Physics 111B: [Josephson Junction]

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We present an experimental framework to study quantum interactions of the Josephson Junction and its relationship to the field of superconductivity. When a Josephson Junction is subject to low temperatures, the DC effect and AC effect can be observed on a digital oscilloscope. Data measured from the AC effect allow us to precisely calculate the ratio of Planck's constant and the elementary charge. Our calculation of the fundamental constants is compared to scientifically accepted calculations of the Josephson Junction. Our observations and calculations provide us with a significant understand of superconductivity and the role it plays in modern electronic systems.

I. INTRODUCTION

A. Superconductivity & Josephson Junction

1. *Superconductivity*

In room temperature, conductors move electrons through a current that is induced by a potential (i.e. voltage) applied to the conductor. The quantum interactions and scattering of the electrons with the conducting material is classically represented as the conductor's characteristic resistance. Insulators are used to prevent current flow; this is due to the nature of their "ideal" infinite resistance. The current-voltage relationship is given by Ohm's Law:

$$V = IR \tag{1}$$

where V is voltage in volts (V), I is current amperes (A), and R is resistance in Ohms (Ω).

Superconducting material (e.g. niobium) is a type of conductor that, when cooled to very low temperatures ($\sim 4°$K), hosts zero electrical resistance. A superconductor needs to be cooled in order minimize the potential energy lost from thermally-excited electron interactions. Electrons in a superconductor no longer behave as a free particle because their internal energies are lower than their Fermi energy. As these electrons occupy low energy states, they superpose and become bounded together as Cooper Pairs.

These pairings can be classically described by positive charges in the superconductor's lattice being attracted to slow-moving negative charges. Other negative charges are then attracted to the positive charge, producing a pair of electrons that overcome each other's Coulomb repulsion.

2. *Josephson Junction*

A Josephson Junction (JJ) is a superconductor-insulator-superconductor (SIS) junction. A nail and screw (both made from niobium) make up the two superconductors while the insulator is a thin layer of oxide from the niobium oxidizing over night.

The JJ assembly is made up of three primary components (labelled in blue in Figure 1. The first component holds the nail in place. The second sliding component holds the needle together and allows the nail to move with respect to the nail. The third component holds the differential screw, which is then connected to the sliding component. The differential screw is a $\frac{1}{720''}$ screw that allows for precise contact between the screw and needle. The point at which the screw and needle make contact is the point-contact junction (PCJ).

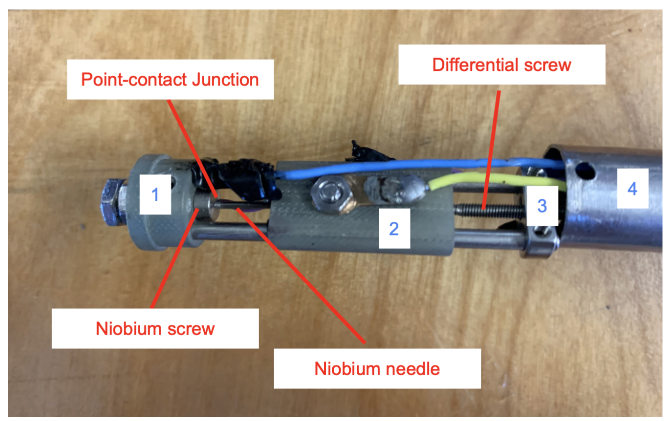

FIG. 1. Assembly of the Josephson Junction that is connected to a probe (4) and cooled in a liquid helium Dewar.

B. The DC & AC Effect

1. *DC Effect*

Room-temperature conductors allow current to move electron in the presence of a potential difference. If there is no voltage then there is no current; this can furthermore be described by the linear relationship between voltage and current in Ohm's Law.

When we cool the entire JJ assembly in liquid helium, the system no longer behaves like a room-temperature conductor. Instead, low-energy electrons sharing quantum states in the superconductor form Cooper Pairs and group up. Since these Cooper Pairs have a non-zero probability of tunnelling through the insulator, a small current is induced in the insulator. Instead of a voltage-induced current, we have a quantum-induced current.

