Superconducting SQUID Measurements

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Abstract

The basic properties of a thin film, high critical temperature Super-conducting Quantum Interference Device (SQUID) are studied. The SQUID is made of yttrium barium copper oxide ($YiBa_2Cu_3O_7$) which becomes superconducting at about 90^0K. Quantitative measurements are made of the DC and AC Josephson effects and the SQUID critical temperature is determined.

This experiment consists of three parts.

1.   Part 1: The basic squid properties are studied. These measurements include a study of the Josephson DC Effect and the direct observation of flux quantization.

2.   Part 2: The AC Josephson Effect is observed and the measurements lead to a determination of h/e. A microwave generator is used for this purpose.

3.   Part 3: The transition temperature of the superconducting material is measured using a silicon diode as a thermometer. The temperature of the squid is varied and the transition temperature to the superconductmg state is determined.

The details are described in the following text which contains a section for each of the three parts. The Appendix contains the squid electrical and mechanical specifications.

REFERENCES

1.   Chapter 21, pp. 21-1 to 21-18 in Feynman Lectures on Physics Vol.3, by Feynman, Leighton, and Sands.

Part 1 : Basic Squid Measurements

The directions that follow assume that you have some familiarity with the basics of superconductivity including zero resistance, flux quantization, and the Josephson effect. If not, you may wish to read some of Section V ("An Introduction to Superconductivity and SQUIDs") before going any further.

The Mr. SQUID chip contains a dc SQUID made with thin film YBCO superconductor. The dc SQUID is a simple circuit that can be schematically represented like this:

The dc SQUID is simply a ring of superconductor containing two Josephson junctions, which are marked by the X's labelled J_1 and J_2 in the circuit diagram above. The Josephson junctions can be thought of as weakened areas of the superconductor, which nevertheless still allow a certain amount of resistanceless current to flow. The simplest experiment to perform upon this circuit is to pass current "I" from left to right across the ring and to measure the voltage "V" that appears across the ring. If the two junctions in the SQUID are identical, in the absence of any magnetic field, the current will divide evenly and half of it will pass through each junction before recombining at the right side.
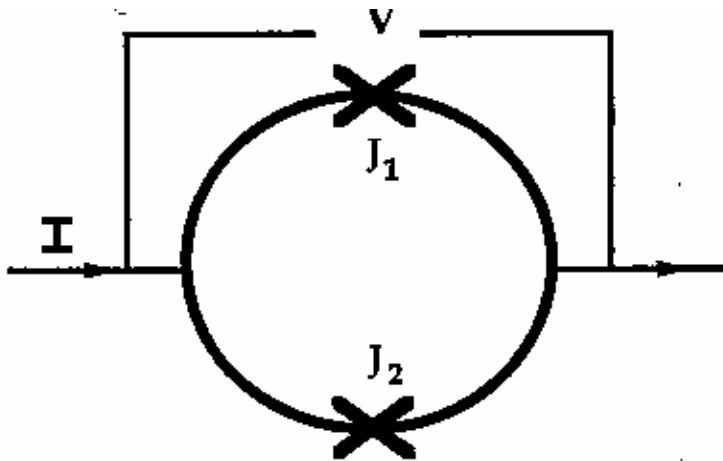

Figure 3.1: schematic representation of a dc SQUID

The Mr. SQUID control box allows you to perform this experiment quite easily. If you have set up the system according to the instructions in the previous section, you are ready to try this voltage-current experiment.

Setting up the Output Device

Once again, we assume that you are familiar with the operation of your oscilloscope or x-y recorder. For initial settings, try an x sensitivity of 0.2 volts per division (or whatever value is closest to this on your instrument) and a y sensitivity of around 50 mV per division. You may want to adjust these values as needed later. Now refer to the diagram of the Mr. SQUID control box (Figure 3.2) below.
STEP 1:
If you are using an oscilloscope, set the oscillator frequency toggle switch (7) to the **osc** (high-speed) position. If you are using an x-y recorder, use the x-y (low-speed) position.

STEP 2:
Before turning on the power, make sure the amplitude control (4) is at its minimum (fully counter-clockwise) position and set the flux bias control (2) and the current bias control (3) to their 12 -o'clock (straight up) positions.
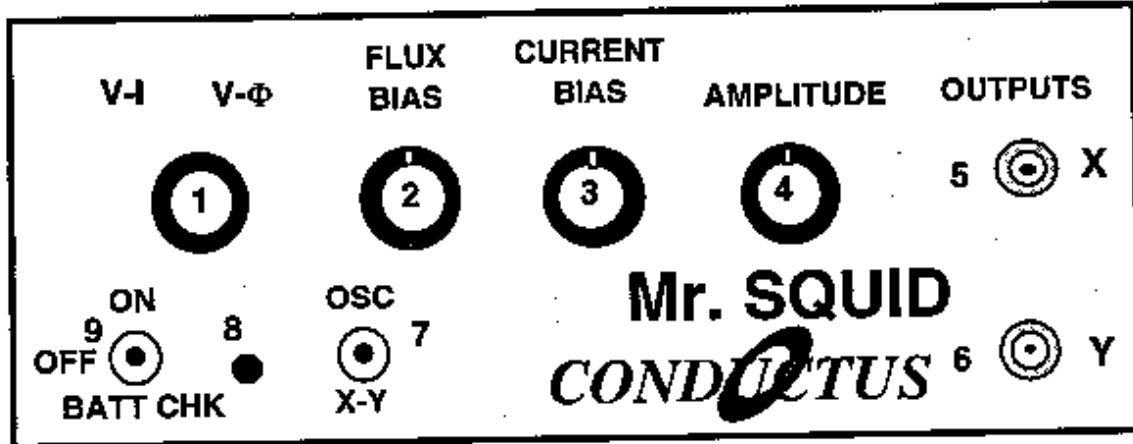

Figure 3.2

STEP 3:

Make sure the function switch (1) is in the V/I position. In this position, the BNC cable connected from the X output on the front panel (5) reads the current being fed through the SQUID. The cable connected to the Y output (6) reads the voltage across the SQUID. Set the power switch (9) to the ON position. On an oscilloscope, there should be a small bright spot on the center of the screen. On an x-y recorder, the pen should be stationary in the middle of the page. You may have to adjust the offset controls on your display device to achieve this in either case.

Varying the current bias

The current bias control (3) varies the current being sent through the SQUID. Slowly turn this knob in either direction. The spot on the oscilloscope screen or the plotter pen will move in response to the changing current. As you turn the knob back and forth, you will trace out a curve representing the relationship between the current fed through the SQUID and the voltage across the SQUID. This curve is called the V-I curve for the SQUID.

Varying the amplitude of the current sweep

Return the current bias control to the 12 o'clock position and now slowly turn the amplitude control (4) in the clockwise direction. This function sweeps the current through the SQUID back and forth between preset values, thus automating the procedure you performed by hand using the current bias control. A solid curve should now appear on the oscilloscope screen; alternatively, the pen on your plotter will repeatedly trace out the curve on the page.

If you now turn the current bias control, the center point of the curve being traced on the screen or page will move. The current bias control sets a single value of current being passed through the SQUID and the amplitude control sweeps the current back and forth about that set value.

Calculating the current

Your output device acts like a voltmeter. The sensitivity settings on it determine how much voltage corresponds to a division on the screen or on the page of graph paper. The current output on the Mr. SQUID box (5) actually represents the voltage across a 10,000Ω resistor in the electronics box. According to Ohm's Law (I = V/R), the current flowing through the resistor is therefore equal to the voltage across it divided by 10,000 Ω.

The typical voltage levels from the SQUID are small enough that we have provided amplification in the Mr. SQUID control box. Thus, to calculate the actual voltages across the SQUID, the measured value on the oscilloscope or x-y plotter should also be divided by 10,000.

