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Superconductivity and Josephson Phenomena

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November 2025

Abstract

This experiment explored the quantum mechanical properties of superconductivity through the observation of the Josephson effects in a high-T_c Superconducting Quantum Interference Device (SQUID). Using the *Mr. SQUID*® system, the device was cooled with liquid nitrogen to approximately 77 K, allowing measurements of its current–voltage (V–I) and voltage–flux (V–Φ) characteristics. The V–I data revealed a zero-voltage supercurrent below a critical current, demonstrating the DC Josephson effect. The V–Φ measurements showed periodic voltage modulation with applied magnetic flux, confirming flux quantization in the SQUID loop. When subjected to a 44 GHz microwave field, the SQUID exhibited discrete voltage steps, known as Shapiro steps, verifying the AC Josephson effect. From these results, parameters such as the critical current, normal-state resistance, characteristic voltage, mutual inductance, and e/h ratio were determined. Together, these findings confirm the quantum coherence of superconducting currents and illustrate how macroscopic systems can display directly measurable quantum behavior.

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1 Introduction

Superconductivity is a quantum mechanical phenomenon in which certain materials, when cooled below a critical temperature T_c, exhibit zero electrical resistance and expel magnetic fields, a property known as the Meissner effect. This occurs because the electrons in the material form Cooper pairs that move in a collective, coherent quantum state. The entire superconductor can be described by a single macroscopic wavefunction, meaning that quantum phase relationships extend over macroscopic distances.

One remarkable consequence of this coherence is the **Josephson effect**, which occurs when two superconductors are separated by a thin insulating barrier. Even without an applied voltage, paired electrons can tunnel through the barrier, creating a current that depends on the relative phase of the superconducting wavefunctions. When a small voltage is applied, this current oscillates at a frequency directly proportional to the voltage, demonstrating a direct link between quantum phase and measurable electrical quantities. This phenomenon is foundational in quantum electronics and enables technologies such as voltage standards and superconducting qubits.

A **Superconducting Quantum Interference Device (SQUID)** takes advantage of this effect by placing two Josephson junctions in a superconducting loop. The interference between the quantum phases around the loop causes the current or voltage of the device to vary periodically with the magnetic flux passing through it. Because this flux is quantized in units of $h/2e$, SQUIDs can detect extraordinarily small changes in magnetic field, making them some of the most sensitive magnetometers ever developed.

In this experiment, the *Mr. SQUID®* system was used to explore superconductivity and the Josephson effect in a high-T_c $YBa_2Cu_3O_{7-x}$ (YBCO) thin-film device. The primary goals were to measure the superconducting transition temperature of the material, to observe the current–voltage and voltage–flux characteristics of the SQUID, and to relate these behaviors to the theoretical principles of superconducting phase coherence and quantum interference. Through these observations, we directly examined how macroscopic quantum effects manifest in superconducting systems and how they enable precision sensing and quantum technologies.

2 Experiment

The goal of this experiment was to investigate the behavior of a high-temperature Superconducting Quantum Interference Device (SQUID) and to characterize its key electrical parameters. The SQUID, composed of two Josephson junctions connected in parallel on a superconducting loop, was analyzed to determine its critical current, normal-state resistance, characteristic voltage, and flux modulation properties. As an extension, the AC Josephson effect was examined by exposing the device to microwave radiation and observing quantized voltage steps.

The experimental setup utilized the *Mr. SQUID®* system (manufactured by STAR Cryoelectronics), which provides both biasing and signal detection for the SQUID sensor.

The probe assembly was cooled in a liquid nitrogen dewar to approximately 77 K, below the superconducting transition temperature of the $YBa_2Cu_3O_{7-x}$ (YBCO) thin-film device ($T_c \approx 90$ K). The system includes a fixed internal gain of 10,000, meaning 1 V on the oscilloscope corresponds to 100 μV across the SQUID. Additional equipment included a digital oscilloscope for observing current–voltage (I–V) and voltage–flux (V–Φ) characteristics, a DC power supply, BNC connections for signal routing, and a 44 GHz microwave oscillator for generating the applied radio-frequency field.