Before applying any voltage to the JJ, a characteristic I-V diagram can be observed on an oscilloscope. In Figure 2, we can see that at zero volts, a current is induced in the JJ. After some voltage is applied, the JJ behaves more like a linear Ohmic conductor.

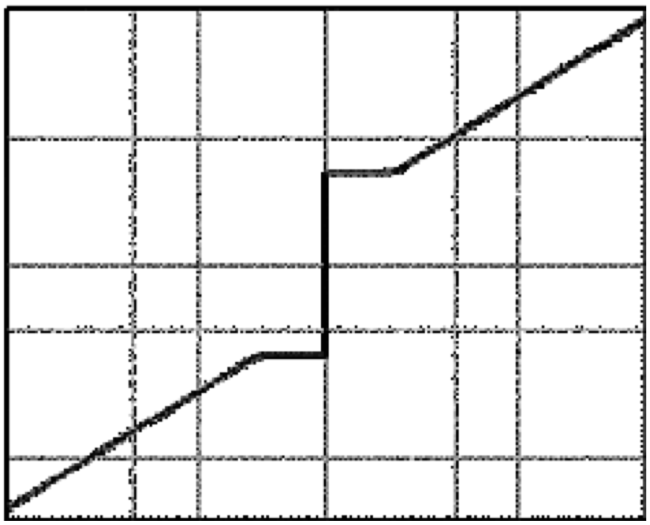

FIG. 2. Characteristic I-V diagram of a theoretical DC Effect (from lab manual)

2. *AC Effect*

Voltages running through the JJ will have characteristic frequency at which the system oscillates. The AC Effect can be observed when we irradiate the JJ with a frequency of light that is proportional to the JJ's characteristic frequency.

Figure 3 displays what one should observe with the system is tuned correctly. We see a stair-like structure that is the result of the JJ resonating at its frequency. Data from the AC Effect is what allows us to precisely calculate the ratio of fundamental constants $\frac{e}{h}$.

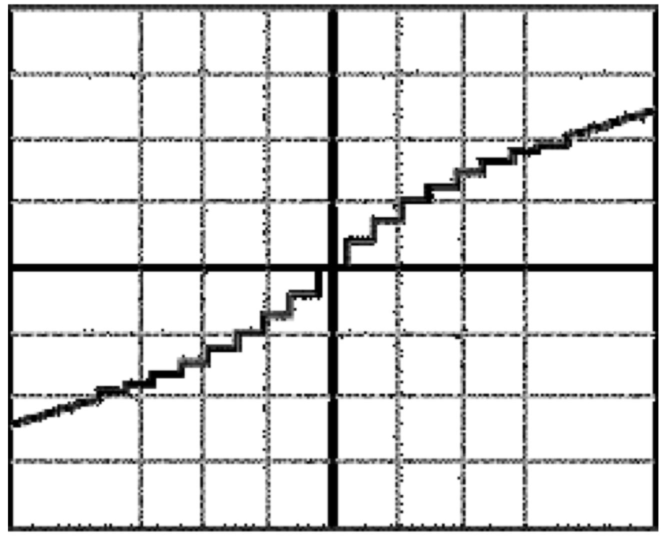

FIG. 3. Characteristic I-V diagram of a theoretical AC Effect (from lab manual)

II. EXPERIMENTAL PROCEDURES

A. Junction Assembly + Probe

1. *Junction Assembly*

The formation of the junction assembly was a difficult process that took a lot of careful planning. The three part junction itself came already assembled, so me and my lab partner's role was to carefully shape the niobium needle.

To model a thin layer of oxide, the niobium needle needs to be sharpened to a $\sim 45°$ point. The niobium needle point was sharpened by using various grades of sand paper. Wearing gloves was necessary to prevent contamination of any unwanted residue. We also used the help of a magnifying glass to make our needle tips as precise as possible. After we finished sharpening around 8 of the needles (in case one of the needles breaks), we left them over night to oxidize and form their oxide layer.

