Physics 111B
Josephson Junction

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1 Abstract

In this lab we conducted an experiment with superconductors. Specifically we looked at the sandwiching of two superconductors with a thin insulating barrier or junction in between in what is called the Josephson Junction. We analyzed the DC and AC Josephson Junctions. The DC effect is without any applied voltage, and the AC we applied microwave radiation. In order to get these measurements we had to use a four wire measurement technique. From the AC effect we were able to compute the fundamental constant ratio e/h. From our data we collected I reached an estimate of $2e/h \approx 443.924 \pm 83.34 \frac{MHz}{\mu V}$.

2 Introduction

This experiment explores some interesting phenomenon of superconductors and for Josephson in the 1960s it provided an improved estimation of the fundamental constant ratio e/h. It was thus a very useful experiment for precise measurements of fundamental constants. Also it is used as a basis for voltage standards presently. Another interesting thing about this ratio e/h is that it turns out that 2e/h is a constant of proportionality between the voltage across the junction and the frequency of the current. That is a very curious result. In fact, it will become more miraculous that this works when I explain the physics behind the Josephson junction shortly. So just keep in mind that this is going to be something very epic, and kind of coincidental.
To begin let's take a look at some physics of superconductors because that is what is used in this experiment. The physics of superconductors is something that developed over time in just the 20th century. In fact, 1911 is when it was first discovered, and then in the 1950s the physics was really explained thoroughly for superconductors in the BCS model. So a superconductor has zero electrical resistance and infinite conductivity. That is we develop a supercurrent in it that does not seem to possess the normal resistance to the flow of the electrons.

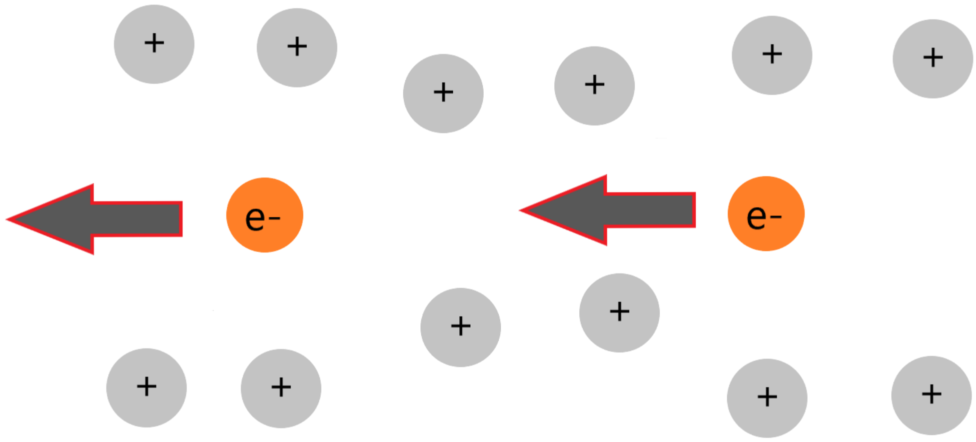


Figure 1: Diagram of the electron-phonon interaction and Cooper pairs. Credit Todd Chaney

Cooper Pairs

The explanation in the physics of this lied in the idea of electron-phonon interactions and in what would be called Cooper pairs. Phonons are collective excitation of atoms in the lattice. This seems to hint at the fact that electrons are interacting with atoms in the lattice that are moving collectively at the same frequency. Let's analyze just what this exactly means though. Cooper pairs represent two electrons that are connected with each other and almost act as a single particle. One interesting result of these electrons working together is that it provides them the property of acting like bosons instead of fermions. Which will prevent the Pauli Exclusion principle applying to the Cooper or electron pairs in the superconductor. This electron pair comes from one electron in a lattice that causes an attraction of the positively charged lattice atoms, which then causes the lattice atoms to interact with another electron and attract it to where it is at. In other words, this is saying that the first electron causes the atoms in the lattice to change their configuration in a way that creates a small area of excess positive that that will attract another electron to their location. But this is not going to happen super easily because the first electron is going to be repelling the second electron. In fact, this is called a weak link in the literature because any type of small thermal agitation will disturb the electron-lattice interaction that created the electron pairs and thus the electrons behave independently of each others existence. This is why superconductivity works only at extremely low temperatures close to absolute zero because it decreases the thermal agitation of the electrons. Once this happens they can behave like bosons and go to the lower ground energy state. In this lower energy state you have almost zero electrical resistance and infinite conductivity of the metal. The explanation kind of comes from saying that all the electron pairs can act together in this lower energy state and thus less scattering of electrons. The cool thing about this result is that it even makes sense in terms of poor conductors. It was noticed that poor conductors are more likely to become superconductors at higher temperatures. Some strong conductors have more difficulty becoming superconducting. This explanation of electron pairs with the interaction of the lattice can prove this observation because the good conductors have electrons that are much more free and less interacting with the lattice. Which is not conducive to the electron pairs which are dependent on the interaction of the electron and atoms in the lattice. (1,2)

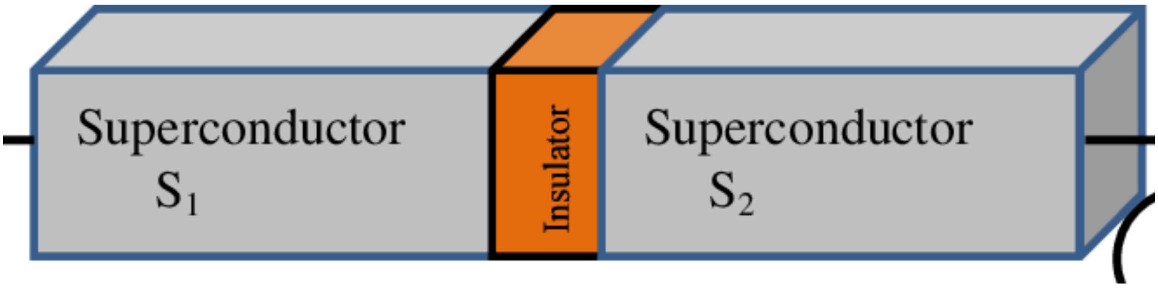


Figure 2: Diagram of the Josephson Junction that shows the superconductors separated by a thin insulating layer. Image taken from https://www.researchgate.net/figure/Schematic-diagram-of-ac-Josephson-junction-Both-electrodes-are-connected-to-an-external_fig1_332245281

Josephson Junction

This experiment is all about the Josephson Junction, so this takes the physics of superconductors and applies it to the case when you have a thin insulating junction that separates the superconductors. The physics of this Josephson Junction is related to the superconductors. So it was discovered that if you take two superconductors and separate them from some distance they will not interact in anyway. But as you move them closer to each other at some separation distance they can develop a supercurrent across the junction. This is somewhat of a quantum mechanical tunneling effect. What we realize is that the electron pairs are somehow moving from the S_1 to S_2

