would also annul the field in the open space inside the cylinder: but Faraday's law requires that the flux of the field inside the cylinder remain unchanged. Thus a second current must appear on the inside surface of the cylinder in the opposite direction so that the flux in the open area is just that of the original applied field. These two surface currents result in zero field inside the superconducting medium and an unchanged field in the central open region. Just as before, the presence of these two surface currents is what would be expected if a magnetic field were imposed on a hollow cylinder of perfectly diamagnetic material.

If now the applied field is turned off while the cylinder is in the superconducting state, the field in the open space within the tube will remain unchanged as before. This implies that the inside-surface current continues, and the outside-surface current disappears. The inside-surface current (called persistent current) will continue indefinitely as long as the medium is superconducting. The magnetic field inside the open area of the cylinder will also persist. The magnetic flux in this region is called the frozen-in-flux. In effect, the system with its persistent currents resembles a permanent magnet. Reactivation of the applied field will again induce an outside-surface current but will not change the field within the open space of the hollow cylinder. One should also be aware of the obvious fact that magnetic field lines cannot migrate through a superconductor.

Incidentally, no perfect conductors are known. However, partially ionized gas of interstellar space (≈ 1 hydrogen atom cm^{-3}) is virtually collisionless with the result that it can be accurately described by the theory of collisionless plasma under the assumption of infinite conductivity.

3.4. BCS theory

The London equation, Eq.(4), is not a fundamental theory of superconductivity. It is an ad hoc restriction on classical electrodynamics introduced to account for the Meissner Effect. However, the London equation has been shown to be a logical consequence of the fundamental theory of Bardeen, Cooper, and Schrieffer - the BCS theory of superconductivity for which they received the Nobel Prize in 1972 [2]. A complete discussion of the BCS theory is beyond the scope of this labguide, but you will find an interesting and accessible discussion of it in [3] (vol. III, chapter 21) and in references [2, 4, 5]

According to the BCS theory, interaction between electrons and phonons (the vibrational modes of the positive ions in the crystal lattice) causes a reduction in the Coulomb repulsion between electrons which is sufficient at low temperatures to provide a net long-range *attraction*. This attraction causes the formation of bound pairs of remote electrons of opposite momentum and spin, the so-called Cooper pairs. Being bosons, many Cooper pairs can occupy the same quantum state. At low temperatures they "condense" into a single quantum state (Bose condensation) which can constitute an electric current that flows without resistance.

The quenching of superconductivity above T_c is caused by the thermal break-up of the Cooper pairs. The critical temperature T_c is therefore a measure of the pair binding energy. The BCS theory, based on the principles of quantum theory and statistical mechanics, is a fundamental theory that explains all the observed properties of low-temperature superconductors.

3.5. Recent developments in high-T_c superconducting materials

The BCS theory of superconductivity led to the conclusion that T_c should be limited by the uppermost value of phonon frequencies that can exist in materials, and from this one could conclude that superconductivity was not to be expected at temperatures above about 25 K. Workers in this field were amazed when Bednorz and Müller [6], working in an IBM laboratory in Switzerland, reported that they had found superconductivity at temperatures of the order 40 K in samples of LaBaCuO with various concentrations. This is all the more surprising because these are ceramic materials which are insulators at normal temperatures.

The discovery of high-temperature superconductors set off a flurry of experimental investigations in search of other high-T_c materials and theoretical efforts to identify the mechanism behind their novel properties. [It has since been reported that samples of YBaCuO exhibit T_c at 90 K with symptoms of unusual behavior at even higher temperature in some samples.] Many experiments have been directed at identifying the new type of interaction that triggers the high-T_c transitions. Various theories have been advanced, but none has so far found complete acceptance.

4. EXPERIMENTAL APPARATUS AND BASIC PROCEDURES

4.1. Checking the level of liquid helium in the dewar

A "thumper" or "dipstick" consisting of a 1/8"-diameter tube about 1 meter long with a brass cap at the end is used for measuring the level of liquid helium in the Dewar. The tube material, being a disordered alloy of Cu-Ni, has very low thermal conductivity (over three orders of magnitude less than that of copper!) particularly at low temperature and will conduct very little heat into the helium. The measurement consists in sensing the change of frequency of pressure oscillations in the tube gas between when the lower end is below and above the liquid level.

After removing the neck plug, hold the dipstick vertically above the Dewar and lower it slowly into the neck at a rate which avoids excessive blasts of helium gas being released from the Dewar. During the insertion, keep your thumb on the top and jiggle the tube up and down slightly as you lower it so as to avoid stationary contact with the neck surface and possible freezing of the tube to the neck. When the bottom end has gotten cold with no noticeable release of gas from the Dewar neck, you will notice a throbbing of the gas column which changes in frequency and magnitude when the end goes through the liquid helium surface. Vertical jiggling of the dipstick may help to initiate the excitation. This pulsing is a thermal oscillation set up in the gas column of the dipstick by the extreme thermal gradient, and it changes upon opening or closing the lower end of the tube.

When the probe is in the liquid, the throbbing is of low frequency and constant amplitude. When pulled above the surface of the liquid, the frequency increases and the amplitude diminishes with distance away from the liquid surface. Identify this change by passing the thumper tip up and down through the surface a number of times, and have your partner measure the distance from the stick top to the Dewar neck top. With a little experience you should be able to establish this to within a millimeter or so. Following this measurement, lower the dipstick to the bottom of the Dewar and repeat the distance measurement. Once the dipstick has been lowered to the bottom, it may get clogged with frozen sludge which has collected in the bottom of the Dewar, and you may have trouble in exciting further throbbing. If this occurs and you want to continue measurements, raise the stick until the tip just comes out of the Dewar and start again. Both partners should assess the level independently. A depth-volume calibration curve for the Dewar is at the lab bench.

Straighten the dipstick before and after insertion - it is easily bent, so take care. Be sure to record the depth reading on the Usage Log Sheet on the clipboard above the experimental station before and after Dewar use.

4.2. Probes

You will be using three different insert probes which contain different active components. Each probe is essentially a long, thin-walled stainless steel tube which can be inserted and positioned in the neck tube of the Dewar. A rubber flange is provided on the probe for sealing between the probe and Dewar neck so that the helium gas can escape only through the probe tube. Various labeled electrical leads from the thermometer, coils, and field-sensor emerge from the top of the probe tube. Helium gas flows up the probe tube, cooling it, and escapes through a side valve at the top, either directly to the atmosphere or through a gas flow gauge – needle valve – vacuum pump system which permits accurate control of the sample temperature.

Probe I has provision for changing the samples (Pb, V and Nb), each in the form of a small cylinder of common diameter 0.60 cm. The samples are inserted in a thin-wall hollow brass cylinder around which is wound a test coil of dimensions given in Figures 2, 3 and 6. Around the test coil is wound a solenoid coil which is longer than the test coil and sample, and which can produce a magnetic field penetrating both test coil and sample cylinder. Immediately above the centered sample is a small commercial silicon diode (Scientific Instruments model Si410). All electrical lines run up the probe tube to the connections at the top.