Once an oxide layer has formed on the needle and screw, we worked on carefully placing the needle in the assembly component 2 (named G10 in the lab manual). The process of fitting the needle in G10 was quite delicate and needed several hands and tools. One has to first find a proper length for the needle to stick out in the direction of the niobium screw. We then had to tighten two nuts connected on opposite ends outside of G10 to secure the niobium needle to G10.

The differential screw then slides into assembly component 3 and then is screwed into G10. Lastly, we check to see that the P1, P2, B1, and B2 wires are properly connected to the junction assembly. We have finished the junction assembly, which can now be connected to the probe (labeled 4 in Figure 1).

2. *Probe*

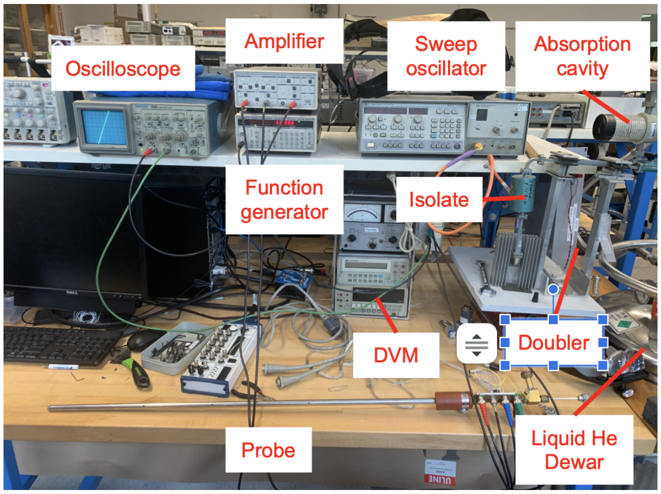

FIG. 4. All of the instruments needed for the Josephson Junction lab.

In Figure 1 and 4, we can see how the JJ is inserted into the probe (labelled 4 and "probe in the figures). To properly insert the assembly into the probe, the head of the differential screw is attached to a connecting rod inside the probe that allows us to adjust the different screw from the outside. Once the assembly is fit tightly inside, we pull out two screws (labelled F in the lab manual) that overlap with the holes of the probe so that the assembly is truly fixed inside the probe.

B. Checking Connections

Before each time we insert the probe in the liquid helium Dewar, we have to analytically check to see that all four wires (P1, P2, B1, B2) are properly coupled (or uncoupled) by running all the different combinations of wires through a digitial voltmeter (DVM). Figure 5 shows how all the four wires should be connected.

In an open junction (i.e. the niobium screw and nail are uncoupled), connecting P1-P2 and B1-B2 should show a small finite resistance (coupled). P1-B1, P1-B2, P2-B1, and P2-B2 should show infinite resistance (uncoupled). Additionally, all connections with the wires and probe should show be uncoupled.

In a closed junction (i.e. the niobium screw and nail are coupled/touching), tighten the PCJ just enough to observe a resistance of about 10Ω. The amount pressure applied to the PCJ during this stage will be very important for observations.

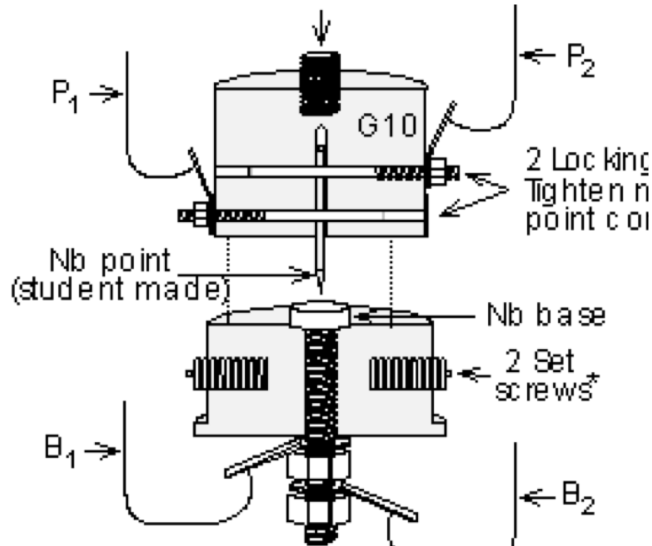

FIG. 5. Diagram of the four wire connections of the junction assembly.