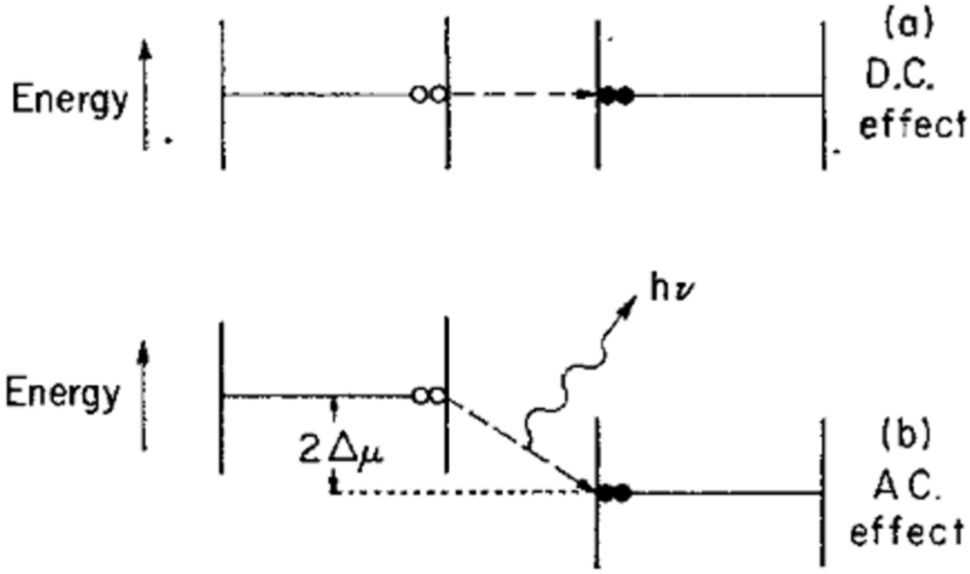


Figure 3: Diagram that shows the difference in energy between the DC Effect and AC Effect. The difference in potential energy means there is a voltage drop across the junction. Image taken from (1)

There are two effects to consider in the Josephson Junction. There is the DC and the AC effect. The DC effect is when you have a supercurrent that develops across the junction but there is zero voltage drop across the junction. Physically this means that there is no difference in potential energy for the electron pairs to be on either side of the junction. However, the AC effect we see that there is a change in the potential energy. That is $\Delta U = qV$, where this is the change in potential energy is related to the charge and voltage. So if we consider electron pairs we say $q = -2e$. This physics of the change in potential energy for the AC effect is very important for computing the e/h. This is where it becomes fascinating for the e/h. Cause the e was from the electron. And h is Planck's constant and it comes from the the fact that that physically if you have a change in potential energy that means you must be emitting or absorbing a photon. This is what actually happens in the AC effect though. There is emission or absorption of photon when the electron pairs crosses the junction, $hf = E_{photon}$. h is plank's constant and it is important because it is related to the energy of a photon. That is with the frequency and h you can find the energy of photon. If we use this physics and suppose that the change in energy across the junction corresponds to the photon $\Delta U = hf$, then we can get the important result $hf = 2eV$, This explains the physics behind how the AC effect will be capable of solving for the ratio e/h. (1)

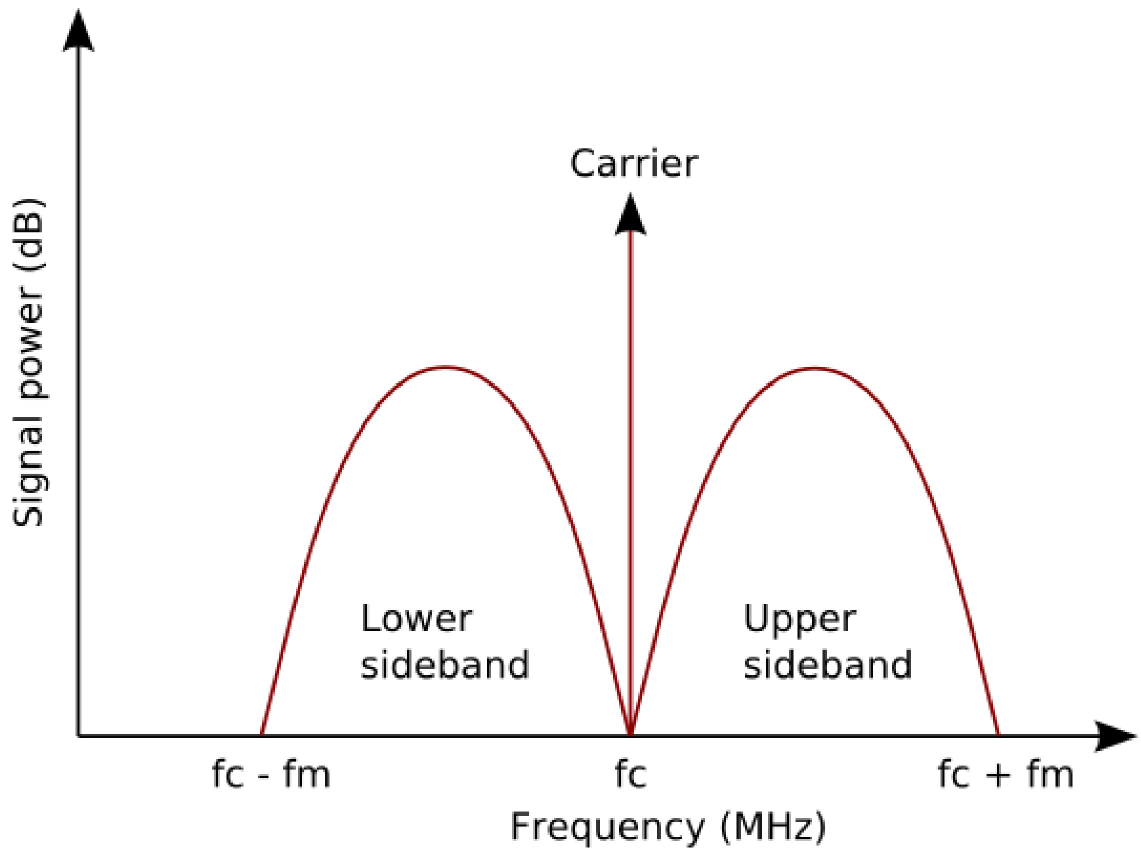


Figure 4: Depiction of the modulation of a carrier frequency. Image taken from https://en.wikipedia.org/wiki/Sideband#/media/File:Am-sidebands.png

A very important component in this experiment is the use of the microwave radiation. But what could possibly make it so important to the physics of the experiment. It seems evident that the microwave radiation is modulating the current to give it many sidebands and increase the bandwidth of the current. This is also why we need a higher bandwidth for the vertical axis which represents the current. Because we are modulating it to increase it's frequency range that is going to be measured on the oscilloscope. The voltage has a small frequency on the other hand and is not being modulated. This microwave radiation is being used to modulate the current. This will give sidebands which are basically the $f_c \pm f_m$, where f_c represents the carrier frequency and f_m represents the modulation frequency. And then the steps on the I-V curve are just the zero frequency or DC sidebands. (1)
There is another question that is important to understand in the introduction of this experiment, which is why do we use the range of around $18 - 26$ GHz for the frequency range after doubling it. I believe it is related to the magnitude of the electric potential (voltage). Because consider the equation that we use in this experiment.