The rubber flange connection on each probe seals the Dewar neck tube to the probe tube, thereby forcing the helium gas to escape through the probe tube. The rubber flange should be stretched over the lip of the Dewar neck and tightened. A knurled, threaded ring at the top of the flange connector permits one to slide the probe tube up or down relative to the rubber flange connector (which of course is in fixed position on the Dewar). This controls the position of the sample in the Dewar neck. A small back-and-forth twisting motion during the process eases the motion. Never apply excessive force in sliding

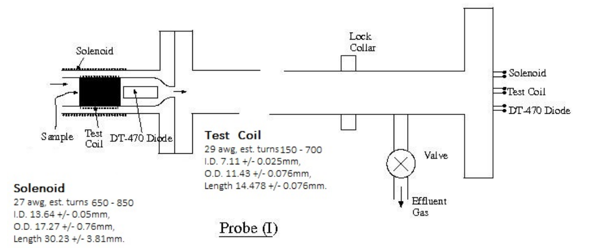

FIG. 2: Diagram of probe I. The distance from the top of the lock collar to the bottom of the probe is 30.5".

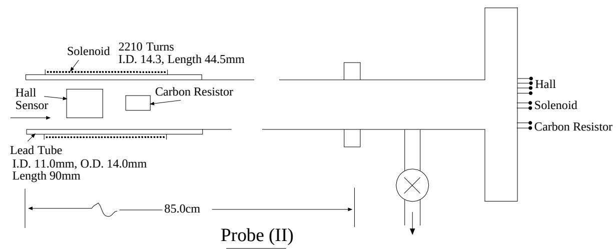

FIG. 3: Diagram of probe II. The distance from the top of the lock collar to the bottom of the probe is 30.5".

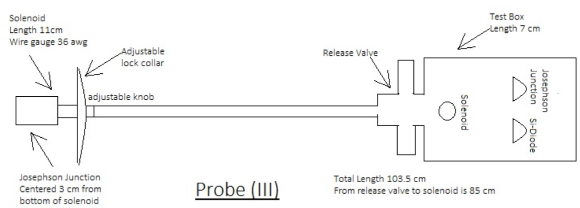

FIG. 4: Diagram of probe III. The distance from the release valve to the bottom of the probe is 91".

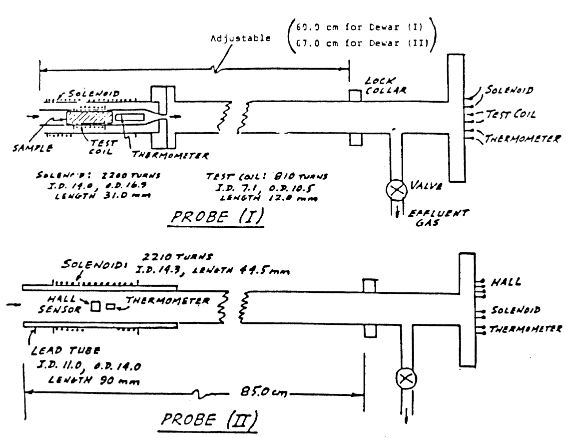

FIG. 5: Diagrams of probes I and II. The distance from the top of the lock collar to the bottom of the probe is 30.5".

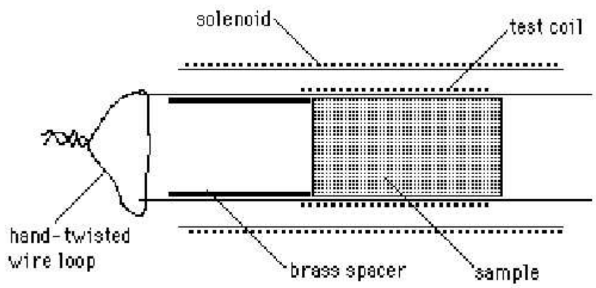

FIG. 6: Placement of the sample in probe I. The test coil has 810 turns of wire with a 7.1mm ID and a 10.5mm OD. It's length is 12.3mm

the probe tube along the flange. The lock collar on the tube and the side valve tube may be used with reasonable restraint as pressure points for providing sliding or twisting. On the top part of the rubber flange assembly, a small gas exit line contains a check valve which serves as a safety release if the pressure in the Dewar exceeds a set point. **Do not disturb it.**

The insert probes are delicate and must be handled with care. This means that they should not be bumped against other objects nor strained when maneuvering them into or out of the Dewar. A storage rack is provided for holding them when not in use. When inserting or withdrawing the probes, keep them strictly vertical. DO NOT bend them.

4.3. Temperature control of samples

Temperature control of the various samples is achieved by control of the flow rate of cold helium gas passing the samples and thermometers in the probe tips.

The probes are designed so that all exiting helium gas must pass by the sample and its nearby thermometer once the probe is sealed on the Dewar. A large temperature gradient exists along the Dewar neck tube. By judiciously positioning the tip of the probe in the Dewar neck tube and varying the gas flow, we can control the temperature of the sample. This can be done by pumping the gas through a needle valve (for control) and a flow gauge (for measurement). In this procedure the normal liquid helium boiling rate is accelerated so that more cold gas passes by the sample, thereby reducing its temperature.

Experience with our probes has shown that a good operating position for the probe is for the bottom of the probe to be about x cm above the bottom of the dewar neck, where x=10 cm for probe I and x=4 cm for probe II. At these insert positions, variation of the flow over the gauge range will provide temperature control over the range of interest (4- 20 K). Gas flow is controlled with a small-angle needle-valve connected in series with the flow gauge. Use the OPEN-CLOSE valve to isolate the

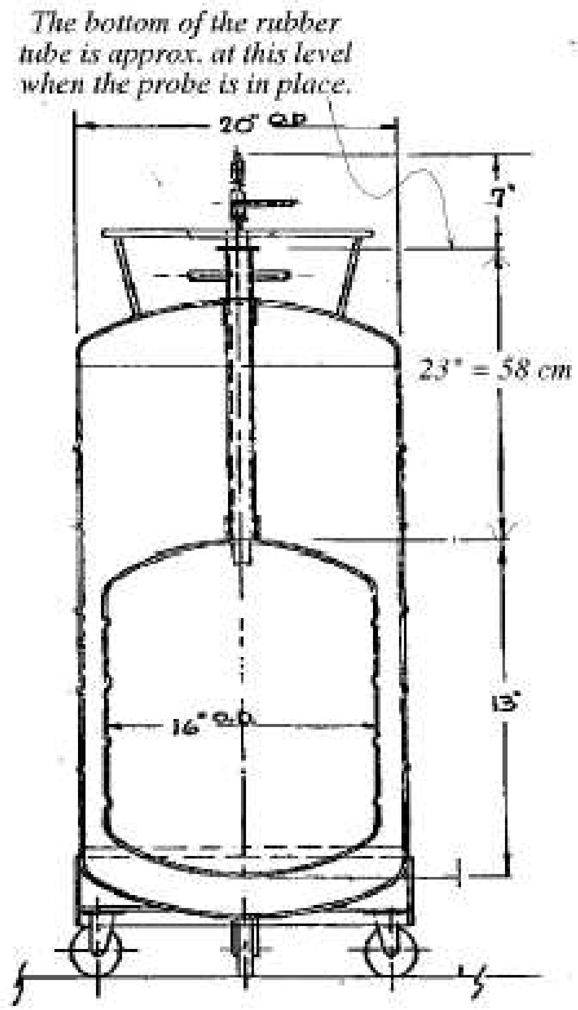

FIG. 7: Illustration of typical storage Dewar.

vacuum-pump from the system and stop the pumping. **Never close the gas flow by tightening the metal needle valve to its fully closed position.** This can damage the fine needle-surface.