The V-I Curve

If the settings on the Mr. SQUID box and your output device are correct, and if the SQUID is behaving properly, you will see a curve that looks more or less like this on the screen or page.
It is important that there is a flat region in the center of the curve as shown above, although its width may vary from device to device. If what you see looks like a straight line, as in Figure 3.4 below, then
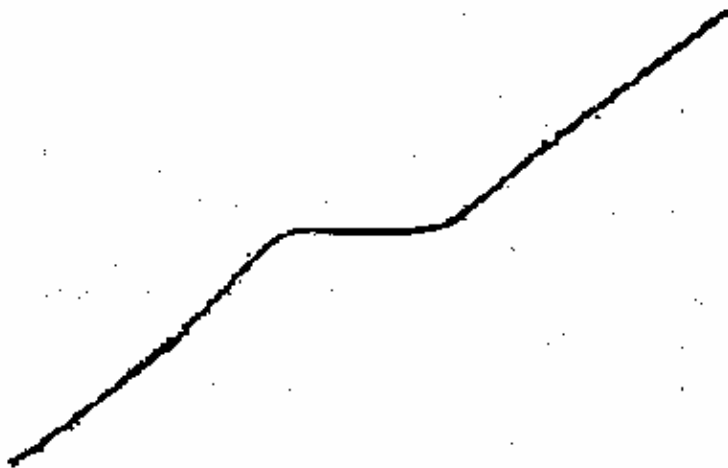
Figure 3.3: typical V-I curve for Mr. SQUID

either you don't have enough liquid nitrogen in the dewar, you have not let the probe get cold, or there may be trapped magnetic flux in the SQUID. The latter is a very common occurrence because the SQUID is very sensitive to magnetic fields in its external environment. Refer to the section on trapped flux in Section VI ("Troubleshooting and Getting Help"), if this appears to be the problem. Assuming you see the proper curve, how can we understand its shape?

What you are looking at is the V-I characteristic of two Josephson junctions connected in parallel with one another. Assuming they are identical junctions (in practice, they are at least very similar), the V-I characteristic you see is the same as for a single junction. The most important feature of the curve is the flat spot in the middle, called the critical current. In this region, there is current flowing with no voltage - it is a supercurrent. This is the dc Josephson effect: a resistanceless current that flows through a superconductor Josephson junction.

A Josephson junction consists of two regions of superconductor that are weakly coupled together. The meaning of this statement is that the junction behaves like a superconductor but can only carry a small amount of resistanceless current before it becomes resistive. Any superconductor has the same property: it ceases to be resistanceless as soon as the current it is carrying exceeds a maximum value called the critical current. A Josephson junction is a weak link between two regions of superconductor, and this weak link carries far less resistanceless current than the superconductor on either side. The maximum supercurrent that can flow through a Josephson junction is called the critical current of the junction.
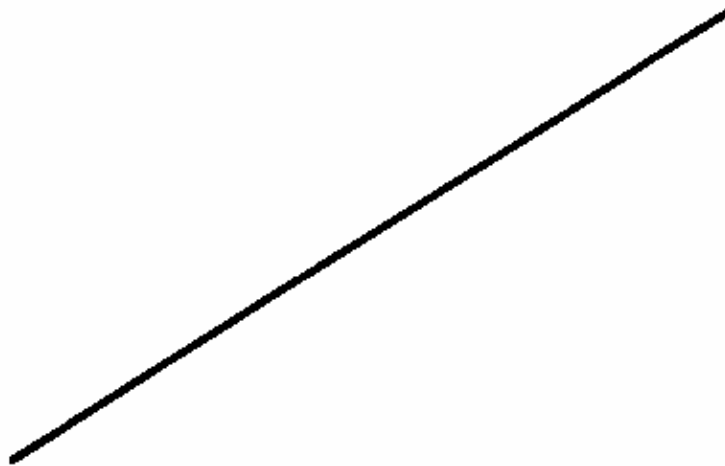
Figure 3.4: a linear V-I curve

At this point, you might want to adjust the flux bias control (2) on the control box. This control feeds current into a small gold coil placed above the SQUID and this current applies a magnetic field upon the loop the SQUID. As explained in Section V, a magnetic field will modulate the critical current in the SQUID in a very specific manner. By turning the flux bias control knob, the critical current in the junction will change visibly on the oscilloscope screen or on your plotter page. At this point, try to adjust the flux bias current such that the flat region of the V-I curve is widest. The response to these changes may be quite sensitive; it may take some practice to tune the critical current to its maximum value. This procedure may be especially useful if some small amount of magnetic field was already present in the SQUID loop. Zero applied field will yield the largest critical current in the junction.

You can determine the critical current of the junctions in Mr. SQUID by measuring the width (in volts) of the flat part of the V-I curve and dividing that number by 10,000 Ω to convert your answer into amperes of current. If the flat region is 1 volt wide, for example, then the corresponding current is 100 microamps. However, you are looking at the current through <u>both</u> of the junctions in the SQUID, not just one. Therefore, assuming the junctions are identical, the current through one junction is half the value you are measuring (in our example, 50 microamps). Is this the critical current of the junction? Not quite. The curve you are looking at drives the current symmetrically about zero (marked in the drawing). The current you have measured is actually composed of a contribution in the positive
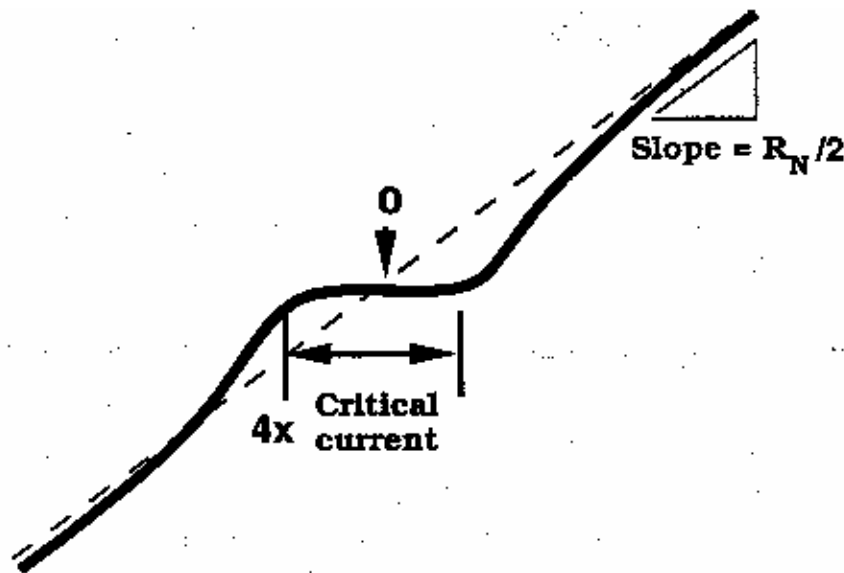

Figure 3.5: parameters of the V-I curve

direction and a contribution in the negative direction. If the curve is symmetric, they are equal. As a result, the real critical current of the junction is half the value you infer from the measurement. Thus, in our example, the critical current is 25 microamps, 1/4 of the original measurement. The flat region on the curve corresponds to 4 times the junction critical current.

Apart from the critical current of the junction (usually written as I_C), there is also a parameter of the junction known as the normal-state resistance or R_N. You can determine it by measuring the slope of the V-I curve out at the ends where it is essentially a straight line. To obtain a resistance, you must convert the x-axis value into amperes from volts and take into account the amplification of the y-axis signal. This is all very simple since the conversion factor for each axis is the same value of 10,000. Remember that the dc SQUID contains two junctions in parallel, so that the measured resistance corresponds to half the resistance of a single junction (assuming they are identical.) Thus, simply taking the slope numbers in volts off your oscilloscope or x-y recorder will give you one-half the normal-state resistance in ohms. The product of the critical current and the normal state resistance $I_C R_N$ is a voltage that is an important parameter for the operation of a SQUID. Make a note of it now for use later. Note that $I_C R_N$ for one of the junctions has the same value for the SQUID, which has two junctions in parallel. For the junctions in Mr. SQUID operating in liquid nitrogen, you will probably obtain a value between 1 and 10 microvolts. This value sets the maximum voltage change in the SQUID by an individual magnetic flux quantum, and is discussed later in this section.

As you observe the properties of the Josephson junctions in Mr. SQUID, realize that such an experiment required liquid helium and several pieces of electronic instrumentation just a few years ago. In this era of high-temperature superconductivity, Josephson electronics is becoming a far more accessible technology.

Observing V-Φ Characteristics using Mr. SQUID

Up to this point, we have been looking at the properties of Josephson junctions. Now we will turn our attention to the properties of the dc SQUID itself.

The dc SQUID has the remarkable property that there is a periodic relationship between the output voltage of the SQUID and applied magnetic flux. This relationship comes from the flux quantization property of superconducting rings that is discussed in detail in

Section V. The Mr. SQUID control box will allow you to observe this periodic relationship in the form of V-Φ characteristics on your oscilloscope screen or x-y plotter page.

You have already observed the effects of a magnetic field on the V-I characteristics of the SQUID by adjusting the flux bias control current. The V-Φ characteristics are basically an automatically plotted version of this behavior. The physics underlying the V-Φ curve is discussed in Section V.