$$eV = hf/2$$

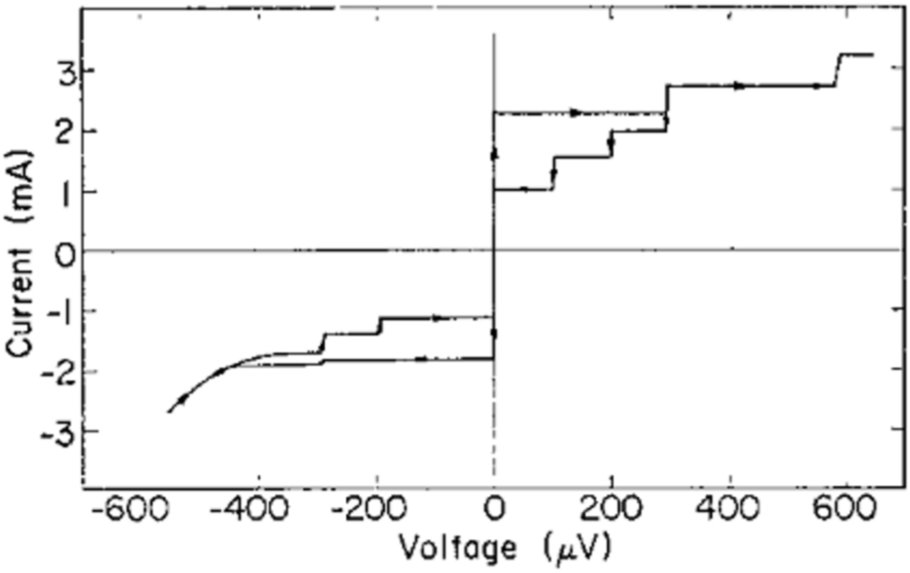


Figure 5: Diagram of the steps for the AC Effect. We measured the length of a step which is the voltage drop across the junction used in the experiment to compute e/h. Image taken from (1).

Suppose we substitute $f = 100$ MHz, where ignoring any uncertainty in this hypothetical scenario. This will give us a voltage difference of $0.2068\mu V$, while if we use a larger frequency such as 25.12 GHz, you get a voltage difference of about $50\mu V$. This seems better because of two reasons that I consider. First off the larger voltage difference will bring with it less uncertainty. The other reason is that it seems to be the case that this microwave range that we use provides a larger bandwidth and makes the steps look more like steps. It seems reasonable to say that if you take the case of a Fourier series and then you construct a square wave from a Fourier series. That basically the smaller frequency range will not provide a square wave with quite as sharp features. On the other hand, the larger frequency range allows a Fourier series with more terms and a better approximation to a square wave with sharper features.

3 Theory

DC Josephson Effect

The mathematics for Josephson Junction relates to quantum mechanics and wave functions. So you begin by supposing you have a time-dependent Schrodinger equation. Where we take ψ_1 and ψ_2 to represent the probability amplitudes on both sides of the insulator. That is 1 corresponds to conductor 1 and 2 corresponds to conductor 2. We suppose that the superconductors are identical and since we are looking at the DC effect we are going to let the potential be zero.

$$i\hbar\frac{\delta\psi_1}{\delta t} = \hbar T\psi_2$$

$$i\hbar\frac{\delta\psi_2}{\delta t} = \hbar T\psi_1$$

Where we suppose that the $\hbar T$ represents the transfer interaction across the insulator or the electron-pair coupling. Another way to consider T is that it represents the leakage of the probability amplitude in superconductor 1 into region 2, and vice versa. In fact, consider the edge case that the insulator is very thick. Then we would suppose that T is equal to zero as there would be no leakage and in fact no pair tunneling. So you perform some substitutions for the probability amplitudes and so on and eventually you get to the following result.

$$J = J_0 sin(\delta) = J_0 sin(\theta_2 - \theta_1)$$

This equation represents the current J of electron pairs across the junction. We see from it that the current depends on the phase difference. Also J_0 represents something very important. It is the maximum current across the junction when applying zero voltage. Thus we get the result that you can attain a current $J \in [-J_0, J_0]$ across the junction with no applied voltage. This is the DC effect. (4)

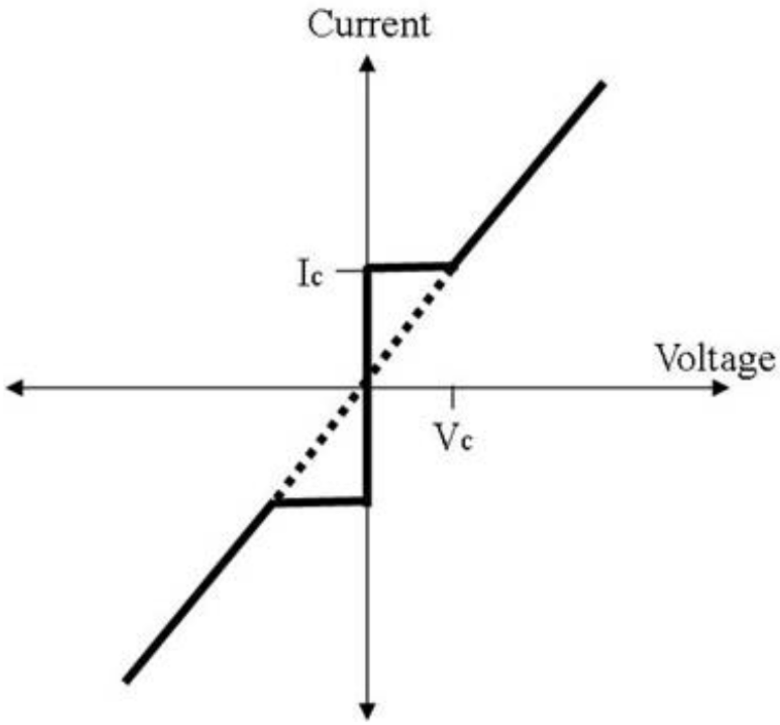


Figure 6: Diagram of the DC Josephson Effect, it shows some crucial elements. For instance it shows the critical current. Notice that the critical current is the current you have when the applied voltage is zero. That is the critical current is the maximum currents that are predicted in the equations for zero applied voltage. Image taken from http://spa-mxpweb.spa.umn.edu/s11/Projects/S11_JosephsonJunction/theory.htm

AC Josephson Effect

Now let's consider the theory of the AC Josephson Effect in a simple manner without the derivations but just showing and discussing the results. So the first thing to understand is that for this effect you need to apply a voltage across the junction. This way you get a difference in potential energy for the electron pair to travel through the barrier.
Anyway we get the following Schrodinger Equations for this new case with a potential energy.