Measure the length of the probes using the lock collar (Fig 5) as a reference so that you know how to position the probes to their desired x-positions. Make a sketch in your lab notebook. **This is important!**

In Probe I, a Silicon diode, located 1 cm above the sample is used to measure the temperature. The 10μA current from the source box through the diode in the forward direction causes a voltage drop of $\sim$ 0.5V at 300K, which changes little until $\sim$ 20K, but there changes rapidly to $\sim$1.6V. Using the table in the Appendix (Table **??**) you can determine the temperature of the sample material. The information in Table **??** is also available on the course website as two text documents, one for temperature and one for the corresponding voltage.

4.4. Preparing the probe

1. Place the probe on the table near the helium gas tank. The probe assembly should be at room temperature and dry. If it is damp from condensation, use the warm (not hot) air blower and Kleenex for blotting.

2. If you are using probe I, slide the selected sample cylinder into the small brass tube. Notice that the sample fits loosely in the brass tube: this permits cold helium gas to pass by the sample and thermometer (see Figure 6) and up the probe tube. Secure the sample in the brass tube by threading a small loop of copper wire through holes in the brass tube and hand-twisting the wire ends.

   Take special care that the sample and spacer cannot fall out into the Dewar when the probe is in the Dewar. When the probe is properly sealed onto the Dewar, all exiting gas must pass up the brass tube and out from the probe at the top.

3. The rubber flange assembly (for sealing the probe tube to the Dewar neck) can be slid on the probe tube by releasing the O-ring pressure with the knurled ring. We try to keep a very light film of grease on the probe tube to facilitate easy sliding. A combination of twisting while sliding will ease the sliding operation. Slide the rubber flange assembly towards the bottom of the probe tube so that it contacts the upper bumper guard. Tighten the knurled ring.

4. Flush the probe tube with low pressure helium gas from the helium gas bottle to displace the air in the probe tube and expel or evaporate any condensed water droplets that may have collected in constricted sections of the probe tube during the previous use. Use a gentle flow of dry helium gas from a high-pressure storage tank to do this. The top center valve on the tank (turning counter-clockwise looking down opens it) releases high-pressure gas (as read on the gauge) to a pressure-regulating valve on the side. Turning the pressure-regulating handle, clockwise, controls the pressure of exiting gas. After turning this handle counter-clockwise so that no gas is released, connect the exit tubing to the local flow gauge and then to the top exit valve (set OPEN) of the probe tube.

5. Carefully turn the handle clockwise to start the gas flow through the tube until you can just hear it flowing from the bottom of the probe. You should feel a modest flow of gas emanating from the bottom tube holding the sample. Continue this flushing operation for 5 - 10 secs then close the valve on the probe. Important: Keep the open end of the probe pointed down so that the trapped helium gas will not escape!

4.5. Precooling the probe

1. Get your instructor or TA to help you with the following operation the first time it is done. Start with the probe in the extended position using the knurled knob assembly. After clearing the inside surface of Dewar neck tube with the neck reamer, hold the probe tube assembly vertically above the neck and lower it into the Dewar. Seat the rubber flange over the Dewar neck lip and push (with some twisting) the rubber flange down as far as it goes. The bottom of the rubber will touch the nitrogen vent tubes. Tighten the lower hose clamp around the Dewar neck but do not tighten (or release) the top clamp ring. The probe tube is now sealed to the Dewar and all exiting gas must escape through the top exit valve, which should now be in the OPEN position.

2. Connect the probe cable to the 9-pin D-connector at the top. We will want to follow the temperature during the precooling operation, so connect the thermometer leads to the 10 microamp source and adjust according to the instructions given previously. Since we are still close to room temperature, the voltage across the silicon diode in probe I should be about 0.5 V. (In probe II the resistance should be about 300 Ω.)

3. Slowly lower the probe tube in the rubber flange assembly by releasing the O-ring pressure with the knurled ring. **CAUTION: if the pressure is released too much, the weight of the probe may cause it to fall abruptly.** Avoid this by holding the probe tube when releasing the pressure. A slight twisting of the probe tube in the O-ring may be helpful in achieving a smooth sliding movement. Continue lowering the probe tube until signs of increased exit gas flow appear, about 2 cm down. Stop at this position, tighten knurled ring, and look for signs of thermometer cooling. Watch the temperature change using the table in the Appendix (Table **??**). Depending upon the liquid helium level in the Dewar, you should notice an increased gas flow; this is cooling the bottom of the probe. The thermometer resistance will show very little change until its temperature gets into the 40-70 K range.

   After waiting a couple of minutes at this 2 cm position to see what happens, continue the lowering over the remaining distance in small steps (perhaps 0.5 cm) always waiting a minute after making a change and locking the knurled ring. The system takes a while to respond to a change in position. In a few minutes the voltage across the temperature sensor should be about 1.6 V, indicating that the sample is close to 4.2 K.

   During this critical precooling operation, there should be a modest flow of cool exit gas – if the gas release becomes uncomfortably cold to your hand held 4 inches from the exit tube, back up a little and let the system settle down before continuing the operation. You should be seeing a thermometer response depending upon this gas flow. Continue the lowering to the lock collar limit and allow the system to equilibrate, at which time the gas flow should have decreased.

4. If you do not see cold gas being released through the top exit valve (and an associated increase of thermometer resistance) during the lowering operation over the last few centimeters, the probe tube may be blocked and the precooling operation must be stopped. Cold gas escaping from the safety-release tube on the side of the rubber flange assembly (with consequent cooling and frosting of nearby metallic components) is another indication that the probe tube is blocked. With a normal precooling gas flow, only the top section of the metal components of the probe tube will get cold and frosted. This frosting will melt and should be wiped with a cloth once the small equilibrium gas flow has been attained. If there is any evidence of blockage in the probe tube, remove it from the Dewar, place it on the table, warm the assembly to room temperature with the cold air blower, dry, and flush with helium gas. Then reinsert the tube into Dewar as above. *IF YOU SEE BEHAVIOR OTHER THAN THAT DESCRIBED OR ANYTHING NOT ANTICIPATED, CONSULT YOUR INSTRUCTOR.*

5. After you have attained precooling thermal equilibrium (with a very small exit gas flow), the thermometer resistance should indicate a temperature below about 30 K. You can then proceed with the experiments. These are best performed with the sample located in the neck of the dewar. For Probe I, place the sample 10cm above the bottom of the neck and for Probe II, place the sample 4cm above the bottom of the neck. Temperature control at this working position is performed by pumping on the helium vapor at various rates, using the mechanical pump beneath the experimental station and the flow-meter/needle valve assembly above the pump.