Modulating the Critical Current of the SQUID

As we saw before, in the V-I operating mode one can apply a magnetic field to the SQUID using the flux bias control. This dial controls a current that is applied to the modulation coil, simply a one-turn gold coil that creates a magnetic field inside the loop of the SQUID, as shown in Figure 3.6. The second coil shown in the photograph is the external modulation coil that allows you to couple other sources of current to the SQUID.
If you slowly turn the flux bias control knob, you can see the change in the critical current and the overall V-I curve that arises from magnetic flux threading the loop of the SQUID. Another way to see the sensitivity of the SQUID to external fields is to rotate a
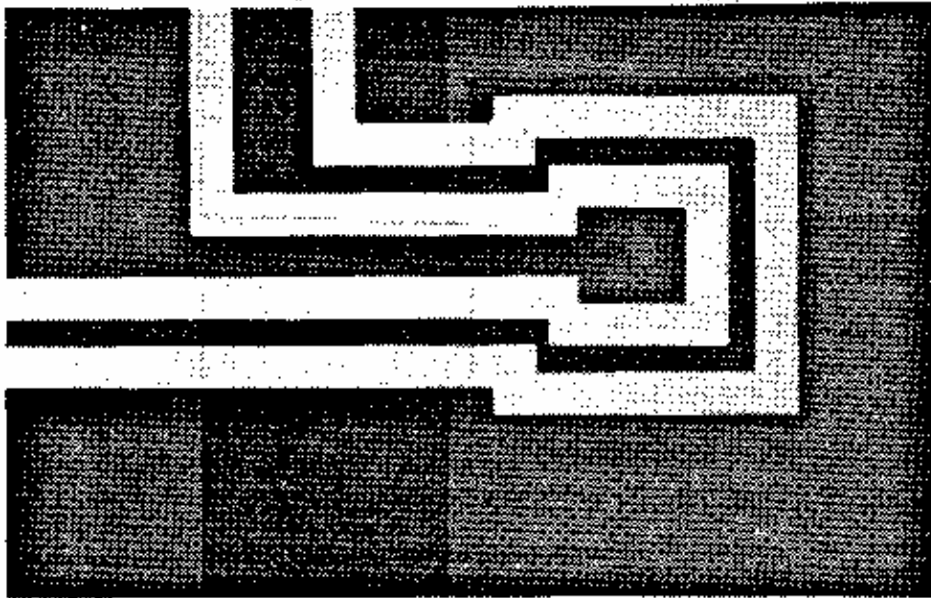

Figure 3.6: the gold modulation coils on the Mr. SQUID chip

small horseshoe magnet slowly in the vicinity of the dewar. if you experiment carefully with the flux bias control, you will see that the critical current of the SQUID oscillates between a maximum value (the flat region of the V-I curve is at its widest) and a minimum value at which point the V-I curve may be more-or-less linear.

The Mr. SQUID control box allows you to view the periodic behavior of the SQUID in a convenient, automated way To obtain the V-Φ plot, you will set the bias current so that the SQUID voltage is most sensitive to changes in applied magnetic field. This occurs at the knee of the V-I curve, the area highlighted in Figure 3.7 below.

To find this point, first adjust the flux bias control (2) so that the critical current is at its largest value. Then, turn down the amplitude control (4) all the way so that only a point is visible on the oscilloscope screen or so that the pen is stationary on the plotter page. In this mode, you can then sweep the point up and down the V-I curve by adjusting the current bias control (3), as you did initially. Set the current bias level so that the point rests at either knee in the V-I curve. Now turn the flux bias control (2), which controls the amount of magnetic flux penetrating through the hole in the SQUID loop. You should see the point move back and forth vertically on the screen or page. This periodic motion arises because screening currents in the SQUID body are sensitive to differences between the magnetic flux applied and integral multiples of the magnetic flux quantum (Φ_0) This phenomenon is a manifestation of the macroscopic quantum nature of superconductivity.
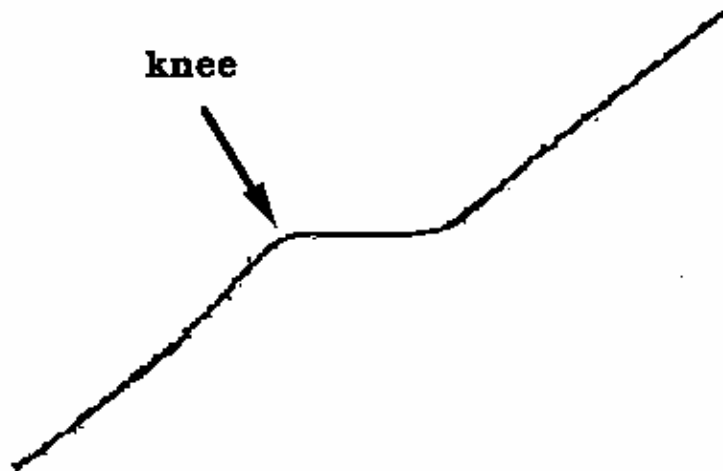

Figure 3.7: the "knee" in the V-I curve

To automate this procedure, switch the function switch (1) from V-I to V-Φ. In this new mode, all of the controls on the Mr. SQUID control box work the same way as before, except for the amplitude control (4). Instead of controlling the sweep of the drive current through the SQUID, it now controls the amplitude of the current through the gold modulation coil, which is linearly related to the magnetic field applied to the SQUID. To view as many V- Φ periods as possible, turn the amplitude control (4) in the clockwise direction. Depending on the particular SQUID and coil in your probe, you should be able to see at least four or five periods of oscillation, as shown in Figure 3.8.

The voltage change that occurs due to the influence of the magnetic field appears now on the vertical axis of your display device. The voltage amplification provided by the Mr. SQUID box is unchanged from before. To determine the actual voltage across the SQUID, you must divide by 10,000. However, since the SQUID modulation signals are smaller than the junction voltages you examined earlier, you will need to increase the sensitivity of the vertical scale on your display device. The peak-to-peak voltage of the SQUID modulation in Mr. SQUID (ΔV) is typically between 0.5 and 5 µV (or 5 to 50 mV output from the front panel of the Mr. SQUID control box). Depending on the setting of the amplitude control, you may wish to change the x sensitivity to more conveniently view the oscillations of the SQUID.

In addition, it may be necessary to use the position knob on your output device to center the curve. If your oscilloscope can be operated in an AC-coupled mode on the vertical channel,
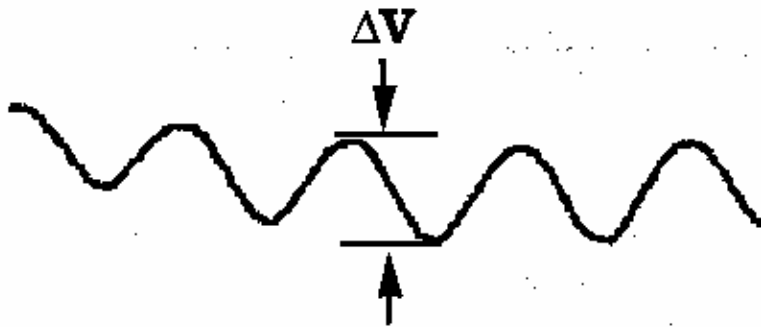
Figure 3.8: an example of the V-Φ Curve for Mr. SQUID
ΔV is generally on the order of 0.5 to 5 µV

you can use this mode for more convenient viewing of the V-Φ curve (never use the AC mode to look at the V-I curve, or it will be completely distorted on the oscilloscope screen.) You should see a curve that resembles the one shown in Figure 3.8. Depending on the particular device and on the settings on the control box, you may see many more periods than shown here. At this point, you can try to maximize the signal by fine-tuning the current bias control (3) to the most sensitive part of the V-I curve (just keep your eye on the V-Φ curve as you tweak the current bias control until you get the maximum modulation). There will be some setting of the current bias control that gives the largest modulation amplitude.

Notice the effect that the flux bias control (2) has on the V-Φ curve. It allows you to set the central value of applied flux about which the amplitude control sweep varies. In other words, this control allows you to apply a static magnetic field to the SQUID on top of the oscillating field applied with the amplitude control. Turning the flux bias control will therefore allow you to move left and right along the V-Φ curve and thereby explore more of it than the amplitude sweep permits. You can accomplish the same thing in a less controlled manner by waving a small permanent magnet near the probe. Another way to see the effect of an additional applied field is to rotate the entire dewar. This rotates the SQUID with respect to the earth's magnetic field and causes a shift. Actually, most of the earth's field is screened out by the magnetic shield on the probe, but the amount of field that gets by the shield is quite enough to move the V-Φ pattern noticeably on the screen.