$$i\hbar\frac{\delta\psi_1}{\delta t} = \hbar T\psi_2 - eV\psi_1$$

$$i\hbar\frac{\delta\psi_2}{\delta t} = \hbar T\psi_1 + eV\psi_2$$

The really only noticeable thing is that our Hamiltonian has the added potential energy.

$$J = J_0 sin[\delta(0) - \frac{2eVt}{\hbar}]$$

This is the result of this added potential energy when deriving the current. We see that we have this added part where the current is oscillating with the frequency $\omega = \frac{2eV}{\hbar}$. Again we get the result from the introduction that says a photon of energy $\hbar\omega = 2eV$ is emitted or absorbed when the electron pair crosses the barrier. (4)

4 Apparatus and Procedure

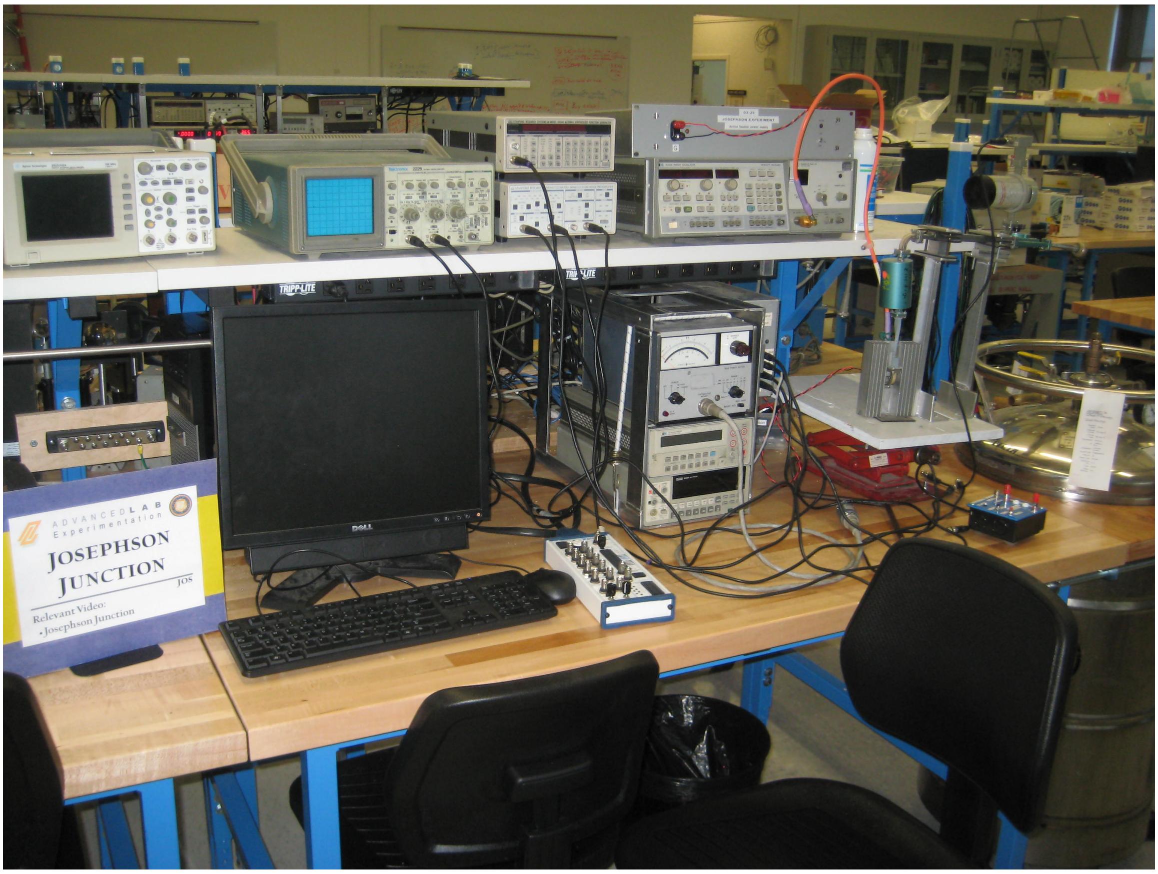


Figure 7: Picture of the laboratory equipment setup. Image taken from Physics 111b Lab manual.

This is the lab equipment for the Josephson Junction experiment. In this experiment the superconductor that is used is Niobium (Nb), We use the Niobium screw and Niobium needle as our superconductors. The thin insulating barrier is a thin oxide layer on the Niobium needle's tip. To achieve superconductivity we need to put this Josephson junction as it is called into liquid helium.

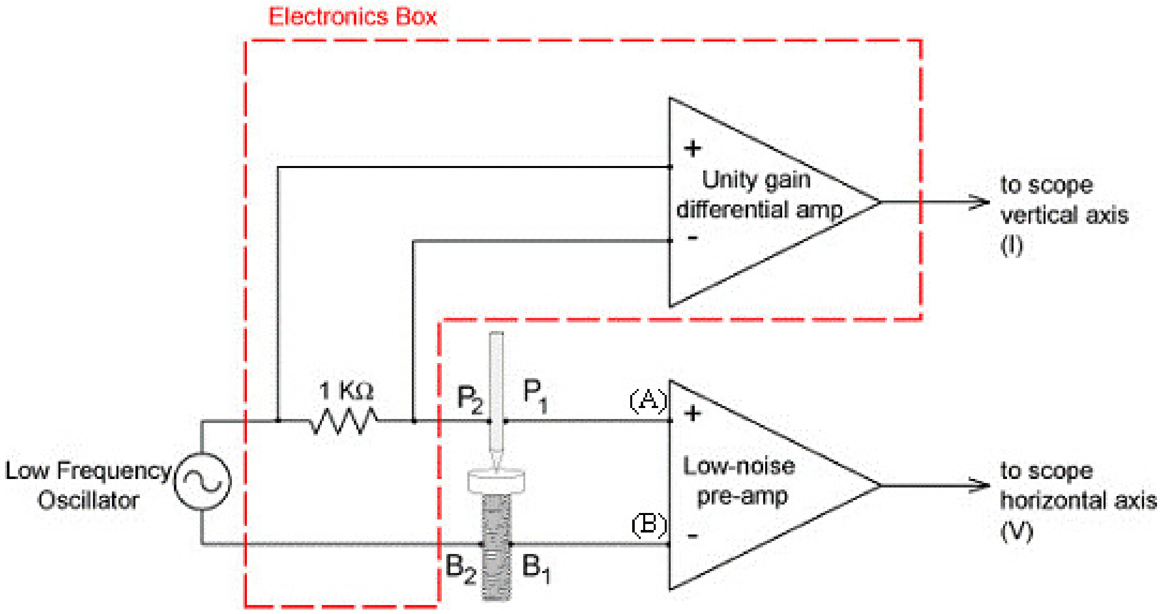


Figure 8: Schematics for the four wire measurement electronic hookups for the I-V curve displayed on oscilloscope.