5. MEASURING T_c AND OBSERVING MEISSNER EFFECTS IN SEVERAL SAMPLES (PROBE I)

5.1. Measuring T_c for Niobium

After loading probe I with the Niobium sample and following the precooling procedures described earlier to place the probe assembly at the optimum operating height, you are ready to experiment with controlling the sample temperature. Connect the probe gas exit to the

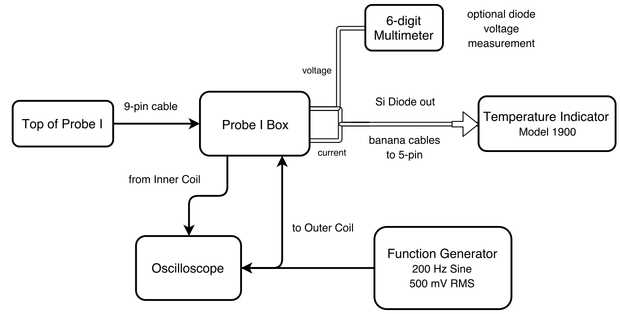

FIG. 8: Block Diagram of Probe I Wiring

flow gauge-control valve- vacuum pump system. With the ON-OFF valve closed, turn on the vacuum pump. Slowly open the ON-OFF valve so as to see gas flow on the gauge. This can be controlled by adjustment of the metal control valve and with fine adjustment through the teflon micrometer valve. Notice the thermometer response after making an adjustment. Remember that the system takes some time to adjust to a new equilibrium condition – be patient and don't hurry the operations.

Determine T_c by observing the change of mutual inductance between the solenoid and the test coil when the electrical conductivity of the enclosed sample changes abruptly. High conductivity implies that surface currents will be induced in a sample if the external field (from the solenoid) is changed with correspondingly less field penetration into the sample volume. If an AC current is passed through the solenoid, the flux passage through the test coil (and hence the inductive signal in the test coil) will depend upon the sample conductivity. If conditions were ideal, the existence of the Meissner Effect would imply no flux passage in the superconductor and hence zero test coil signal at temperatures below T_c. Our conditions are not ideal, but there will still be a recognizable change at the transition, permitting an accurate determination of T_c.

Connect a function generator, set for a 200 Hz sine wave, at 500 mV$_{RMS}$ amplitude to Channel 1 of the oscillosope and tee-it to the solenoid marked "OUTER COIL". Because of the low impedence of the outer coil (5.8Ω), the function generator will be loaded down and the measured amplitude on the scope will be $\sim$100 mV$_{RMS}$. Connect the "INNER COIL" output to Channel 2 of the oscilloscope and observe the induced signal (it should be about 85 mV$_{RMS}$ with the sample in the normal state). Observe the sudden reduction of the test coil signal when the sample is cooled through the transition, and vice-versa, by manipulation of the gas flow rate.

To measure T_c, record both the test coil signal and the temperature sensor voltage simultaneiously. With experience, you can adjust the gas flow rate so that the temperature drifts slowly through the transition value during which you and your partner can record both signal and temperature sensor values. A slow drift of the temperature will achieve close agreement between sample and thermometer temperatures. A graph of these quantities can be used to assess the resistance of the thermometer at the transition, and hence T_c. Do this a number of times, in both directions, upward and downward in temperature, looking out for possible hysteresis action, and noting how reproducibly the transition can be established. T_c values are usually taken at the midpoint of the transition. Make graphs of these drift runs as you take them – seeing them displayed can help with the next one.

Experience has shown that the hysteresis difference between cool-down and warm-up transition curves is strongly dependent upon the speed of passage through the transition. This is probably due to different time constants associated with temperature flow in (or out) of the sample rod relative to that of the temperature sensor.

5.1.1. *Change of T_c in Niobium with magnetic field*

According to the phase diagram in Figure 1 and described by Equation 1, the presence of a constant DC magnetic field on the sample will shift the superconducting transition to a lower temperature. We can see and measure this shift if we apply DC current to the solenoid in addition to the AC current needed in the measurement process. Since there is a limitation on the magnitude of the DC magnetic field that can be used (I^2R losses in the solenoid fine wire would perturb the temperature distribution), the magnitude of the transition temperature shift will be very small and careful measurements must be made to observe the effect.

This is best done by fine-tuning the flow rate so that the test coil inductive voltage is being held fixed in time at the midpoint between the superconducting (SC) and normally conducting (NC) signal levels (which you have established from the transition graphs of the previous section.) If this is accomplished then the drift rate effects are eliminated and the thermometer resistance at the mid-range set point can be used as a temperature marker. Repeating the same type of measurement with the magnetic field on, we can then observe the shift in critical temperature. We note that this procedure for measuring ΔT_c also eliminates the effect of a possible temperature difference between sample and thermometer caused by their different positions in the gas stream.

After getting the mid-range set point data for zero DC magnetic field, connect the output of the solenoid DC Current Supply Box in parallel with the AC current supply and adjust to a DC current of 150 mA. In connecting the DC and AC sources in parallel, the output AC voltage from the audio oscillator will drop (there is extra load on it). You should readjust this to a standard 70 mV$_{RMS}$. Now redetermine the SC and NC test coil signal levels (they may differ from the earlier levels) by varying the gas flow rate and again establish the thermometer resistance at the mid-range test signal value which is being held constant in time.

You can calculate the magnetic field at the sample from the solenoid parameters given earlier and what you expect for ΔT, as indicated by Figure 1. Note that from Equation (1), we have the useful relation

$$\left.\frac{dB_c}{dT}\right|_{T=T_c} = -\frac{2B_0}{T_c} \qquad (6)$$

Both measurements, DC ON and DC OFF, should be made under identical conditions.

5.2. Transition temperature of other samples

After you have finished the measurements on Niobium, withdraw the probe from the Dewar neck in the prescribed manner, close the Dewar neck, and carefully place the probe tube horizontally on the lab table. Parts of the probe tube are very cold and will frost-up. There is an air blower available to speed its return to room temperature. (CAUTION: the air blower blows either room-temperature air or very hot air according to the switch setting – **DO NOT** direct hot air on the probe or you will damage insulation components on the probe). It is prudent to keep one hand in the air stream to guard against this. After the probe has warmed to room temperature and the frosting has disappeared, water droplets will remain. They should be gently blotted (not rubbed) dry with a Kleenex tissue. Be careful never to insert anything with moisture on its surface into the Dewar neck.

The vanadium rod will slide out from the probe into your hand (NOT dropped on the floor) after removing the twisted clamp wire. **The small sample cylinders are delicate (and expensive), so do not mishandle them – keep them in the storage box when not in use so that they don't get lost.**

5.2.1. *Transition temperature of lead*

Replace the vanadium sample with the lead sample and its brass spacer and follow the same procedure described ealier for obtaining its transition temperature. You will find for the lead sample that the inductive signal in the test coil decreases slowly with lowering temperature as you approach T_c, followed by an abrupt, discontinuous change when the sample becomes superconducting. The small change, occurring when the sample is still a normal conductor, reflects the temperature dependence of lead's normal conductivity above T_c, but is NOT part of the superconducting transition. Lead is a good conductor at these temperatures.