Later on, you may want to warm up the probe to room temperature and carefully remove the magnetic shield from the bottom of the probe, by loosening the small set-screw that holds the shield. Set both the shield and the screw aside in a safe place so that they can be reinstalled later. If you now cool down the probe and set up the V-Φ measurement, you will find that the SQUID is tremendously more sensitive to its environment. In fact, you may have a great deal of difficulty in getting a good V-I curve without flux trapping (see the discussion in Section VI). Assuming you succeed in observing the V-Φ curve without the magnetic shield (which may be impossible in many environments), you will find that almost any magnetic disturbance anywhere near the dewar will be visible on an oscilloscope screen.

The most sensitive technique for SQUID operation consists of operating the SQUID in a "flux-locked loop" which essentially uses a feedback mechanism to counteract any change in external magnetic field. One actually measures the amount of feedback current, a technique that permits the detection of fields corresponding to a tiny fraction of a flux quantum.

Additional SQUID Measurements

Now that you can measure a variety of properties of the SQUID in the Mr. SQUID probe, you can determine a key parameter of the device, namely the β_L parameter. We define it by:

$$\beta_L = \frac{2I_C L}{\Phi_0} \qquad (3.1)$$

where L is the inductance of the SQUID loop.

Earlier we mentioned that the modulation voltage depth ΔV as measured from the V-Φ curve is related to the $I_C R_n$ product that could be determined from the V-I curve. As we will discuss in Section V, that relationship can be expressed simply in terms of the β_L parameter.

$$\beta_L = \left(\frac{4I_C R_n}{\pi \Delta V}\right) - 1 \qquad (3.2)$$

The above expression provides a simple way to determine the β_L parameter empirically (i.e., without knowing the inductance (L) of the SQUID). This expression is strictly correct only if the critical currents of the two junctions are equal, although this is an approximation for the junctions in your Mr. SQUID.

To calculate β_L from Eq. 3.1, keep the following facts in mind. The horizontal axis of the V-Φ curve measures the current through the modulation coil, and this is linearly related to the magnetic flux in the SQUID. The current gain in the Mr. SQUID control box is 10,000 V/A (i.e., 1 volt = 10^{-4} amperes). The period of the modulation of the magnetic flux in the Mr. SQUID loop is the flux quantum, Φ_0 (2.07 x 10^{-15} Wb in MKS units.) By measuring the amount of current in the coil that is required to induce one fluxon change in magnetic flux through the hole of the SQUID, you can determine the mutual inductance (M) of the SQUID and the coil, using the following formula:

$$M\Delta I = \Phi_0 \qquad (3.3)$$

Because of the excellent coupling of the thin-film gold modulation line to the SQUID itself, one can assume that the current induced in the SQUID ring is equal to half the current in the gold coil, and that the mutual inductance is, in fact, equal to about half the inductance (L) of the SQUID.

$$L \approx 2M \qquad\qquad (3.4)$$

A typical value for thin-film SQUIDs of this variety is about $L \approx 93$ pH, so your measurement of M should be in the range of 40-45 pH. Using the value calculated from Equation 3.4, you can find the value of β_L for the SQUID in your Mr. SQUID probe using Equation 3.1. From the measured values of I_C and ΔV, you can calculate β_L using Equation 3.2. Compare these two values. Do they agree?

The fact that Equations 3.1 and 3.2 do not agree was a mystery for a number of years after the 1986 discovery of high-T_C materials, as these equations worked quite well for SQUIDs made using traditional low-T_C materials. This lack of agreement was resolved in 1993 with the recognition that thermal effects were playing a large role in the behavior of high-T_C SQUIDs. The lack of agreement between Equations 3.1 and 3.2 is in large part due to the fact that the Mr. SQUID is at a relatively high temperature where thermal energies (kT) are no longer small compared to the energy of a flux quantum $\left(\dfrac{\Phi_0{}^2}{L} \right)$. The relationship between the observed voltage modulation and β_L at a nonzero temperature T changes Equation 3.2 to:

$$\beta_L = \left(\frac{4I_C R_n}{\pi \Delta V} \right)\left(1 - 3.57 \frac{\sqrt{kTL}}{\Phi_0} \right) - 1 \qquad (3.5)$$

Figure 3.9 illustrates the differences between the β_L's calculated using Equations 3.1, 3.2 and 3.5.

As one can see from Figure 3.9, the method of calculating β_L which takes into account the thermal effects agrees quite well with the inductive β_L measurements.

On the following page, we include a data sheet for your SQUID. You may wish to use it to enter your measurements on Mr. SQUID. An interesting and important issue for SQUID applications is how the SQUID sensor varies with age.

Summary of Basic Experiments

By going through the previous set of experiments, you should have been able to observe the fundamental properties of Josephson junctions and SQUIDs and calculate the values of these key parameters:
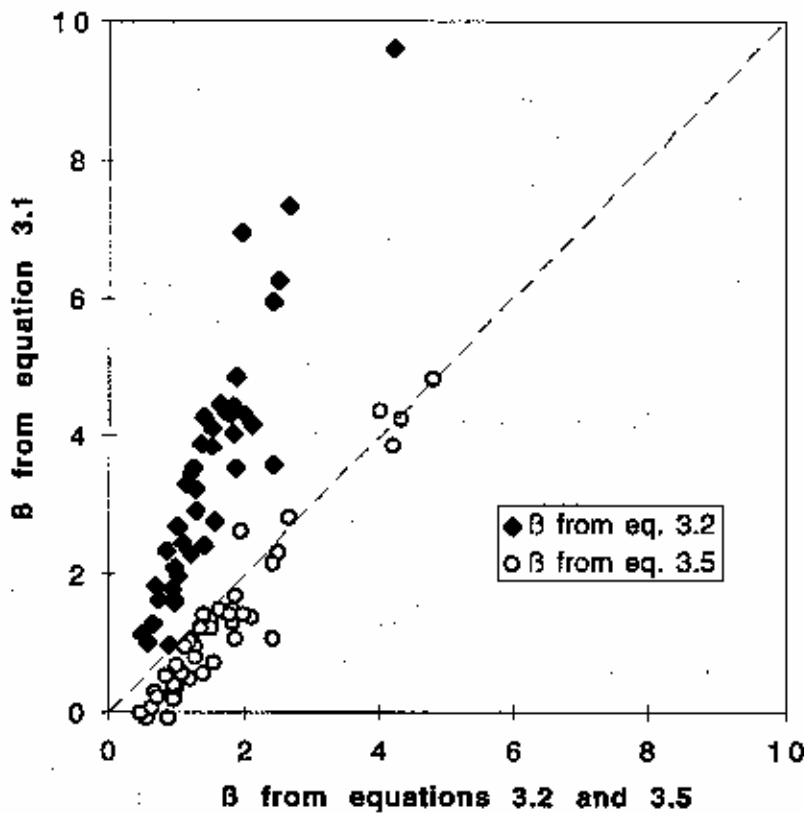

Figure 3.9: $\dfrac{2I_cL}{\Phi_0}$ versus measurements of ß based upon $\dfrac{I_cR_n}{\Delta V}$ for 44 Mr. SQUID's

- the critical current of the SQUID, I_C,

- the normal-state resistance, R_n,

- the characteristic voltage of the SQUID, $I_C R_n$,

- the voltage modulation depth, ΔV,

- the inductance of the SQUID, L, and

- the β_L value of the SQUID, using two methods.

Mr. SQUID Data Sheet

SQUID Serial Number:		
Date:	Symbol - Units	Measured Value
Critical Current:	I_c μA	
Normal-state Resistance:	R_N Ω	
Characteristic Voltage:	$I_c R_N$ μV	
Modulation Depth:	ΔV μV	
SQUID Inductance:	L pH	

β_L from Modulation Depth:	
β_L from Inductance:	

Part 2 :   The *ac* Josephson Effect

Microwave-induced (Shapiro) Steps at 77K & h/e

Purpose and Discussion:

The following discussion of the ac Josephson effect contains a fair amount of mathematical rigor in order to quantitatively explain the origin of the microwave-induced steps in the V-I curve of a Josephson junction.

The current density (J) of a Josephson junction with a fixed dc voltage (V) across it oscillates according to the equation:

$$J(t) = J_0 \sin\left[\delta(0) - \left(\frac{4\pi eVt}{h} \right) \right]$$

where e is the charge on an electron (1.602 x 10^{-19} coulomb), $\delta(0)$ is the superconducting phase across the junction at time t=0, and h is Planck's constant (6.62 x 10^{-34} J-s). This is called the ac Josephson Effect. This means that the current in the junction oscillates with a frequency of $\omega = 2\pi\nu = 4\pi e$V/h . A 1 μV dc voltage across a Josephson junction will cause the current to oscillate at ν=4.83593420 x 10^8 Hz. Note that this formula contains neither materials parameters nor extrinsic quantities such as temperature. This formula holds for a niobium Josephson junction at 0.01K as well as the high-Tc grain-boundary Josephson junctions in your Mr. SQUID unit. The frequency (v) only depends on the ratio of twice the electronic charge, to Planck's constant. In fact, the National Institute of Standards (NIST) uses the ac Josephson Effect to set the standard for the "0fficial" value of the volt.