We used a four-wire measurement for impedance matching to generate the I-V curve on the oscilloscope by use of our function generator. In schematics for this experiment there are a couple of important elements to notice. First off we have an electronics box that is already assembled. But we are providing a unity gain to the signal in the electronics box that we send to the vertical or 'y' axis of the oscilloscope. This is to measure the current. Then we have the four wire-measurement on the Josephson Junction (the junction between the needle and the base of the screw). We call these electrical connections P_1, P_2, B_1, and B_2. We are sending in a signal into the needle and the screw. We then have the number 1 connections connected to inputs A, and B of a Low-noise pre-amp. A pre-amp is essentially boosting our weak signal to a line level. This then is sent to the horizontal or 'x' axis of the oscilloscope and this will be our V measurement.

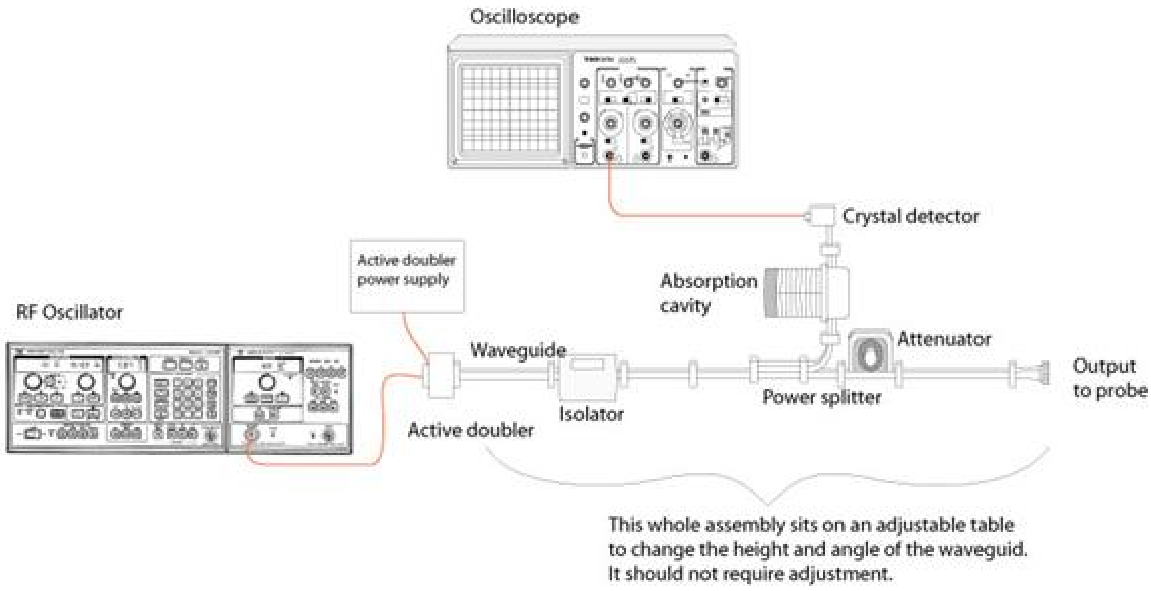


Figure 9: Schematics for the RF oscillator. Image taken from Physics 111b Lab manual.

So we are generating a RF electromagnetic (3kHz to 300GHz) radiation that through the sweep oscillator, which is set at the maximum power level 20 dBm, where 20 dBm = 0.1 Watts. Also dBm is a measurement of the absolute power level with reference to 1 mW. Also we set it in CW mode which means constant frequency mode. Then we send the signal to an active doubler to double the frequency. This is connected to a rectangular waveguide. This gets sent to the power splitter, which is where some of the RF power will be sent to an absorption cavity and a crystal detector to measure the power. You can measure the RF frequency by tuning the absorption cavity until you see the straight line on the oscilloscope shifting vertically. We then read the frequency from the absorption cavity.

Step 1: Pointed Part

You need to make a Nb tip from Nb wire, this will be the Nb needle with the tip that should be in a conical shape. With an angle of 45 degrees with respect to a cross section through the needle. After that you will need to leave the Nb tip in the air overnight in order to develop the thin oxide layer.

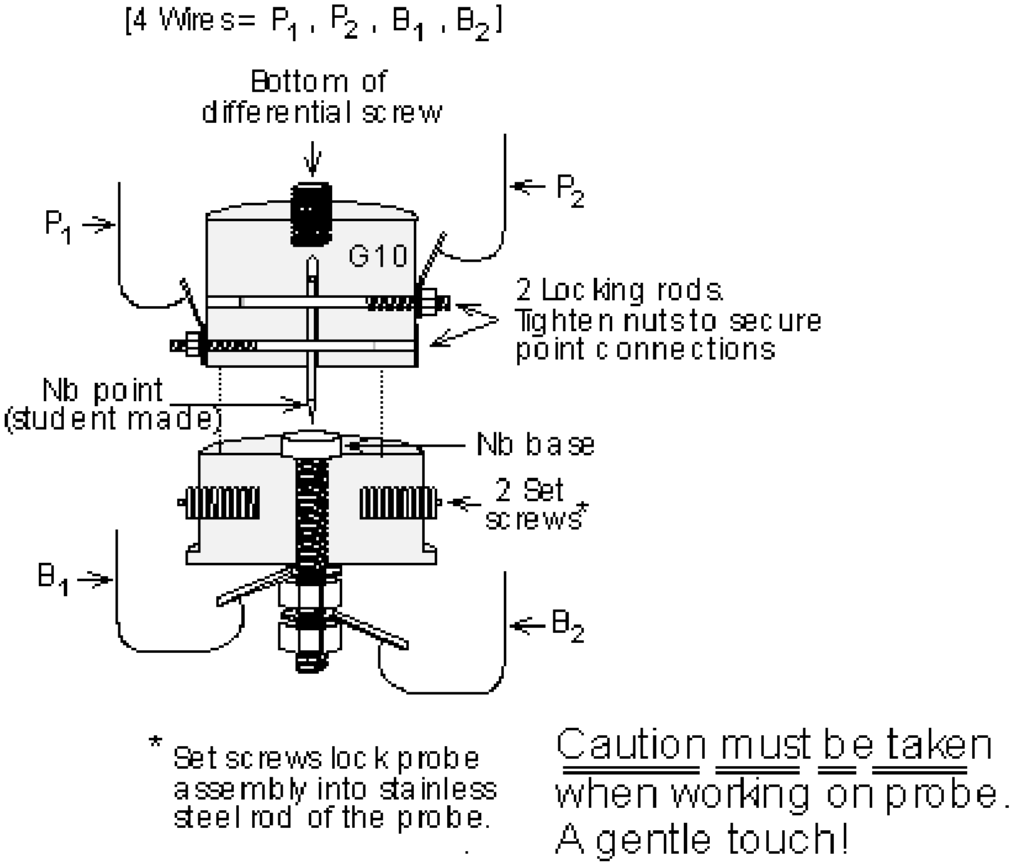


Figure 10: Diagram of the Josephson Junction with the Niobium needle and screws. Image taken from Physics 111b Lab manual.