You may also notice that the magnitude of the fractional change in inductive signal in going through T_c for lead is smaller than it was for vanadium. This again reflects the higher conductivity of lead above T_c. If you are careful in adjusting the RMS value of the voltage being applied to the solenoid so that it is the same for the lead case as it was for the vanadium case, you should find the same value for the SC inductive signal. The sample geometry is the same and infinite conductivity below T_c characterizes both samples. On the other hand, the magnitude of the inductive signal above T_c depends upon the normal state conductivity. This varies from sample to sample, and in fact can be used to measure it.

5.2.2. *Meissner effect in lead*

When you have the lead sample in probe I for determining its T_c value, you can do another experiment that unequivocally demonstrates the Meissner Effect: namely, the flux exclusion from a superconductor. By applying a DC magnetic field to the sample in the NC state and then simply cooling it below T_c, the flux should be suddenly expelled in a transient manner. This would induce a transient voltage (and current) in the test coil of our assembly. We can see this transient signal by connecting the test coil to a current integrating circuit (for total charge measurement) as available in a circuit box.

The transient current integrator is simple op-amp circuit, with the induced voltage delivered from the test coil being amplified and driving a speaker.

Apply a DC field with the solenoid current supply ($\approx$200 mA) in the normal state and connect the test coil output to the current integrator box, with the box output connected to the oscilloscope. Set the oscilloscope to a slow 'rolling display mode' ($\approx$ 2 sec/division) and AC-couple the input, so that you can see the transient change in potential. Upon cooling the sample through T_c with gas flow regulation, a kick in the oscilloscope beam should be observed (up or down) indicating flux passage outward through the test coil. Warming the sample through T_c should give an oppositely directed kick when the field goes back in. You can check the absolute sense of the direction by merely turning off the solenoid current when the sample is in the normal state. With our charge-measuring circuit, the inductive kick is on the scale of 100 mV, so set the oscilloscope sensitivity appropriately.

It is to be emphasized that this test for the presence of the Meissner Effect is a most unequivocal one for a superconductor. It does not occur in a PC. Additionally, there have been reports in the literature of experiments in which the sample's electrical conductivity (σ) was found to change drastically with T_c (so one would observe an AC test coil signal change), yet the Meissner action failed to appear. An abrupt change in normal conductivity could accompany, for example, a crystallographic transition occurring at low temperatures, and this could mimic a superconducting transition in producing an AC mutual inductance change. **Note:** There is little analysis to do for this experiment; however, it is important to observe the Meissner Effect because it is unique to superconductors.

5.2.3. *Transition in niobium*

Determine the transition temperatures for niobium in the same way as you have done for vanadium and lead above. Lead is a Type I superconductor which means that the transition is very sharp, unlike Type II superconductors. Type II superconductors have "vortices" in them which allow for small regions with magnetic fields – so long as the "width" of these vortices is smaller than the penetration depth, this behaviour is allowed. These vortices act to slow the transition from "normal" to "superconductor." This is why the niobium and vanadium (two of the only three elemental Type II superconductors) show rather wide transitions compared with that of lead.

6. PERSISTENT CURRENT IN A SUPERCONDUCTOR (PROBE II)

We can demonstrate the existence of a persistent current in a superconductor using the hollow lead cylinder sample in Probe II. According to an earlier discussion, if we apply an axial magnetic field to the sample above T_c, cooling the sample below T_c will generate two oppositely-flowing persistent currents on the inside and outside surfaces of the cylinder. Thereafter, removing the external field will remove the outside-surface current but leave the inside-surface current producing the frozen-in-flux inside the cylinder. We can measure this flux, or magnetic field, with the Hall magnetic field sensor, which is positioned along the tube axis of Probe II as indicated in Fig.5.

Probe II contains a hollow cylindrical sample of pure lead (I.D. 1.11 cm, O.D. 1.43 cm, length about 9 cm) around which is wound a solenoidal coil of fine Cu wire (2210 turns, length 4.45 cm). Current in the solenoidal coil will produce a reasonably uniform magnetic field throughout its volume. The field strength can be calculated from the dimensions of the coil and the current. Inside the lead cylinder and along its axis is a tiny magnetic field sensor (a Hall field probe described later) and also a small thermometer (a carbon resistor). The electrical lines run inside the probe tube to the connections at the top of the probe. All of the components of probe II are in a fixed assembly and will remain unchanged during the experiment.

Probe II uses a small carbon resistor to determine the sample temperature. It's resistance varies from $\sim 300\Omega$ at room temperature to $\sim 2000\Omega$ below 20K. Simply using an ohmeter to measure the resistance would produce too much heating ($I^2R = 10^{-4}$W). We therefore limit the current I to 10μA using the current source box and measure the voltage drop in which case the power dissipated is $\sim$$10^{-6}$W. The calibration is not given, you will have to establish it using T_c for lead.

In a Hall probe a longitudinal DC current is passed through a semiconductor (InSb in our probe) in the presence of the magnetic field to be measured. A transverse potential appears across the material which varies linearly with the magnetic field and with the DC current. Our Hall probe has a sensitivity of about 20 mV gauss^{-1}, as you will determine, when operated with a standard DC current of 35 mA at low temperature. A Hall-probe circuit box is located at the experiment station. Before using it for field measurement, it must be balanced with a bias voltage in zero magnetic field.

Probe II should be flushed first with helium gas as described earlier. The lock collar on probe II is in fixed position 85.0 cm above the sample and thus this probe can be lowered farther into the Dewar than probe I. It is imperative that you use Figure 7 to help determine the position of the probe bottom after it is inserted into the Dewar. After insertion, follow the same precooling sequence as with probe I and approach low temperature thermal equilibrium at the position where the probe bottom is 2 cm above the Dewar neck bottom. The resistance of the carbon thermometer will be about 2800Ω at $T_c \approx 7$ K for lead (and 300Ω at room temperature). The thermometer response and gas release pattern offer guidance in this precooling. After stability is attained, raise the probe to X ≈ 4 cm where the experiment is best performed and connect the gas pumping system for temperature control. Practice controlling the temperature.

Connect the DC solenoid current supply box to the solenoid and the Hall-sensor current and potential leads to the Hall probe box, taking care to match the color codes. After bringing the probe temperature to low temperature but above T_c so that the lead sample is in the normal state, turn on the Hall current (35 mA by adjustment of rheostat control). With zero solenoid current (hence zero magnetic field), adjust the bias control so that zero Hall voltage (less than 2 mV) is read on the most sensitive voltage scale of the Agilent 34401A multimeter. This bias adjustment must be done at low temperature, namely when the thermometer resistance is about 1400-1500Ω. Now apply 100 mA of DC solenoid current from its supply box (Agilent E3611A). Note that the current supply box is capable of providing a much greater current, up to 1.5 A, so the display is not very precise in the range of 100 mA. Take care in setting the current, and monitor it using a multimeter. Measure the resulting Hall voltage (it should be around one millivolt) corresponding to the magnetic field at the Hall-sensor that is produced by the solenoid current. This serves to calibrate the Hall-sensor since you can calculate the field produced by the solenoid current. The Hall voltage should be proportional to the field and you can get a calibration curve for the Hall probe by measuring the Hall voltage for several values of the solenoid current.