As a practical matter, one cannot dc voltage bias a Josephson junction to a few microvolts, set a radio receiver next to it, and tune in to the radio frequency (RF) radiation emitted by the junction. The main reason is that the impedance of free space is ~370Ω while the junction is usually much less than 1Ω. For this reason, the RF will stay in the junction rather than radiate away into free space.

The *ac* Josephson Effect is usually observed by placing the *dc* voltage biased junction in an applied oscillating electric field. In this case, V → V(t), which alters the *ac* Josephson Effect equation to:

$$J(t) = J_0 \sin\left[\delta(0) - \int_0^t \left(\frac{4\pi e V(t')}{h} \right) dt' \right].$$

If $V(t) = V_0 + V_a \cos(\omega_a t)$, then

$$J(t) = J_0 \sin\left[\delta(0) - \left(\frac{4\pi e V_0 t}{h} \right) - \left(\frac{4\pi e V_a}{h\omega_a} \right) \sin(\omega_a t) \right].$$

The above equation can be expanded in a Fourier-Bessel series using the relations:

$$\sin(X \sin\alpha) = \sum_{-\infty}^{+\infty} B_n(X) \sin(n\alpha)$$

$$\cos(X \sin\alpha) = \sum_{-\infty}^{+\infty} B_n(X) \cos(n\alpha)$$

where, to avoid confusion with the current density J, the symbol $B_n(X)$ has been used for the Bessel function of order n and argument X. The current density then becomes:

$$J(t) = J_0 \sum_{-\infty}^{+\infty} B_n\left(\frac{4\pi e V_a}{h\omega_a} \right) \sin\left[\delta(0) + \left(n\omega_a + \left(\frac{4\pi e V_0}{h} \right) \right) t \right],$$

This equation is a sum of components at infinitely many frequencies, $n\omega_a + \dfrac{4\pi e V_0}{h}$. In particular when the frequency $n\omega_a + \dfrac{4\pi e V_0}{h}$ vanishes, so $nh\omega_a = -4\pi e V_0$ where $n = 0, \pm1, \pm2, \dots..$ there will be a component of the supercurrent density at zero frequency. A dc supercurrent will therefore be present in the junction whenever the dc voltage V_0 across the junction has one of the values:

$$V_0 = n\left(\frac{h\omega_a}{4\pi e} \right)$$

where n is any integer. These zero-frequency supercurrents correspond to the appearance of a dc Josephson effect at a non-zero voltage V_0 across the junction when the junction is irradiated with electromagnetic radiation of frequency ω_a. There will thus be a discontinuous shift in the *dc* current, with no change in the *dc* voltage across the junction. If one is sweeping out a V-I curve while applying an ac electric field to the Josephson junction, one will see a curve similar to the one which appears below. Such constant voltage steps (i.e. discontinuous shift in the ac current) in the V-I curve are called Shapiro steps.

There are a number of ways to impress an *ac* voltage on Josephson junctions. The easiest way is to simply send microwaves (v >1 GHz) into the cryogenic container holding the Josephson junction. Due to the high sensitivity of the Josephson junctions, even at very modest RF power levels a significant amount of radiation will couple into the junctions despite the large impedance mismatch between the junctions and free space.

For this experiment you will need:

- Mr. SQUID & liquid nitrogen
- An oscilloscope
- A microwave source of known frequency, capable of operating
 somewhere between 1 GHz and 10GHZ.

Illustrated below is a procedure to couple microwaves (MW) from a generator into the Mr. SQUID dewar. For the illustration which follows, we used an HP8616A function generator which
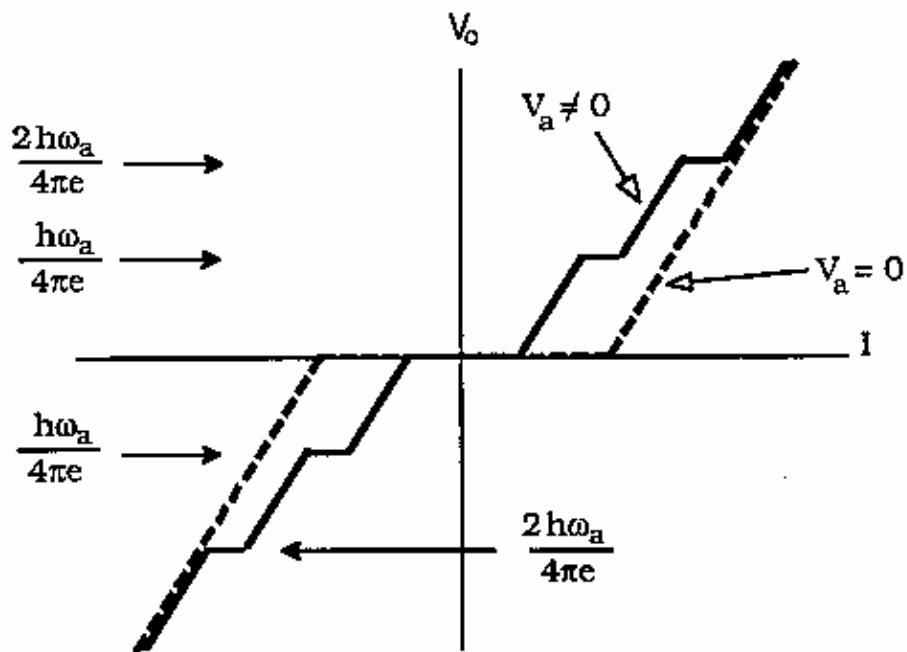
can produce microwaves with frequencies in the range of 1.6 GHz to 4.5 GHz. Any microwave source that you can couple into the Mr. SQUID dewar should work.

A coaxial cable is connected to the generator. The other end of the coaxial cable is devoid of a connector. Instead, approximately 2-3 cm of the coax cable's shield was removed to expose a 2-3 cm length of the center conductor, which acts as an antenna. If you do not have access to a microwave function generator, a microwave generator with a horn antennae may be used and pointed down into the dewar. Due to possible resonances and spurious microwave modes developing inside your Mr. SQUID dewar at specific frequencies, a generator with some frequency tuning will make this experiment easier to perform.

A word of caution: Microwave radiation can be dangerous even at relatively low levels, especially in the frequency range of this experiment, 1-10GHZ. For example, microwave ovens operate at -2.45 GHz where H_2O is very strongly absorbing. The maximum safe level, as specified by the U.S. Government, for RF and MW radiation is 10 mW/cm^2 However, this is
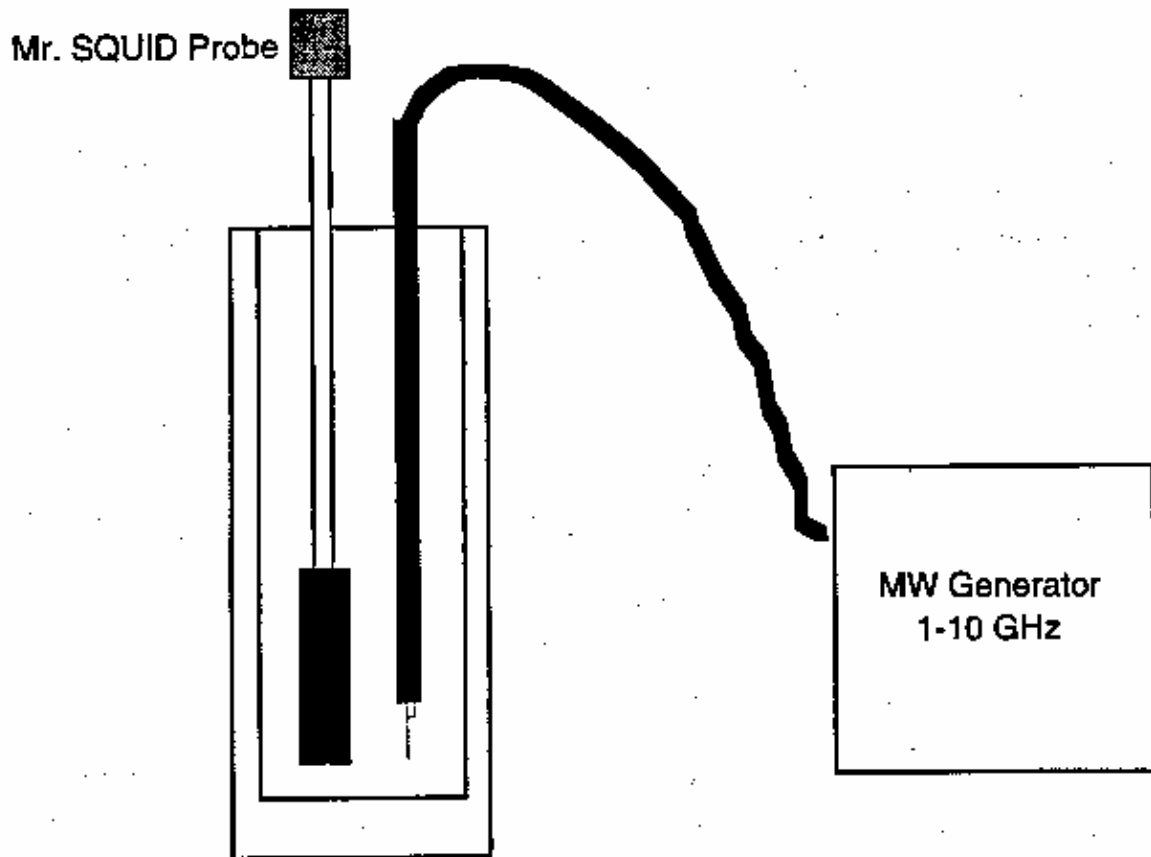
higher than the maximum safe levels specified by many countries[27], some of which have specified maximum safe levels as low as 0.01 mW/cm^2. Read the instructions for your microwave generating equipment and follow ALL safety instructions.