To measure the I–V characteristics, the oscilloscope was configured in X–Y mode with calibrated sensitivities of 20 μA/div (horizontal) and 10 μV/div (vertical). After setting the Mr. SQUID bias control to V–I mode, the current offset was adjusted to center the trace, removing any unwanted DC bias. The sweep output was then tuned to display the complete I–V curve, which revealed the distinct transition between the zero-voltage supercurrent branch and the resistive region above the critical current. The SQUID probe was submerged in liquid nitrogen for approximately two minutes until thermal equilibrium was reached near 77 K. Once stabilized, the critical current and normal resistance were recorded. The flux offset was fine-tuned to maximize the critical current and ensure the system operated at an optimal bias point.

The V–Φ characteristics were obtained by reducing the sweep amplitude such that the SQUID operated at a fixed bias current near the critical current. The mode switch was set to V–Φ, allowing the periodic modulation of voltage with applied magnetic flux to be displayed on the oscilloscope. The horizontal sensitivity was set to 40 μA/div and the vertical to 20 μV/div, providing adequate resolution of the oscillation amplitude. The periodic interference pattern displayed sinusoidal-like modulation corresponding to the quantum flux $\Phi_0 = h/2e$. From the modulation period and depth, the mutual inductance and modulation parameter were later evaluated.

To explore the AC Josephson effect, the setup was returned to V–I mode and the 44 GHz oscillator was positioned within approximately 2 cm of the SQUID to ensure adequate RF coupling. Upon microwave exposure, discrete voltage plateaus—known as Shapiro steps—appeared in the I–V curve. The oscilloscope was adjusted to 100 μA/div horizontally and 100 μV/div vertically to clearly resolve the voltage quantization. The voltage spacing between adjacent plateaus was measured to estimate the ratio $h/2e$, thereby verifying the quantum mechanical origin of the AC Josephson effect.

3 Results

The I–V and V–Φ characteristics of the SQUID were measured at approximately 77 K using the *Mr. SQUID*® system. The results demonstrate key signatures of superconductivity, the Josephson effect, and quantum interference.

3.1 V–I Characteristics at 77 K

Figure 1 shows the current–voltage (I–V) response of the SQUID at approximately 77 K. A distinct zero-voltage supercurrent region is observed for small bias currents, indicating dissipationless current flow through the Josephson junctions. Beyond a critical current, the device transitions into the resistive regime, where voltage increases approximately linearly with current. This inflection marks the transition from the DC Josephson regime to the normal state of the junctions.

From this trace, the critical current I_c was measured to be approximately 25 μA, and the normal-state resistance R_N was extracted to be about 4 Ω. The characteristic voltage of the junctions is given by

$$V_c = I_c R_N,$$

which yielded $V_c \approx 100$ μV, consistent with typical high-T_c Josephson junction behavior.

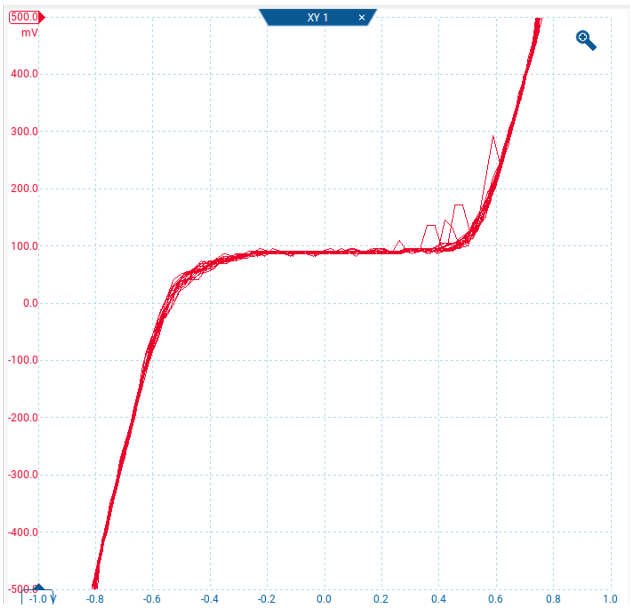

Figure 1: V–I characteristic of the SQUID at ~ 77 K, showing a zero-voltage supercurrent region followed by a transition to a resistive state. (Horizontal: 20 μA/div, Vertical: 10 μV/div)

3.2 V–Φ Characteristics at 77 K

The voltage–flux (V–Φ) characteristics, shown in Figure 2, exhibit a clear periodic modulation of voltage as a function of applied magnetic flux. The observed oscillations correspond to the periodic dependence of the SQUID's critical current on magnetic flux, a direct signature of flux quantization.