Step 2: Point Installation

Now it is time to install the Nb tip into the junction assembly. The Junction assembly is basically the Josephson junction. I am not going to explain every single detail but to say that the main goal is to remove any old Nb Tips from the junction assembly and then add your new one. It is best to use needle-nose pliers to pull the Nb tip out of the housing. You can hold both sides in order to prevent the screws from falling out of place that are in the side of the junction.
Now to install the needle you will want to first rub all parts of the needle except for its tip with a sand paper to remove the oxide layer, because you desire good electrical conductivity between other parts of the needle. Only the tip requires the thin insulating oxide layer. It was easiest to insert the new needle with a needle-nose plier holding it just above the tip. and then inserting it from the bottom into the junction assembly. It is recommended to not allow the Nb tip to touch the Nb screw cause that can rub off the oxide layer for the junction, so try to move the housing to give yourself room to insert the needle. Then you can move the needle down but not touching the base

and screw the differential screw into the housing again.
There is one more step before inserting the junction assembly back into the probe. You will want to follow figure 8, and connect the wires as seen in the bloch diagram. This can be seen in figure 10 where you have wires P_1, P_2, B_1, and B_2 connected to the assembly. So the P wires are connected under the screws in the housing and you have the B wires connected under the Nb base screw.

Step 3: Electrical Continuity

The next step is important in order to ascertain that all electrical components are hooked up as desired. This is an important check before moving into a farther part in the lab, cause it is a hassle once you get to the cryostat part. So the proper electrical continuity is basically that you should check the wires B1-B2 and P1-P2 should show a resistance less than 1 Ohm on a Multimeter. And the rest of the hookups should show infinite resistance. This is important do anytime before you place it into the liquid helium.

Step 4: Contact

There is one more step before inserting probe into the cryostat. This is the contact between the Nb tip and Nb base. The goal is to get a reading on the Multimeter between P1 and B1 of a few Ohms, possibly from like 3-15 Ohms. This means the circuit is closed now and you are getting some form of current pass from the Nb tip to the Nb base.
Now you can insert it into the probe as shown in figure 11. It is helpful to make sure that the rod in the probe is aligned so that it can turn the differential screw in the junction assembly. That is how you can adjust the location of the Nb tip relative to the Nb base screw once you are in the cryostat and collecting data.

Step 5: I-V Curve

Following the bloch diagram which is figure 8 that shows the electronics hookups. The oscilloscope should be set to X-Y mode because you have an x and y axis input. The LFO should be set at 60 Hz, and a preamp should be set up. I am glossing over some minor details but you need to set these. This should give a straight line on the oscilloscope that has a slope. The slope should represent the room-temperature resistance of the junction. This should be the same as the resistance on the Multimeter.

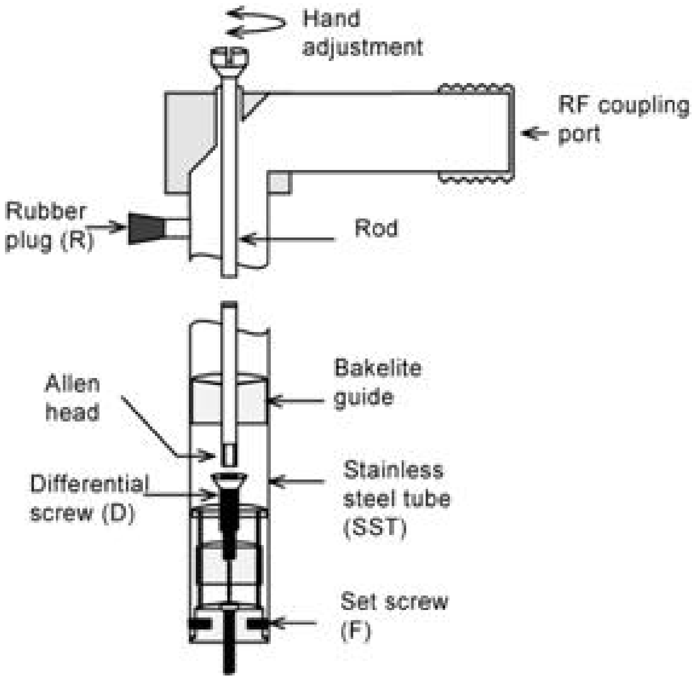


Figure 11: Diagram of the probe to be placed in the cryostat. Image taken from Physics 111b Lab manual.

Step 6: Cryostat

The probe should be inserted into the cryostat carefully after you first check that there is liquid helium in the cryostat. You can use a metal tube to estimate the liquid helium level in the cryostat by finding a vibration change in the metal tube at certain heights. When the vibration changes this is the depth of the liquid Helium. Now it is time to insert the probe into the cryostat. You want to rotate it as you insert it slowly so that it does not get frozen. You want to go slowly and whenever you hear a loud noise continue to rotate but stop lowering until the sound subsides. Then continue to lower it slowly into the liquid helium.

Step 7: DC Effect

The key is to slowly turn the rod in the probe whenever there is little resistance until you get the few Ohms on the Multimeter and you should see the DC effect as shown in figure 6. You can use a permanent magnet and bring it near the cryostat to make certain that the DC effect fluctuates. This is the DC effect if it fluctuates.

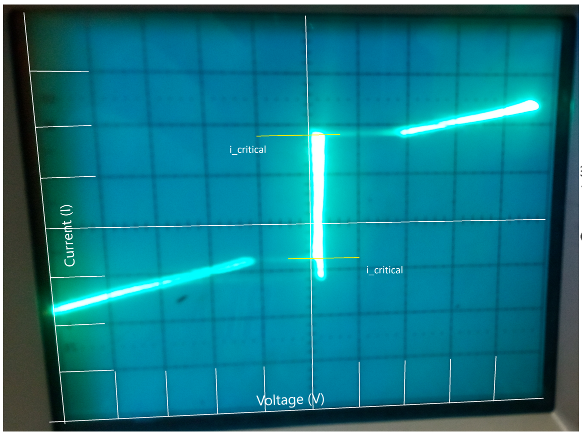
Step 8: AC Effect

Now it gets a little bit trickier in order to attain the AC effect there are quite a loops to work around. The first thing is that you want to follow the Bloch diagram of figure 9. You will have the RF oscillator, active doubler, an attenuator set to 20 dB. The main goal of this part is to sweep through different frequencies which you can measure in the absorption cavity and get the characteristic AC effect with the steps as seen in figure 5. It will require some finessing of the rod in order to get the effect to appear on the display. Once you get that you want to hook everything up to the DAQ to send a large amounts of data to be saved into a .dat file by a LabView program. This is what can be used to compute the voltage by taking the step sizes.