Set up your Mr. SQUID unit and cool it down with liquid nitrogen. Turn it on in the V-I mode. This is the only mode we will be using in this experiment. You will need to have a fairly clean V-I curve as illustrated below, free of flux trapping and RF interference.
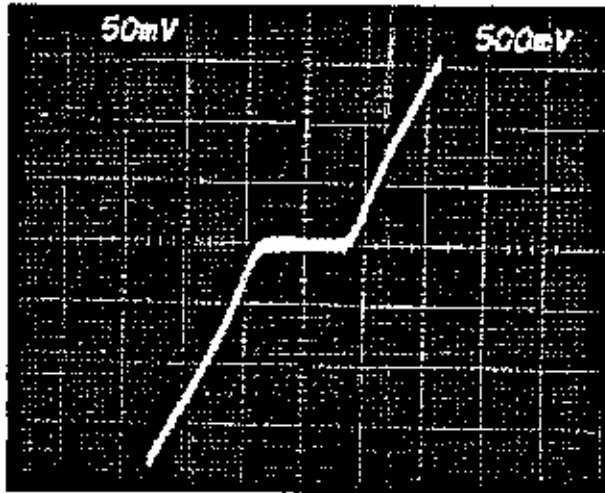
*Procedure for using a coaxial cable/microwave generator:*

Step 1.
Once you have a clean V-I curve, reset the microwave generator to its lowest frequency setting or 1GHz, whichever is higher. Slowly increase the amplitude on the microwave generator. At some point, you should see the V-I curve flatten out, with a complete disappearance of the su-percurrent. You may or may not see steps in the V-I curve before this point. The reason is that the Mr. SQUID dewar - coaxial cable combination acts as a complicated resonator with many modes. Many of these modes may couple with the SQUID junctions enough to exceed their critical currents, but do not couple with the junctions correctly to display the *ac* Josephson Effeet. If you have reached the maximum amplitude of your MW generator, but have not surpassed the critical current by at least 70%, try moving the coaxial cable closer
to the cold end of the squid.

27 For example, ***Pethig*** states on page 235 that in the USA and UK, permissible microwave exposure levels are a maximum power density of l0 mW/cm^2 and exposures should not exceed lmW/cm^2 for a continuous period of less than 0.1 hour. In the Former Soviet Union, the limit is stated by ***Pethig*** as 0.0lmW/cm^2 for one working day, and wearing protective equipment is required for exposures not to exceed lmW/cm^2 for 20 minutes or 0.lmW/cm^2 for 2 hours. ***Dielectric and Electrical Properties of Biological Materials*** by Ronald Pethig, (John Wiley and Sons, 1979)

Step 2.

Once you have surpassed the critical current, back the amplitude back down until part (one half to one third) of the original supercurrent has returned. At this point, slowly change the frequency. Watch the V-I curve while you are doing this. Agaln, due to the various electromagnetic modes which can arise inside the squid dewar, not all frequencies will properly couple into the squid. Keep slowly varying the frequency until you see a symmetric pattern of steps in the V-I curve. Below is an illustration of the squid V-I curve from step 1 after tuning to 4.520 GHz, which shows two steps, one at about +1.9 divisions and one at about -1.9 divisions.

Trouble-avoidance tip: If you cannot see any steps in the V-I curve after tuning the frequency up all the way, go back and repeat step 1 at a slightly higher frequency, then repeat step 2. Due to the spurious electromagnetic modes which form in the squid dewar due to the silver coating inside the glass dewar, getting the microwaves to couple properly can be somewhat of a "black art".
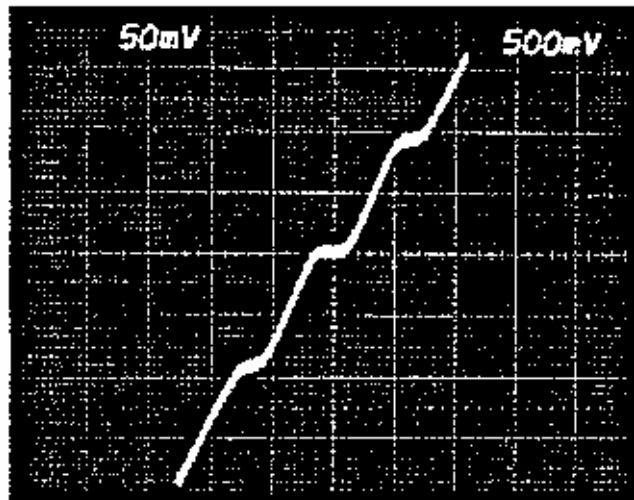
Determining e/h

To determine the value of e/h, we need to measure the voltages at which the steps occur. From the trace shown above, we would place the steps at +9.25 μvolts and at –9.25 μvolts.   (NO'IB: The vertical scale on the scope display is 50 mV per major division, which with the 10^4 gain of the squid controller, means the scale of the display is really 5 μV per major division). Since

$$V_0 = \frac{nh\omega_a}{4\pi e} = \frac{nh\nu_a}{2e}$$

then

$$\frac{e}{h} = \frac{n\nu_a}{2V_0}$$

As can be seen by comparing the oscilloscope trace immediately above with the Shapiro step illustration earlier, our steps correspond to the n = ±1 steps. So for our data above:

$$\frac{e}{h} = \frac{\nu_a}{2V_0} = \frac{4.52 x 10^9 \text{ Hz}}{2 \text{ x } 9.25 \text{ x } 10^{-6} \text{ V}} = 2.44 x 10^{14} \frac{\text{Hz}}{\text{volt}} \quad .$$

The "official" value of e/h is 2.4179671 x 10^{14} Hz/volt which means our measurement was good to about 0.8%. This relatively high level of accuracy using such a simple measurement is the reason the *ac* Josephson Effect is used by the National Institute of Standards.

However, for us to claim that we made this measurement to this level of accuracy would be somewhat misleading. The reason is that if you look at the scope picture of the Shapiro steps above, the steps are not perfectiy flat, and show some rounding. This might be due to small fluctuations in the microwave generator frequency or they might also be due to thermal noise in the squid. Remember, although 77 K may seem cold to us, it is rather "hot" compared to the superconducting transition temperature of your squid $\left(\dfrac{77 \text{ K}}{T_C} \approx 0.85 \right)$. So there is some uncertainty in the placement of the steps. The voltages at which the steps appear could be stated to be at $9.25 \pm 0.3 \mu\text{V}$. This uncertainty corresponds to an uncertainty in e/h of about 6%. So our value for e/h is $\left(2.44 \pm 0.16 \right) x 10^{14}$ Hz/V,

as compared to the "official value" of 2.4179671 x 10^{14} Hz/V. One can increase the accuracy of this measurement by cooling the squid to reduce the thermal rounding of the steps, by stabilizing the microwave source so that its frequency does not fluctuate, and shielding the squid from RF interferences (other than the microwave source) which can also cause rounding of the steps. By doing all these things, the ratio of value for e/h has been determined to a large number of decimal places.[28] Since ultra-stable frequency sources are relatively easy to build (e.g. atomic clocks), the U.S. National Institute of Standards (NIST) uses such time references along with the *ac* Josephson Effect to set the standard for the *"official"* value of the volt.