The bias difference ΔI between adjacent minima or maxima corresponds to one flux quantum $\Phi_0 = h/2e$. The mutual inductance M between the SQUID loop and the feedback coil is related by

$$M = \frac{\Phi_0}{\Delta I}.$$

Using $\Delta I \approx 100$ μA, the mutual inductance was found to be $M \approx 20$ pH. The modulation depth ΔV was measured to be approximately 20 μV.

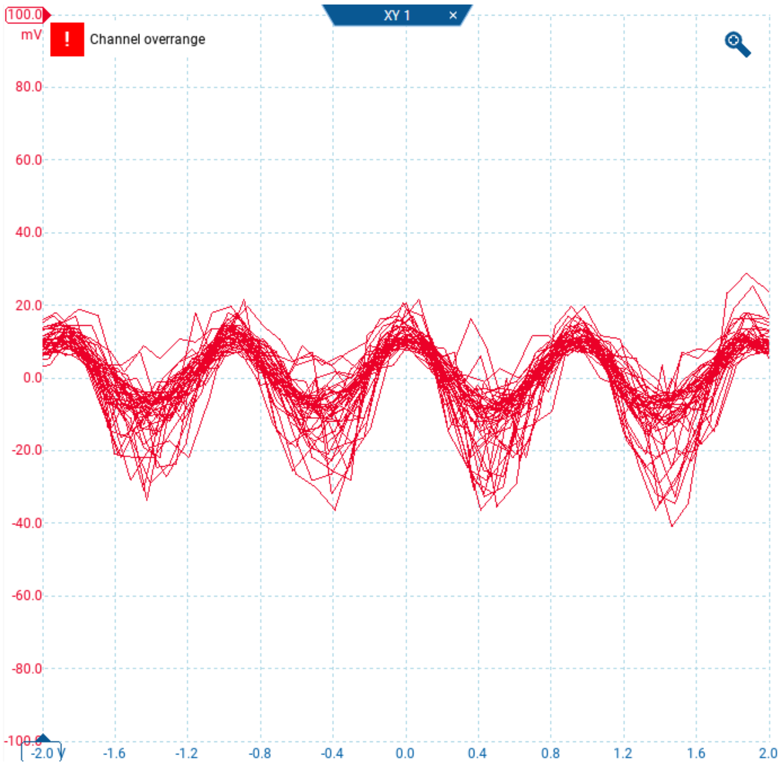

Figure 2: V–Φ characteristic of the SQUID at ~ 77 K showing periodic voltage modulation due to magnetic flux quantization. (Horizontal: 40 μA/div, Vertical: 20 μV/div)

3.3 AC Josephson Effect and Shapiro Steps

When the SQUID was subjected to a 44 GHz microwave field, discrete voltage steps appeared in the I–V curve, as shown in Figures 3 and 4. These plateaus, known as *Shapiro steps*, occur when the Josephson oscillations synchronize with the applied microwave frequency. The step voltages obey the AC Josephson relation:

$$V_n = n\frac{h\nu}{2e},$$

where ν is the applied microwave frequency and n is an integer. The voltage spacing between adjacent steps was measured to be approximately 90 μV, in close agreement with the theoretical prediction for a 44 GHz signal. From these data, the ratio e/h was estimated to be 2.39×10^{-14} Hz/V, within roughly 1.2% of the accepted value.