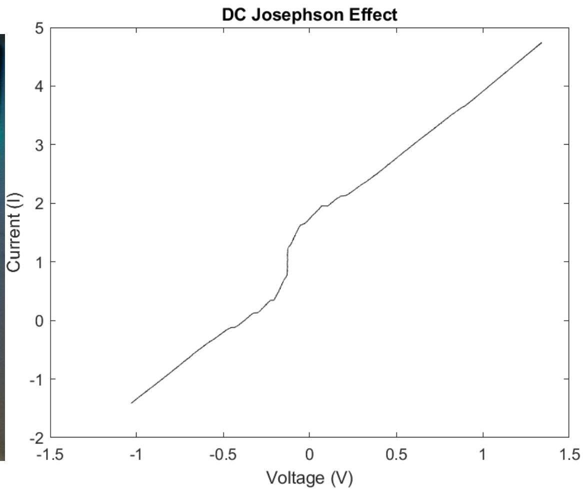
Step 9: Calibration

This step is crucial because the voltage output that we were collecting was amplified, assuming that the voltage at the junction is very small. Thus in this step you want to use a known voltage source and take a measurement of what this voltage shows on the scope. This will help you calculate the gain to be used for scaling the results from prior when estimating e/h.

5 Analysis



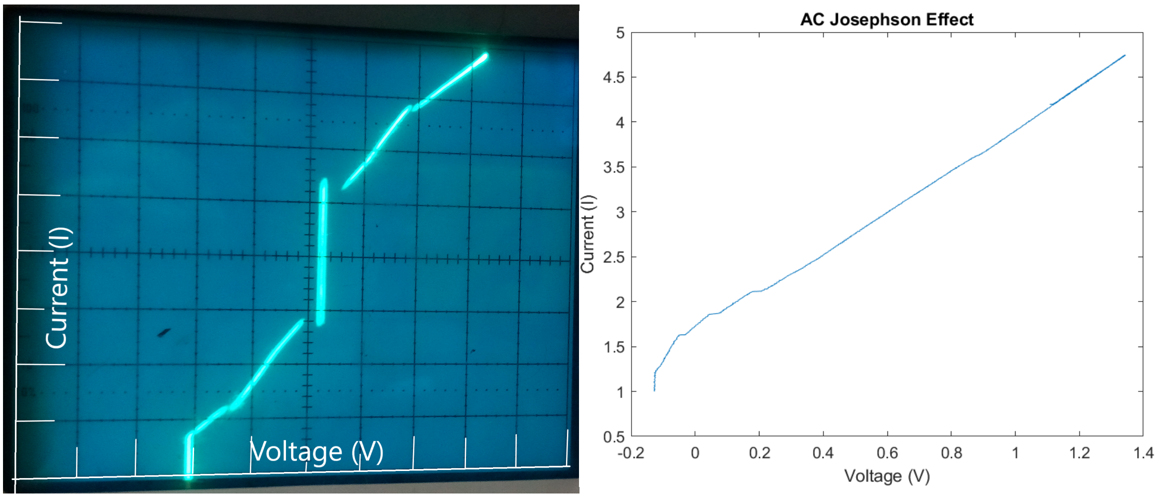
(a) Oscilloscope



(b) LabView Program

Figure 12: DC Josephson Effect

This figure from the computer program is not the best, it does not exactly have that one step where it is basically vertical. It at least looks like it was forming the correct graph but it is very rounded and not what we were hoping to see. This is probably because the oscilloscope picture was taken from a later time when we were able to improve upon the DC Effect. However, the data collected by the LabView program was from an earlier DC Effect that was not quite as characteristic.



(a) Oscilloscope

(b) LabView Program

Figure 13: AC Josephson Effect

The data collected into the LabView program looks good but only at a range of about -.2 to .2 V does it have anything that looks like steps. which makes sense because we only saw a few steps on the oscilloscope display as well. I discuss below that the reason for so few steps could lay in difficulties with the Niobium tip. To analyze the data I will compute the results from the scope and the collected data on our program. The data does seem to have some steps forming, we never were able to get perfect steps seen on the oscilloscope. But it relatively looks like it is forming multiple steps and does resemble the expectation of the AC Josephson effect.
Before computing anything we had to scale our Voltage axis. For this we followed the procedure for calibration which essentially we used a known voltage input into the oscilloscope to take a measurement of the gain of the signal as it was transported from the Junction to the scope.

$$V_o = gV_i$$

Where V_o represents the output voltage, and the other one represents the input voltage into the junction. g represents the gain.
We determined that our input voltage for calibration was 512 $\pm$ 1 μV by measuring it on the Multimeter.
By looking at the oscilloscope we were able to measure the output voltage. We had our oscilloscope set on 2 Volts/Division and the line spanned about 0.4 of a Division. I determined the uncertainty to be about 0.05.

$$2\frac{V}{Div} * 0.4Div = 0.8V$$

$$g = V_0/V_i \Rightarrow g = \frac{0.8 \pm 0.05V}{512 * 10^{-6} \pm 10^{-7}V}$$

I used the normal error propagation formula for multiplication and division.

$$z + \Delta z = (x + x) * (y + \Delta y)$$

$$\Delta z = z * (\frac{\Delta x}{x} + \frac{\Delta y}{y})$$

Where Δz is the error propagated. By using this equation for error propagation.

$$g = 1562.5 \pm 97.96$$

So this was the gain on the signal. So I use this to scale my axis that is I took the distance between the steps as seen in the figure 13(a). This turns out to be about $1.8 \pm 0.5V$ in order to compute the input voltage we take.

$$V_i = \frac{1.8 \pm 0.5V}{1562.5 \pm 97.96} \approx 1152 \pm 392\mu V$$

This is the voltage drop across the insulator barrier.

$$\frac{f}{V} = \frac{2e}{h} = \frac{25120 \pm 300MHz}{1152 \pm 392\mu V} \approx 21.8 \pm 7.68\frac{MHz}{\mu V}$$

This is not even close to the value reported by Parker, Taylor and Langenberg (483.5912 + 0.0012) $\frac{MHz}{\mu V}$