After activating the Hall-sensor when the lead sample is NC and measuring the field, reduce the sample temperature so that it is SC (by increasing the gas flow) thereby inducing the two persistent surface discussed earlier. For ideal conditions (long solenoid, long tube, complete Meissner effect), we expect no change in the field at the Hall-sensor. With our geometry, you will probably notice a small drop in the magnetic field at the transition T_c, but the important observation is that the field inside the open area of the tube is maintained. This small change in Hall voltage at T_c can be used to identify the onset of the transition and in essence it serves to calibrate the carbon resistance thermometer at T_c. With the DC field on, arrange the gas flow so that the temperature drifts down slowly through the transition region. Record your thermometer resistance and Hall voltage readings as the change occurs. Graphing these data as you go along will help you to determine the resistance of the thermometer at the transition.

Now in this SC state, turn off the solenoid current supply (and this is the "punch-line"), and observe that the field remains. This shows that there is a persistent current on the inside surface of the lead cylinder with no outside field. Flowing without resistance, the current should continue indefinitely as long as the lead sample is in the superconducting state. You have thus made a "Persistent Current Superconducting Magnet" like those which are now commercially available and which have almost entirely replaced electromagnets in technical applications where steady, uniform high-intensity fields are required. If the sample is now warmed slowly by reducing the cooling gas flow, the internal frozen-in field will suddenly disappear (quench) at the transition. Record the resistance and Hall voltage readings during this change and compare with the earlier cool-down graph. (What happens to the magnetic field energy when a quench occurs?)

Another series of observations will show that one can generate a "frozen-in zero-flux" state. With zero field, cool the sample below T_c and then turn on the field by passing a DC current through the solenoid. What is the Hall probe response during these steps, and how do you explain it? You can now understand why superconducting assemblies are sometimes used to provide nearly perfect shields against electromagnetic disturbances, as in the experiment now under development at Stanford University to detect the Lense-Thirring effect on a gyroscope in orbit about the earth.

QUESTIONS:

1. Is there an upper limit to the magnitude of this persistent current and frozen field that we can generate in our sample? Why?

2. What current can we pass along a long SC wire of radius 1 mm and still expect the wire to remain superconducting (use lead wire at 4 K)?

3. What is the areal current density (amp cm^{-2}) in the persistent current that you measured (assume $\lambda_L = 10^{-6}$cm), and how does it compare with that flowing in a wire (1 mm diameter) supplying a household 100-watt light bulb?

7. THE JOSEPHSON EFFECTS (PROBE III)

The passage of electrons through a thin (<50 Å) insulating barrier is a well-known example of quantum-mechanical tunneling. The current-voltage (I-V) characteristic of such a barrier is ohmic (linear) at low bias. In accordance with the Pauli exclusion principle, the current is proportional to the number of electron states per unit energy in the conductors on either side of the barrier.

Giaever [7] discovered that if the electrodes are superconducting the curve becomes highly non-linear, with the current remaining nearly zero for voltages up to $V = 2\Delta/e$, where Δ is the superconducting energy gap, as illustrated in Figure 9. Above $V = 2\Delta/e$, the current becomes linear, as would be expected for NC electrodes.

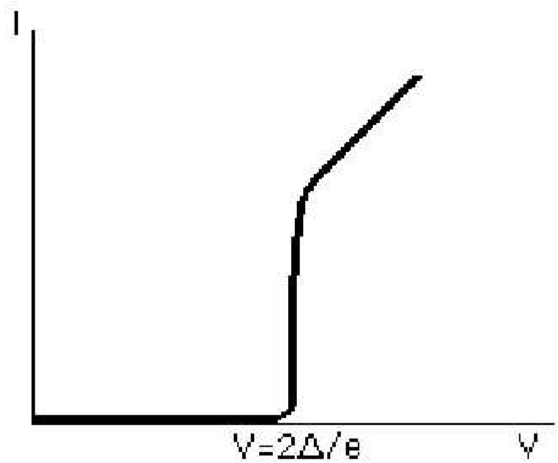

FIG. 9: Single particle tunneling at T = 0 K.

According to the BCS theory of superconductivity, all of the electrons near the Fermi level (at 0 K) are condensed into pairs of opposite spin and momentum. Single electrons are not available for the tunneling process, nor are there any available electron states to receive them. Hence, $I = 0$. As the voltage is raised to the energy gap, pairs are broken up into normal single electrons (quasiparticles), which exhibit ohmic tunneling.

The remarkable discovery of Josephson [8] was his theoretical prediction that not only can the quasiparticles tunnel through the insulating barrier, but the Cooper pairs can also do so. This occurs provided that the barrier is small compared to the decay length of the wave function of the Cooper pairs in the barrier ($< 10\mathring{A}$), as in any quantum tunneling scenario. This is a consequence of the inapplicability of the Pauli exclusion principle to bosons, which fermion pairs effectively are.

When the two superconductors are separated by a large insulating barrier, the condensed state of the Cooper-pair bosons in each superconductor can be described by a wave function with a single phase value, δ_1 and δ_2. But as the barrier becomes smaller, phase correlations extend across the intervening space and the two superconductors act like coupled oscillators. The isolated pieces of superconductor begin to act like a single superconductor with phase $\delta_0 = \delta_1 + \delta_2$, although the superconductivity in the insulating region is weak (i.e. the order parameter is small, which is a measure of the ratio of pairs to single electrons), and electromagnetic potentials can still be sustained across the barrier.

Perhaps the most accessible description of the theory of the Josephson effect has been provided by Feynman [3]. He derives the following relations:

$$J(t) = J_0 \sin\delta(t) \tag{7}$$

and

$$\delta(t) = \delta_0 + \frac{2e}{h}\int V(t)dt \tag{8}$$

where J is the Josephson current density, $\delta(t)$ is the phase difference across the junction, and V is the voltage across the junction. These simple equations are the basis of the theory for both the DC and AC Josephson effects.

7.1. The DC Josephson Effect

If the coupled superconductors are linked to a current source by an external circuit, the tunneling current that flows without an applied voltage is given by Equation 7. The maximum critical current, J_0, which corresponds to a phase difference of $\pi/2$, is proportional to the strength of the coupling across the barrier. It is determined by the dimensions of the barrier region, the materials and the temperature. It is inversely proportional to the normal ohmic resistance of the junction at room temperature.

With a DC voltage across the junction, the current will oscillate at a frequency given by

$$\nu = \frac{2e}{h}V_0 = 484\ MHz\ \mu V^{-1}. \tag{9}$$

In the $V \neq 0$ region, the current oscillates too fast to be seen on the low frequency I-V plot, averaging to zero. As Feynman points out, one obtains the curious situation that, with no voltage across the junction, one can have a large current, but if any voltage is applied, the current oscillates and its average goes to zero. The current will remain zero as the DC voltage is raised until, as mentioned above, the (Giaever type) quasiparticle tunneling region is reached at the gap voltage, $V = 2\Delta/e$. This type of curve, illustrated in Figure 10, is sometimes obtained; more commonly, particularly with the circuitry that we will be using, the results look like Figure 11. In this experiment the current will be swept by a symmetrical sine wave so that the current-voltage characteristics will appear in two quadrants of the plane. Note the hysteresis which is usually too fast for the oscilloscope to record. It can, however, be observed by reducing the bandwidth of the Y amplifier on the oscilloscope.