[28] W.H. Parker, B.N. Taykor, and D.N. Langenburg, **Phys. Rev. Letters 18,** 287 (1967)

Part 3:   Resistance vs. Temperature of the YBCO SQUID

Purpose:

This experiment will allow you to observe the superconducting transition of the YBCO film that forms the SQUID in Mr. SQUID. By tracking the resistance of the SQUID with the V-I curve, you can watch the YBCO undergo its superconducting transition. The additional equipment needed for this experiment allows you to measure the temperature of the SQUID chip as it is cooled down to liquid nitrogen temperature.

For this experiment you will need:

- A glass encapsulated silicon diode.

- 200 cm of coated copper magnet wire of size 32 to 40 AWG (this corresponds to a diameter of 0.020 to 0.008 mm).

- A digital volt meter (DVM) with sub-millivolt resolution.

- A soldering iron & electrical solder.

- A binder clip (available from any stationery supplier).

- One or two cotton balls.

- Masking tape.

- An active & constant current source capable of supplying 10 μA of current with a voltage compliance of at least 2 volts.

If you do not have a constant current source then you will also need:

- A general purpose operational amplifier (741 type).

- A zener diode in the range of *2.5* to 7 volts.

- A selection of resistors in the range of 1 kΩ through 100 kΩ.

- A capacitor within the range of 100 pF to 100 nF.

- A 9-volt transistor battery.

- A solderless breadboard.

In this experiment, we will use a common silicon diode to measure the temperature of the SQUID in the Mr. SQUID probe. Silicon diodes are a common and accurate way to measure temperature from 300 K down to liquid helium temperatures (4.2 K). They are simple to use, inexpensive, and the voltage across such a diode varies linearly with temperature. The reason a diode can be used as a linear temperature sensor is explained in a section at the end of this experiment, but this information is not required to perform the experiment.

Diode sensor calibration
Set-up: First, trim the leads of the diode to be as short as possible, then carefully solder on new leads using the copper magnet wire, each one at least 50 cm long. Be careful not to overheat the diode with the soldering iron. After the leads are attached to the diode, check the diode with an ohm-meter to verify continuity through its leads and that it still acts as a rectifier (in one direction, it should have a moderate resistance; in the opposite direction, the resistance should *be* extremely high).
Connect the silicon diode to the 10 μA dc constant current source and DVM as shown in Figure A1.1. If you do not have a suitable constant current source available, a procedure to make one is outlined at the end of this experimental section. Be sure to use at least 50 cm of fine copper wire (no larger than 30 AWG) between the DVM and the diode. Turn on the constant current source and the DVM. You should get a reading across the diode of between 0.3 and 0.4 volts. If you do not, check the wiring for shorts. If the DVM reads several volts, check to see if you have the correct polarity wired between the diode and the current source.

.

Temperature Calibration:

The next step is to calibrate the temperature response of the silicon diode. The diode voltage will increase linearly with decreasing temperature. Using an ordinary thermometer, determine the temperature of the laboratory in the vicinity of the diode (the value in kelvin should be in the vicinity of 293 K for most rooms) and record the diode voltage at this temperature. This is our first calibration point for the sensor. Next, fill the Mr. SQUID dewar with liquid nitrogen without the Mr. SQUID probe in it. Slowly lower the diode into the liquid nitrogen. Once the diode is at the bottom of the dewar, push an additional 20 cm of the diodes wires into the liquid nitrogen (be careful to avoid skin contact with the liquid nitrogen). The voltage across the diode should increase to 0.9 to 1 volts. It may take several minutes for the diode voltage to reach a stable value. This is our second calibration point, at 77 K. Strictly speaking, we need only two calibration points for a linear sensor. However, if your lab has facilities to create a "dry ice & acetone" bath, you should place your diode in that bath to get a 195 K calibration point.

(Caution: These calibrations are for the diode, not the Mr. SQUID probe. Do not expose the Mr. SQUID probe to acetone.)

On a piece of linear graph paper, plot the diode voltage as a function of temperature using your two (or three) data points. Determine the best line fit to the data. A straight line fit should be sufficient for your accuracy.
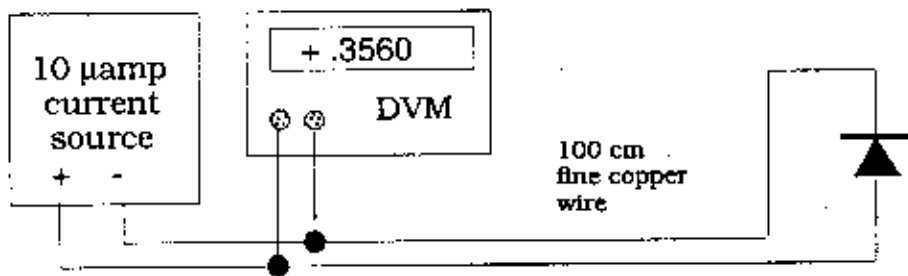

Figure A1.1

Temperature Calibration: The next step is to calibrate the temperature response of the silicon diode. The diode voltage will increase linearly with decreasing temperature. Using an ordinary thermometer, determine the temperature of the laboratory in the vicinity of the diode (the value in Kelvin should be in the vicinity of 293 K for most rooms) and record the diode voltage at this temperature. This is our first calibration point for the sensor. Next, fill the Mr. SQUID dewar with liquid nitrogen without the Mr. SQUID probe in it. Slowly lower the diode into the liquid nitrogen. Once the diode is at the bottom of the dewar, push an additional 20 cm

of the diode wires into the liquid nitrogen. The voltage across the diode should increase to 0.9 to 1 volts. It may take several minutes for the diode voltage to reach a stable value. This is our second calibration point, at 77 K.

On a piece of linear graph paper, plot the diode voltage as a function of temperature using your two data points. Draw the best fit line to the data in order to produce a calibration curve that scales diode voltage with temperature. At this point, your diode is calibrated sufficiently for temperature measurements.

Mounting the diode:

Next, we need to attach the diode to the Mr. SQUID probe in order to measure the SQUID chip temperature. Since we do not want the diode to permanently mounted on the probe, we will use masking tape to hold the diode on the back side of the probe as shown in Figure A1.2. We want the wires to trail downward under the magnetic shield and out the bottom of the probe. Be sure to wait until your diode is at room temperature and is dry before taping it to your Mr. SQUID probe. Also, try to avoid getting tape onto any part of the chip (front) side of the Mr. SQUID probe. Place the Mr. SQUID magnetic shield on the Mr. SQUID probe so that the diode wires come out of the bottom. Stuff a small amount of cotton into the bottom of the magnetic shield to block the opening. This will improve the temperature uniformity of the region inside the magnetic shield.

Next, empty the Mr. SQUID dewar until there is only 10-12 cm of liquid nitrogen left at the bottom (you can pour the unwanted nitrogen onto the floor, making sure to avoid people's feet, etc.) Place the Mr. SQUID probe into the dewar as shown in Figure A1.3. You can use the binder clip in conjunction with the foam dewar cap that was shipped with your Mr. SQUID unit. If you no longer have the foam cap, a suitable replacement can be fashioned out of styrofoam or cardboard, with a small hole large enough to fit the probe stick as shown in figure A1.3. The binder clip is used to keep the Mr. SQUID probe from sliding down into the dewar. You want to start with the Mr. SQUID probe at the very top of the dewar.
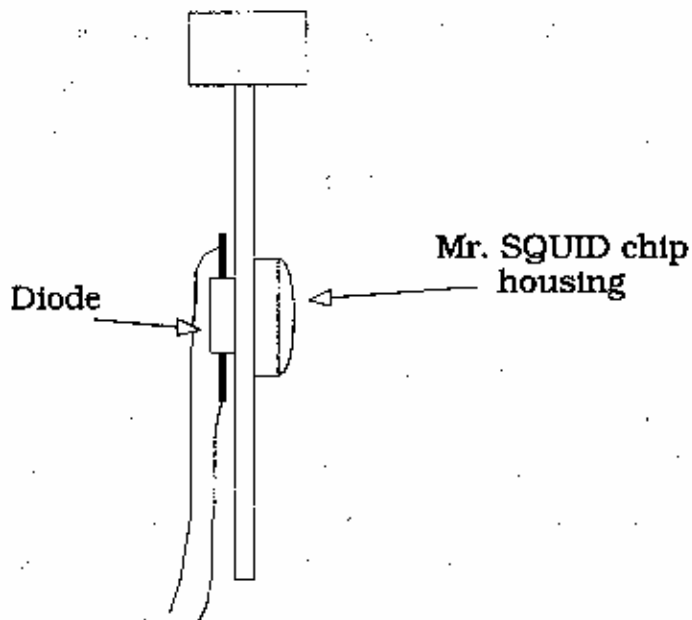

Figure A1.2

At this point, connect the Mr. SQUID probe to the Mr. SQUID electronics box using the cable, and connect the Mr. SQUID electronics box to the oscilloscope with BNC coaxial connectors. Turn on the Mr. SQUID electronics and set the unit to the V-I mode. Turn on the current source for the silicon diode and verify that it is indicating that it is near room temperature according to your calibration curve. You should see a straight line on the oscilloscope. The slope of this line is the resistance of the Mr. SQUID. At room temperature this should be several hundred ohms.