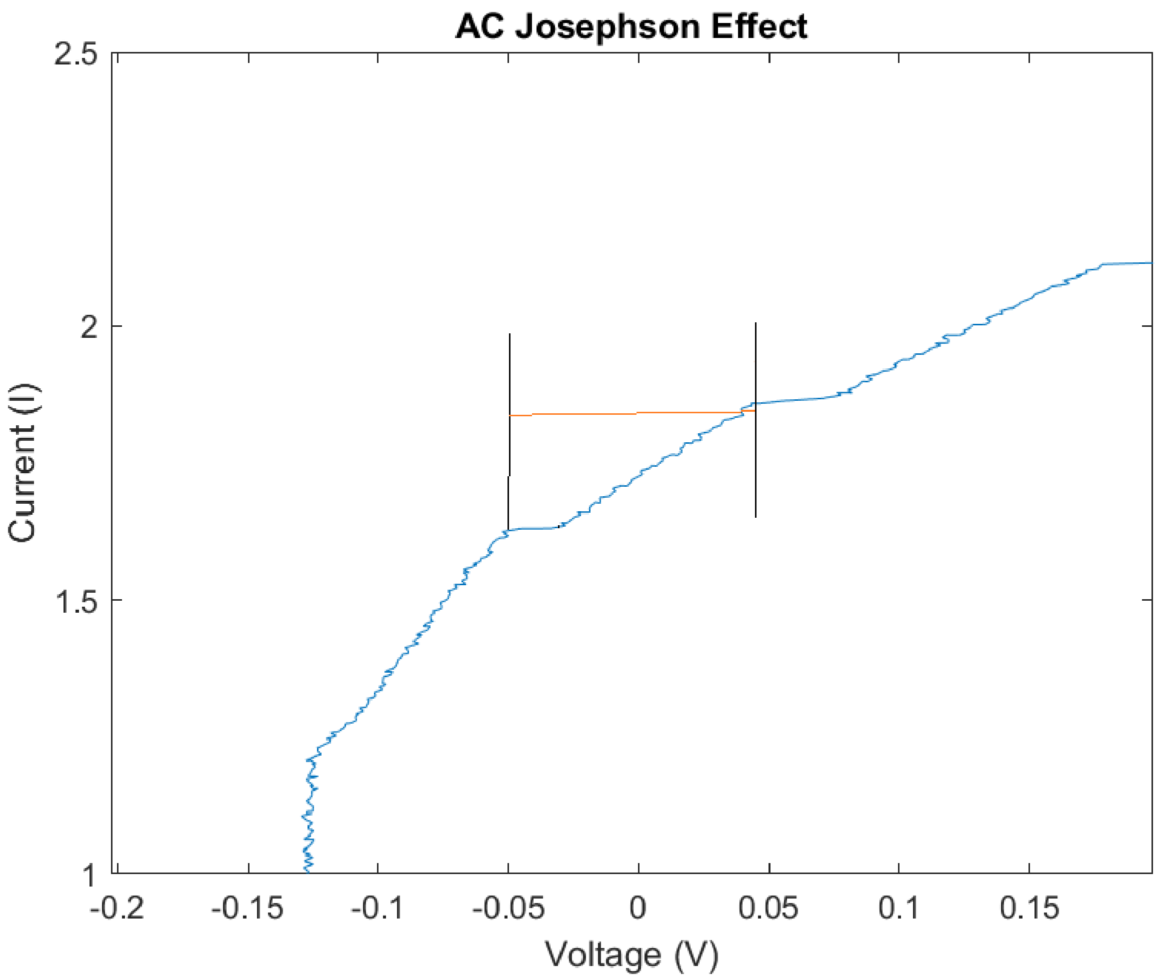


Figure 14: Zoomed in on figure 13(b).

I computed the Voltage across the junction for this range of voltage for what looks like a step in our data. The voltage difference by the graphical analysis is $V_o = 0.088416 \pm 0.01$. I provided a somewhat large uncertainty because the data just does not look clear in the graph. It is a little bit tricky to see where the steps are exactly. Then from the gain calculated above to be $g = 1562.5 \pm 97.96$. I computed the input voltage to the LabView Program or in other words the voltage across the junction. $V_i = \frac{0.088416 \pm 0.01V}{1562.5 \pm 97.96} = 56.58624 \pm 9.948 \mu V$ Where I am using the error propagation equation from above to compute the uncertainty after division. The next step is to compute $f/V = 2e/h$.

$$\frac{25120 \pm 300GHz}{56.58624 \pm 9.948\mu V} = 443.924 \pm 83.34 \frac{MHz}{\mu V}$$

This result is not the same as the 483.5912 MHz per every μV. But our result is reasonably close to the actual result compared to the value from the scope. The program collected many more data points then the scope and improved the accuracy. However, there was still a lot of uncertainty in our data for the following reasons.

The first reason is that we did not get the best formed steps as can be seen by the graphs of our data. We tried many days to get a very good AC effect, but it was rather difficult. I presume that the reason it did not work so well is that the oxide layer acting as the thin insulator could have been rubbed off while we were adjusting to display the AC Effect. And there could have been other problems with our Niobium tip, as we took a lot of effort to get the setup in the cryostat.

I allowed for a lot of uncertainty in my measurements so with the error it actually does push the range of possible values from around 360 to 527 $\frac{MHz}{\mu V}$ which the 483 does fall within that range. I included quite a large uncertainty for the graphical analysis as well because of how poor the resolution of the steps were, this contributed a large factor to the uncertainty.

I also included the uncertainty in the measurement of the RF frequency from the absorption cavity because you could move it around a certain range and it appeared to move the line on the oscilloscope indicating it was at resonance and that was the RF frequency that was in our junction.

6 Conclusion

In this Experiment we were able to get a somewhat reasonable measurement for e/h considering the uncertainty and errors in our technique. The value measured by Parker, Taylor, and Langenberg was $(483.5912 + 0.0012) MHz/\mu V$. We measured from our data collected a value for 2e/h to be $443.924 \pm 83.34 \frac{MHz}{\mu V}$, which the actual value does fall within my huge uncertainty in my calculation. This experiment was interesting in retrospect because it had us measuring an effect of superconductivity. However, in the process of setting it up every time with the probe into the cryostat, and using multiple Niobium tips, it was possible that we kept rubbing off the oxide layer on the tip. Especially when we were turning the rod in the probe in order to adjust for the DC and AC effect on the oscilloscope. I think knowing how to perform the lab right now it would be easier to get a better computation if I were to perform the experiment again cause now I know many elements that can go wrong. So should be able to do it with less deterioration of the oxide layer on the Niobium needle tip. So my recommendation is have experience before you do the lab.

The one thing I think that could use better explanation is the calibration section. Was not certain what that was about and a dot spanning is not very descriptive of what we are looking for. I think instead of a dot it was probably a line that was spanning. That was suppose to be used to figure out with a known voltage what the gain is when the signal reaches the scope and is displayed. Also I think it is best that get everything ready before inserting the probe into the cryostat for the DC effect. The best strategy for the lab seems to be do as much as you can such as check electrical

continuity and stop right befor eyou put into cryostat. But wait is not that simple, you should do it in a different order as I lay out below.
This will be modification of the procedure that was given for the lab. I believe the best bet is to get everything ready for DC, and then learn everything for the AC effect, that is set up the RF sweeper and measure the RF frequency in the absorption cavity. This requires a lot of practice to understand. Once you master the measuring of the frequency and attach the waveguide to the power meter. You should do everything that you can for the AC effect that doesn't require the use of the liquid helium. Now after doing a major portion of the AC effect, everything you could. It makes the most sense to get the DC effect and then set it up for the AC effect all in one day. And then you can do this a couple of days to try to improve on the AC effect cause it is rather difficult to get a good one.

7 References

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