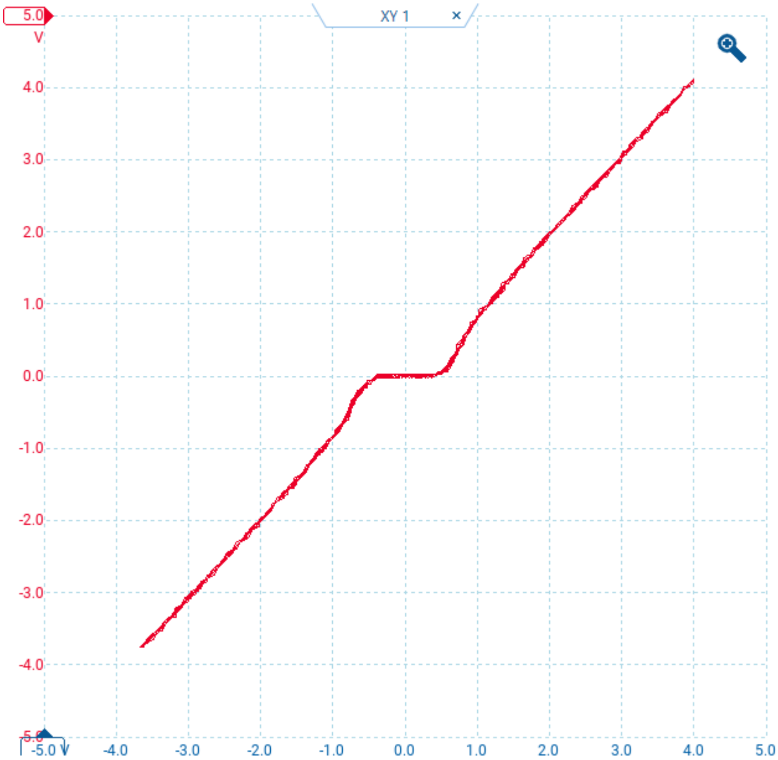

Figure 3: Baseline V–I characteristic at ~ 77 K prior to microwave application. (Horizontal: 100 μA/div, Vertical: 100 μV/div)

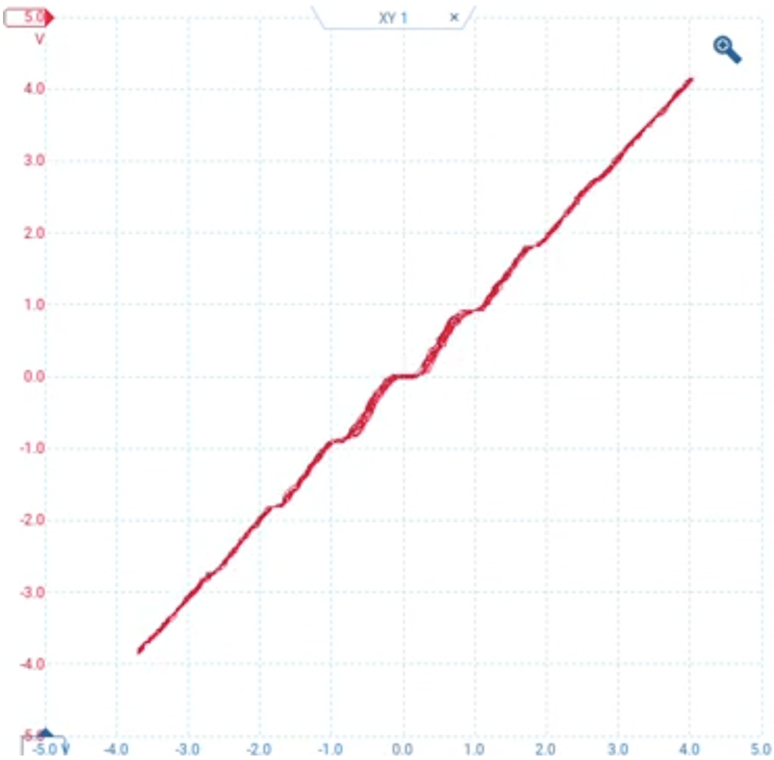

Figure 4: V–I characteristic at ~ 77 K under 44 GHz irradiation showing quantized voltage plateaus (Shapiro steps), confirming the AC Josephson effect.