C. Liquid Helium

The most dangerous part of the lab deals with what goes in and out of the liquid helium Dewar. Before we insert the probe into the Dewar, we check to see that the Dewar's pressure is zero to prevent any explosions. We can now turn the value 180° to open the Dewar. As we slowly insert the probe in the Dewar (with protective gloves and face shields on), we have to be careful that there isn't any build up of ice by twisting the probe. We need to reach to a height just tall enough for the probe to fully screw into the proper output terminal (which connects to the entire circuit).

III. RESULTS & ANALYSIS

A. DC Effect

Figure 6 shows the DC effect that we observed given our experimental procedures. The get this result, we had to input a 6-8V and 60Hz signal from the SRS DS345 function generator to P2 and B2. The output signal is then connected to the SR 560 Low-Noise preamplifier that applies a gain to the system. This is gain is precisely calibrated later into the lab. When we connect the input and output to the oscilloscope, change the settings of the oscilloscope to properly display the I-V characteristic, and carefully adjust the pressure at the PCJ, we were able to observe the DC effect. To check that this was in fact the DC effect (and not just some lucky artifact) we ran a large magnet near the Dewar. Since superconductors are very sensitive to changes in magnetic

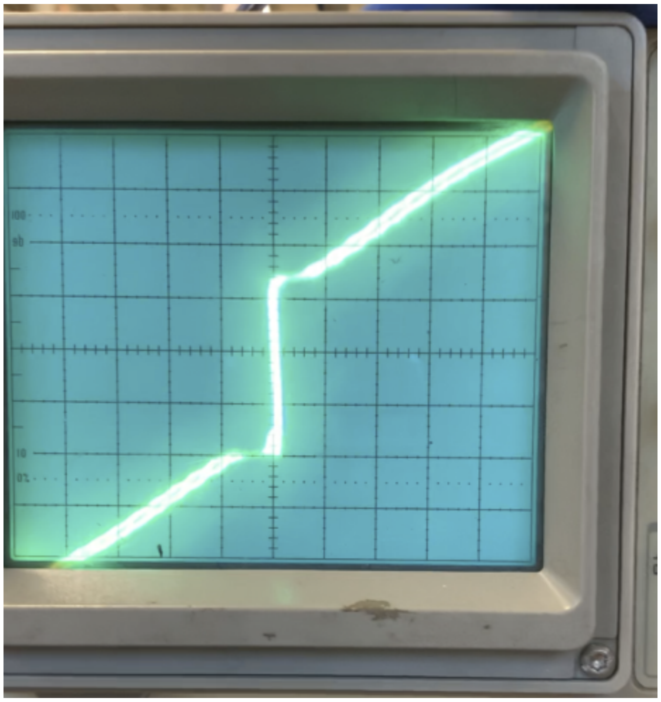

FIG. 6. The observed DC Effect from our experiment

field, we observed fluctuations on our oscilloscope that corresponded to the large moving magnet.