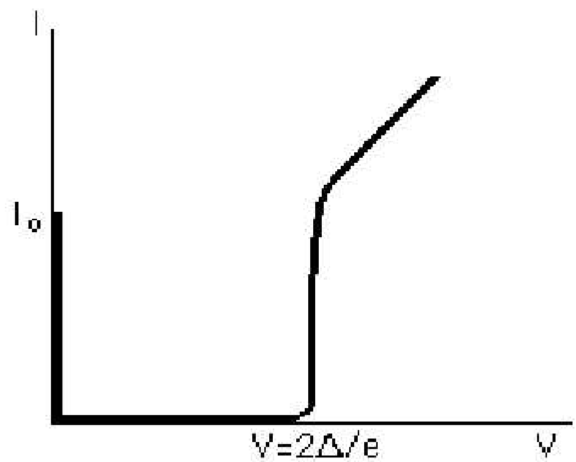

FIG. 10: Tunneling I-V curve showing both Josephson tunneling and single-electron (quasiparticle) tunneling.

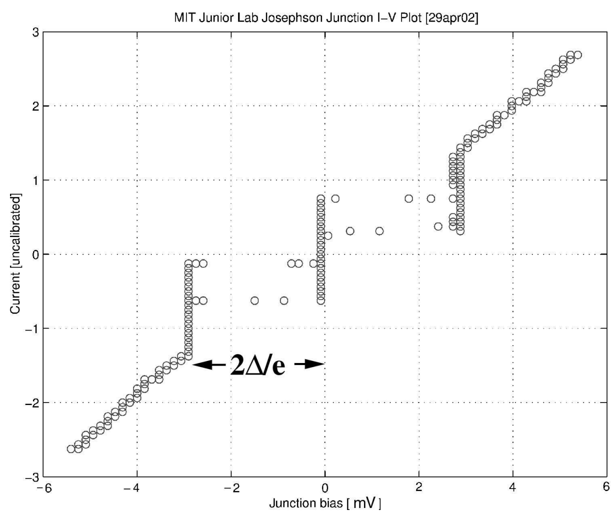

FIG. 11: Typical oscilloscope trace of Josephson junction I-V curve.

7.2. The AC Josephson Effect

There are two categories of high frequency effects which can be observed in these systems, though not with the equipment used in this experiment. We have seen that the application of a DC voltage across the junction causes the current to oscillate at the frequency shown in Equation 9. An applied voltage of approximately 50 μV produces 24 GHz oscillations, corresponding to K-band microwaves. Such oscillations have been detected with extremely sensitive apparatus. Feynman explains that if we apply a high-frequency voltage to the junction (in addition to the DC voltage), oscillating at a frequency related to the DC voltage by Equation 9, we will get a DC component of the Josephson current. This can be seen as steps in the I-V curve at voltages corresponding to harmonics of the applied frequency.

7.3. Josephson Junctions

Thin-film tunnel junctions are commonly made by depositing a narrow stripe of the superconducting metal on an insulating substrate, usually glass, and then causing an oxide layer of the desired thickness to build up on the exposed surface. Next another stripe, running perpendicular to the first stripe and consisting of the same or different superconducting metal, is deposited on top of the oxide layer. Tunneling occurs between the two stripes in the rectangle of oxide in the crossing area.

The niobium-niobium junctions used in this experiment are shown in Figure 12.

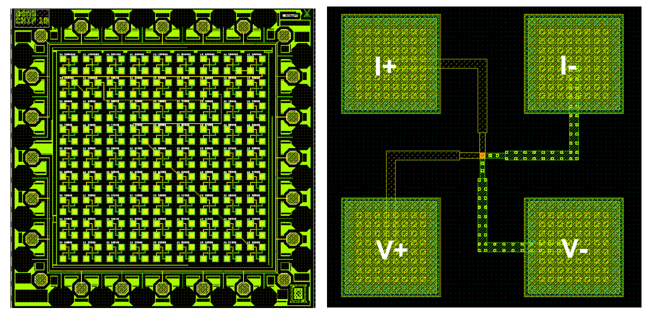

FIG. 12: Images of the Junior Lab Josepshson Junction chip provided by Dr. Will Oliver of MIT's Lincoln Laboratory and Professor Terry Orlando of MIT. There are 81 circular junctions with 4-pt measurement structures present on the chip (at left). A close-up of one 4-pt measurement structure is shown at right. The 15 μm diameter junction that Junior Lab uses can be found on the top row in the left-most column in the figure at left.

The active junction is circular with a diameter of 15 μm and the critical current is 5 μA μm^{-2}. The aluminum oxide barrier thickness is 1.5 - 2.0 nm. There is an additional very thin layer of aluminum between the oxide layer and the Nb, but this should have a negligible effect on the penetration depth. The London penetration depth for Nb at $T = 0$ K is 39 nm. This value changes slightly at $T = 4.2$ K, through a correction factor of $\sqrt{1-(T/T_c)^4}$ (which is about 1.02 at $T = 4.2$K.) Thus

$$\lambda_L \approx 39nm \times 1.02. \tag{10}$$

The junction is mounted on the bottom of the third probe, and 6 electrical lines (4 for the junction I-V measurements and 2 for the solenoid) run up the inside of the probe tube to the blue junction box on the top of the probe.

The Josephson Junction chip used in this lab actually has 81 circular junctions of varying diameters in a 4-pt measurement structure (Figures 12 and 13), but only one of them is active in the experiment. The active junction is $\pi(\frac{15}{2}\ \mu\text{m})^2 \approx 176.7\mu\text{m}^2$ in area, and is probed by sourcing current from I_+ to I_-, while measuring the voltage drop from V_+ to V_-.

A photograph of a Josephson Junction probe assembly is shown in Figure 14.

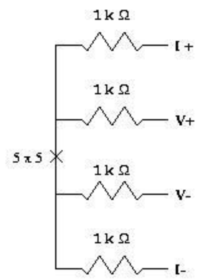

FIG. 13: Schematic circuit for Josephson Junction chip. The junctions are denoted by × symbols, and represent regions where two niobium layers overlap with a thin layer of insulating oxide between them.

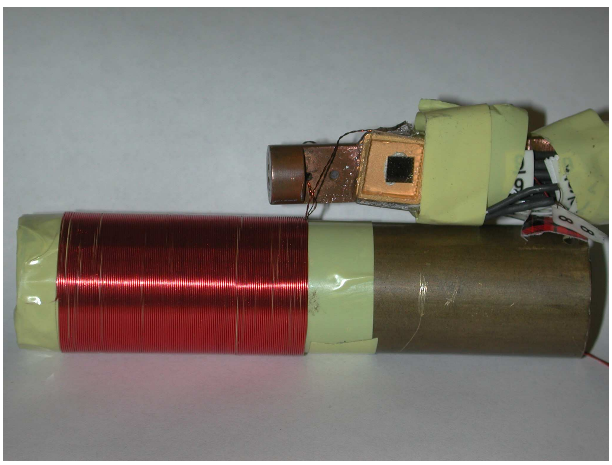

FIG. 14: Photograph of the Junior Lab Josepshson Junction Probe Assembly. Note that the outer solenoid is shown dis-assembled.