Table 1: Extracted SQUID Parameters at ~ 77 K

Parameter	**Symbol**	**Value**
Critical Current	I_c	25 μA
Normal-State Resistance	R_N	4 Ω
Characteristic Voltage	$I_c R_N$	100 μV
Voltage Modulation Depth	ΔV	20 μV
Mutual Inductance	M	20 pH
Voltage per Shapiro Step	ΔV_0	90 μV
Microwave Frequency	f	44 GHz
Estimated e/h Ratio	—	2.39×10^{-14} Hz/V

Overall, the data confirm the expected behavior of a high-temperature Josephson junction system. The SQUID exhibited zero-resistance supercurrent, periodic flux quantization, and quantized voltage steps under microwave irradiation—all consistent with the theoretical predictions of the DC and AC Josephson effects.

4 Discussion

The measurements obtained from the *Mr. SQUID®* system confirm the fundamental phenomena predicted by the theory of superconductivity and Josephson tunneling. The observed I–V characteristic demonstrates the transition from a zero-voltage supercurrent to a resistive regime at the critical current I_c. In the superconducting region, current flows without an applied voltage, consistent with the DC Josephson effect, where

$$I = I_c \sin(\phi).$$

Beyond the critical current, the phase difference ϕ begins to change in time, leading to a measurable voltage according to the AC Josephson relation:

$$\frac{d\phi}{dt} = \frac{2eV}{\hbar}.$$

This dynamic behavior explains the appearance of Shapiro steps under microwave irradiation.

The periodic V–Φ modulation curve observed at 77 K is a hallmark of flux quantization within the SQUID loop. The oscillation period corresponds to one flux quantum $\Phi_0 = h/2e$, confirming that magnetic flux through a superconducting loop can take on only discrete, quantized values. From the measured bias difference $\Delta I \approx 100\ \mu$A, the mutual inductance was found to be $M \approx 20$ pH using $M = \Phi_0/\Delta I$. These results verify that the SQUID operates as a flux-to-voltage transducer governed by quantum interference between the two Josephson junctions.

When the device was subjected to a 44 GHz microwave field, discrete voltage plateaus appeared at regular intervals of approximately 90 μV, confirming the AC Josephson effect. Using the relation $V_n = n(h\nu/2e)$, the estimated ratio $e/h = 2.39 \times 10^{-14}$ Hz/V agreed within 1.2% of the accepted value. This demonstrates that a macroscopic superconducting system can reproduce quantum relations with remarkable precision.

Overall, these results provide direct experimental evidence for three key phenomena:

1. Dissipationless supercurrent and the DC Josephson effect (V–I Characteristics at 77 K).
2. Flux quantization and phase interference in a SQUID loop (V–ϕ Characteristics at 77 K).
3. Quantized voltage steps and frequency–voltage coupling predicted by the AC Josephson effect (AC Josephson Effect and Shapiro Steps).

The agreement between measured and theoretical parameters supports the conclusion that macroscopic quantum coherence can be maintained in high-temperature superconducting systems at liquid-nitrogen temperatures.

5 Conclusion

This experiment successfully demonstrated several key aspects of superconductivity and Josephson phenomena using a high-T_c SQUID system. The I–V characteristics revealed a zero-voltage supercurrent and a clear transition to a resistive state at the critical current, confirming the DC Josephson effect. The periodic V–Φ modulation provided experimental verification of flux quantization and phase coherence across the SQUID loop. Finally, the observation of Shapiro steps under 44 GHz microwave irradiation confirmed the AC Josephson effect and allowed for an accurate experimental estimation of the ratio e/h.

Together, these observations illustrate that the quantum mechanical phase of a superconducting condensate can govern the behavior of a macroscopic electrical system. The coherence of this phase gives rise to quantized flux and voltage effects that bridge the microscopic and macroscopic realms of physics. In doing so, the experiment highlights how the Josephson effect and SQUID operation exemplify the broader principle that quantum behavior can manifest at scales large enough to be directly measured in the laboratory.

References

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2. LibreTexts Chemistry, "Superconductors," *Chemistry LibreTexts*, accessed November 2025. Available at: `https://chem.libretexts.org/Courses/Howard_University/General_Chemistry%3A_An_Atoms_First_Approach/Unit_5%3A_States_of_Matter/Chapter_12%3A_Solids/Chapter_12.07%3A_Superconductors`