B. AC Effect

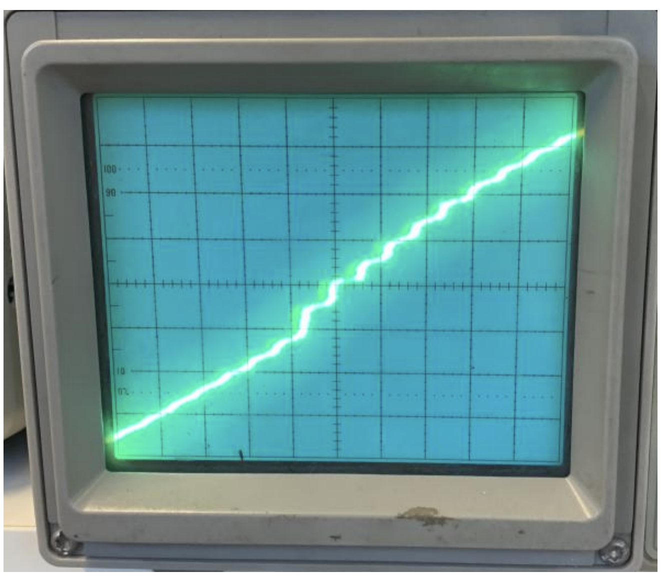

FIG. 7. The observed AC Effect from our experiment

The same instruments were used for observing the AC effect with the addition of a HP 8350B sweep oscillator that sent a microwave signal (9-13 GHz) into the junction. When we confirmed that there was indeed power coming from the oscillator by using an HP 431B Power Meter, we arbitrarily used a frequency around 10 GHz as our basis.

The irradiation of a microwave signal is important for us to observe the AC effect because it is at these frequencies where the JJ resonates. When carefully adjusting the power/attenuation from the oscillator, pressure at the PCJ, and frequency of the oscillator we were able to observe the AC effect as seen in Figure 7. We ran the same test with the large magnet to confirm our observation really was the AC effect. We surprising found that adjusting the absorption cavity made no changes to the output signal.

C. Calibrations

In order to properly calibrate our output signal, we use a signal generator with a known output ($517\mu V \pm 50ppm$). We calibrated our signal by running the known output and measuring the nominal gain of the system. We set the amplifier to a gain of 500x, but in our calibrations we measured a gain of 496.7 ± 0.0147 by measuring the bias voltage of the input and measuring the output the calibration device with a Fluke 8842A Digit Multimeter. This calculated gain was accounted for in our AC effect.

D. Calculated Ratio of Fundamental Constants

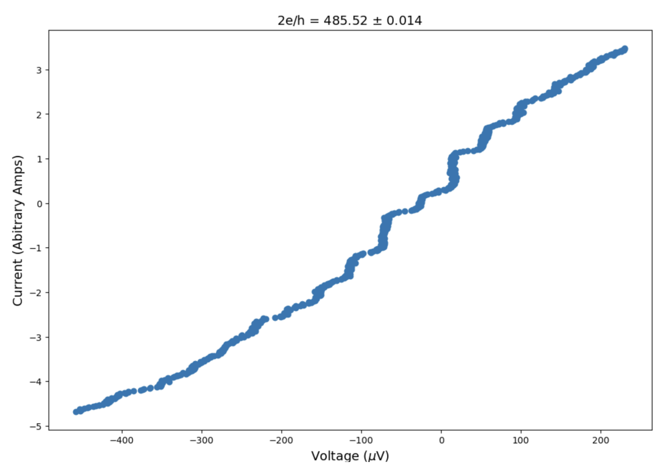

FIG. 8. The observed AC Effect from our experiment plotted with Python. We identified 12 steps in a voltage range of about 684.8 μV.

To calculate the ratio of fundamental constants $\frac{e}{\hbar}$, we used the equation:

$$\frac{2e}{\hbar} = \frac{2fn}{V} \tag{2}$$

where f is the frequency of the sweep oscillator, V is our chosen voltage range, and n is the number of steps from within that voltage range. Figure 8 is out plot from the data we took with the lab computers. After calibrating the output by dividing by the calculated gain, we measured a value of $485.5 \pm 0.014\ \frac{MHz}{\mu V}$.

IV. CONCLUSION

We were able to calculate an accurate ratio compared to Parker, Taylor and Langenberg. This ratio is important because it gives us insight into the laws of superconductivity. The carefulness with practiced in our procedures is reflected by the quality of our data. The microwaves are important for this experiment because the JJ had a characteristic resonance frequency in the microwave frequency range, which is why we did not use another frequency range.