7.4. Josephson junction experiments

The Josephson Junction probe is a very delicate instrument and needs to be handled with extreme care! Before hooking up the cables between the blue box at the top of the probe and the switch box, please ensure that all the switches are in the 'DOWN' position. This will ground and short together the leads of the Josephson junction, which is extremely sensitive to electrical discharges. Only raise the switches to the 'UP' position when the current supply and the voltage preamplifier have been turned on and their settings verified. Also, never flip the switches back and forth like a light switch. That can cause shocks to the very delicate junction. Additionally, do not unplug the Josephson Junction wire if the switches are un grounded/ not in short position. NEVER exceed 200mA through the solenoid coil surrounding the josephson junction. Now let's begin!

1. Connect the V_p and V_n signals from the switch box to the voltage preamplifier inputs using two BNC cables. Configure the preamplifier inputs as DC Coupled A-B, and initially set the filtering to 'FLAT' or 'DC'. Start with a gain of 100.

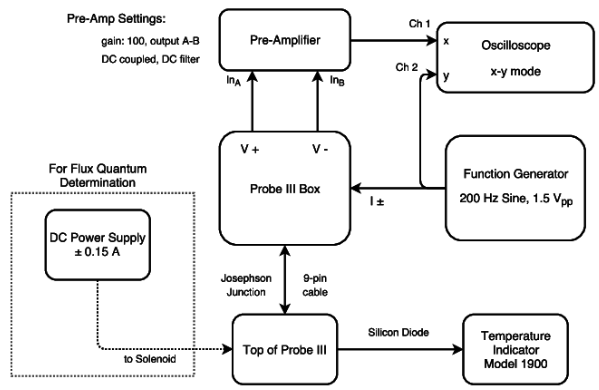

FIG. 15: Block Diagram of Probe III Wiring

2. Connect the output of the voltage preamplifier to channel 1 (the X input) on the scope.

3. Use a BNC T-connector to send the output of the function generator to the I_+ and I_- BNC input on the switch box (the coax's shield provides the return path for I_-). Use the other half of the BNC T-connector to monitor the current on channel 2 (the Y input) of the oscilloscope. Start with a 200 Hz sinewave at 1.5 V$_{pp}$ amplitude.

4. Set the oscilloscope to XY mode. Now, with all the switch box switches still in their 'DOWN' position, you should be able to see a vertical line on the scope. This is simply the oscillating output of the function generator being monitored on the scope.

5. Now connect the cables from the temperature sensor readout box and from the switch box to the blue box on the top of the Josephson Junction probe.

6. Carefully insert the probe into the dewar, clamping the flange to the dewar neck with the junction itself in the RAISED postion. VERY SLOWLY lower the probe until it begins to cool, as it reaches the helium vapor above the liquid. SLOWLY cool the probe at no more than a few degrees per second. It should require about 5-10 minutes to reach Tc (about 9.2 K for Niobium). When you've reached about 100 K you can raise all the switch box switches into their 'UP' position. You should observe an 'ohmic' IV trace.

7. As you reach T_c, the ohmic trace on the scope should distort into the nonlinear IV trace similar to that shown in Figure 11.

The current spike at V=0 represents the Josephson current (tunnelling by Cooper pairs). Record this current; you can deterimine its magnitude by finding the vertical distance between the two points where the I-V curve becomes nonlinear. There are 1 kΩ resistors in series with each of the four Josephson junction leads, which will enable you to convert the scopes measured voltage into a true "current". The curve obtained should resemble Figure 11, although the horizontal parts switch so fast they may not show up on the scope. It should be possible to estimate the superconducting energy gap, Δ, from this curve. The magnitude of the zero-voltage Josephson current is strongly dependent upon magnetic field, and it is just this dependence which provides the basis for Josephson devices such as SQUIDs (superconducting quantum interference devices.)

7.5. Determination of the Flux Quantum

The probe includes a solenoid coil which can be used to produce a magnetic field in the plane of the junction. Using a DC power supply as your current source, vary the coil current in the range $\pm$ 150 mA. (You should use the known value of the flux quantum and the dimensions of the junction to calculate *a prori* the range of B-fields to explore). The coil was produced by wrapping 2000 turns of 36 AWG magnet wire (Belden 8058) around a brass cylinder, and produces a field of 540 Gauss A^{-1}. Explore both positive and negative currents to extract the local effect of the earth's magnetic field The best results are obtained by reducing the function generator output voltage to about 350 mV_{pp} to minimize local heating of the junction, which can obscure the effect you're looking for.

Record and plot the zero-voltage Josephson current against the solenoid current and its magnetic field. You should be able to see at least two zeros. Be careful not to apply very large currents to the solenoid. You may also want to have the scope average the preamp output signal to reduce its noise. From this and the dimensions of the junction cited above, you can estimate the magnitude of the flux quantum (see Reference [9]).

Congratulations on your first investigations into superconductivity! Feel free to use the experiments in this labguide as a spring board for your own investigations. Other useful references include: for **Superconductivity;** [10–12], for **Josephson Effects:** [13–15], for **Miscellaneous Topics:** [16, 17].

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Voltage	Kelvin	Voltage	Kelvin
1.69812	1.4	1.13598	23
1.69521	1.6	1.12463	24
1.69177	1.8	1.11896	25
1.68786	2	1.11517	26
1.68352	2.2	1.11212	27
1.67880	2.4	1.10945	28
1.67376	2.6	1.10702	29
1.66845	2.8	1.10263	30
1.66292	3	1.09864	32
1.65721	3.2	1.09490	34
1.65134	3.4	1.09131	36
1.64529	3.6	1.08781	38
1.63905	3.8	1.08436	40
1.63263	4	1.08093	42
1.62602	4.2	1.07748	44
1.61920	4.4	1.07402	46
1.61220	4.6	1.07053	48
1.60506	4.8	1.06700	50
1.59782	5	1.06346	52
1.57928	5.5	1.05988	54
1.56027	6	1.05629	56
1.54097	6.5	1.05267	58
1.52166	7	1.04353	60
1.50272	7.5	1.03425	65
1.48443	8	1.02482	70
1.46700	8.5	1.01525	75
1.45048	9	1.00552	80
1.43488	9.5	0.99565	85
1.42013	10	0.98564	90
1.40615	10.5	0.97550	95
1.39287	11	0.95487	100
1.38021	11.5	0.93383	110
1.36809	12	0.91243	120
1.35647	12.5	0.89072	130
1.34530	13	0.86873	140
1.33453	13.5	0.84650	150
1.32412	14	0.82404	160
1.31403	14.5	0.80138	170
1.30422	15	0.77855	180
1.29464	15.5	0.75554	190
1.28527	16	0.73238	200
1.27607	16.5	0.70908	210
1.26702	17	0.68564	220
1.25810	17.5	0.66208	230
1.24928	18	0.63841	240
1.24053	18.5	0.61465	250
1.23184	19	0.59080	260
1.22314	19.5	0.56690	270
1.21440	20	0.54294	280
1.17705	21	0.51892	290
1.15558	22	0.49484	300

TABLE I: Probe I Si-diode (DT-470) calibration. Also available on the 8.13/8.14 website as two text documents.