As shown in Figure Al.3, the chip end of the probe is to be suspended well above the liquid nitrogen level in the dewar.
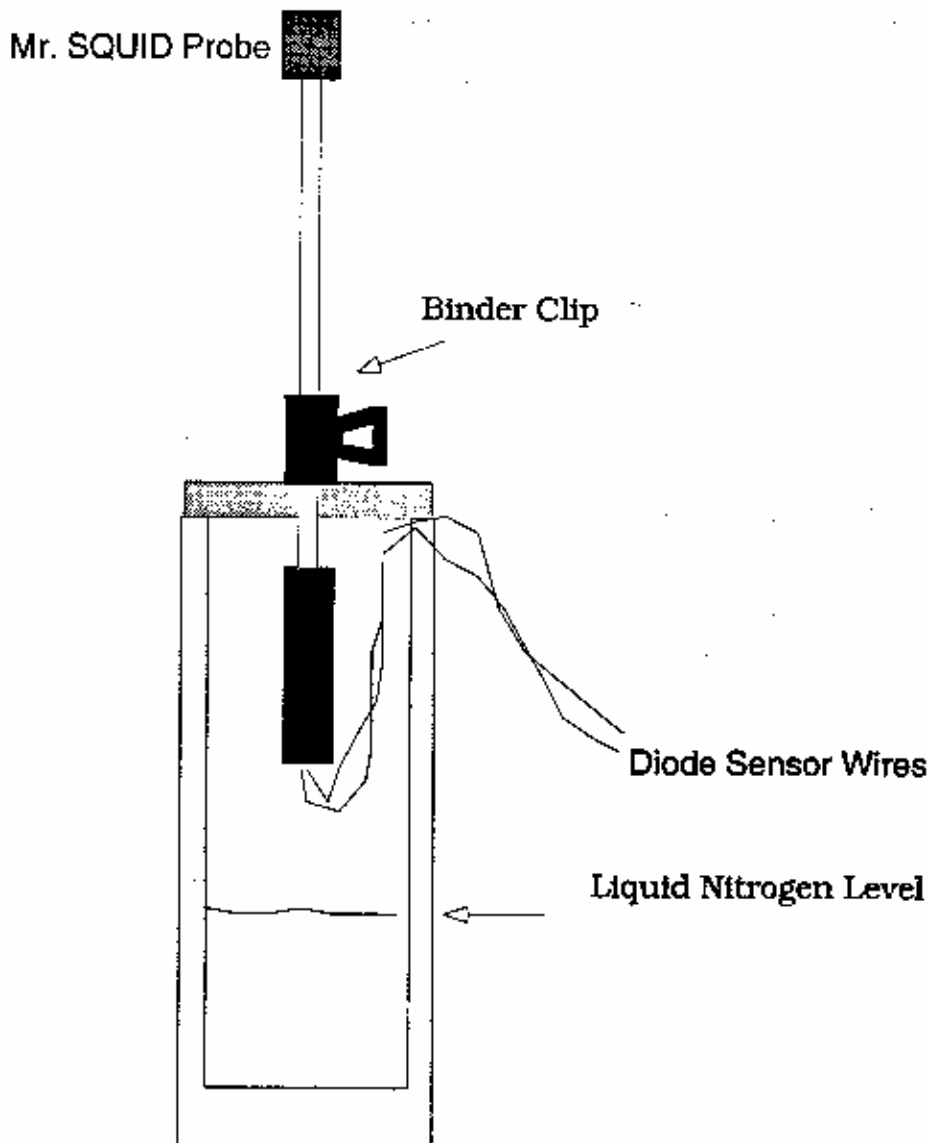

Figure A1.3

position with respect to the foam cap on the dewar. Start with the end of the probe just under the level of the foam and follow the procedure below to record the temperature and resistance of the squid.

The Resistance vs. Temperature measurement procedure:

Step 1. Wait until the voltage on the diode stabilizes. This can take as much as 10 minutes.

Step 2. Record the diode vo1tage in your lab notebook.

Step 3. Record the slope of the squid V-I curve near the origin (V=0 point) in your lab notebook.

Step 4. Carefully loosen the binder clip while holding the squid probe
        and lower the probe about 2 mm further down into the dewar.

This procedure is repeated until the probe has been lowered all the way into the nitrogen and has reached 77 K. The diode voltage should correspond to liquid nitrogen temperature at that point. The accuracy of the measurements and the number of data points you record is determined by your patience. If you want to spend less time, lower the probe in larger steps. You will get fewer temperature readings this way. However, if you do not wait until the diode voltage at each point is stable before recording the temperature, it will be very inaccurate.

Trouble-avoidance tip: Don't let the wires from the silicon diode extend far below the Mr. SQUID magnetic shield. If they do, they might dip into the liquid nitrogen before the probe end does. If this happens, the thermal conductivity of the copper wires can cause the diode to indicate a temperature as much as 10-15 K lower than the squid chip. This is something to watch for particularly when below 120 K.

The following data were taken using a glass encapsulated switching diode as the diode sensor. Data can be taken all the way down from room temperature, but in Figure Al .4, we only show the region around the transition temperature of the YBCO film, which will generally be near 90 K.

This concludes the instructions for the R vs. T experiment for Mr. SQUID. The following optional help section will tell you how to build a simple dc constant current source suitable for use in this experiment and some of the other advanced experiments, and also will explain the physics behind the operation of diode temperature sensors.

Building a simple constant current supply

A simple constant current supply can be built using a zener diode, two resistors, one capacitor, one general purpose operational amplifier and two 9 volt batteries. The schematic diagram is shown in Figure A1.5. This circuit can be assembled using a solderless breadboard, although we recommend that it be built on a solderable breadboard and housed in a metal or plastic box.
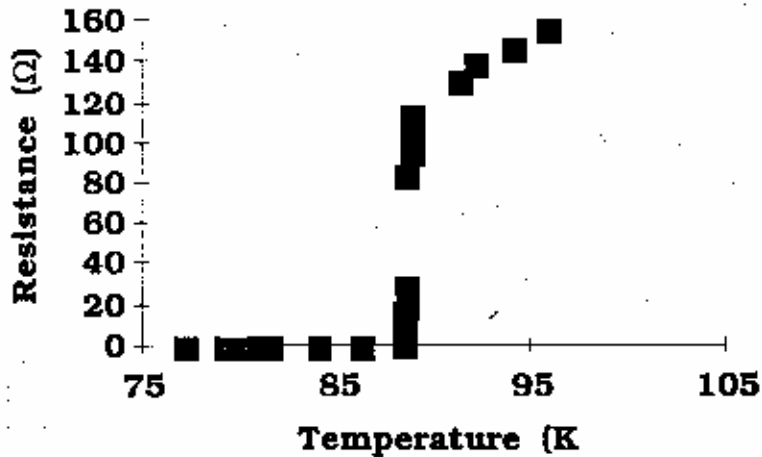

Figure A1.4

APPENDIX : SQUID Chip (nominal):

System Specifications:

SQUID 4-probe resistance
(using Mr. SQUID Electronics):   300-400 Ω @ 295K
                                           0.2-0.5 Ω @ 77K @ high currents
                                           0 Ω @ 77K @ low current

Critical current (minimum):   5 μA @ 77K

Magnetic field modulation (minimum): 1 μV @ 77K

Internal & external coil mutual
inductance to the SQUID (M):   ~43 pH

SQUID self inductance (L):   ~93 pH

Internal & external coil resistance: 22 Ω @ 295K
                                          18 Ω @ 77K

SQUID Noise Floor:

    Mr. SQUID electronics limited at $\sim 10^{-3} \Phi_0 / \sqrt{\text{Hz}}$ @ 100Hz

    SQUID intrinsically limited at $\sim 10^{-4} \Phi_0 / \sqrt{\text{Hz}}$ @ 100Hz @ 77K

SQUID washer dimensions: 250 μm x 250 μm outer body
                                          20 μm x 20 μm hole
                                          155 μm slot, 2 μm wide