From SLUGs to macroscopic quantum phenomena

Research at Cambridge University: My Route to UC Berkeley

Research at UC Berkeley

Macroscopic variable

Energy-Level Quantization

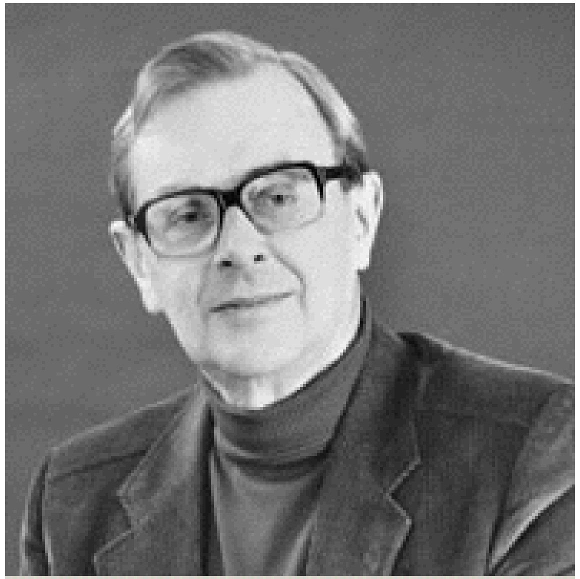
Macroscopic Quantum Tunneling

Research at Cambridge University

The Royal Society Mond Laboratory

Free School Lane
Cambridge
England

1 October 1964

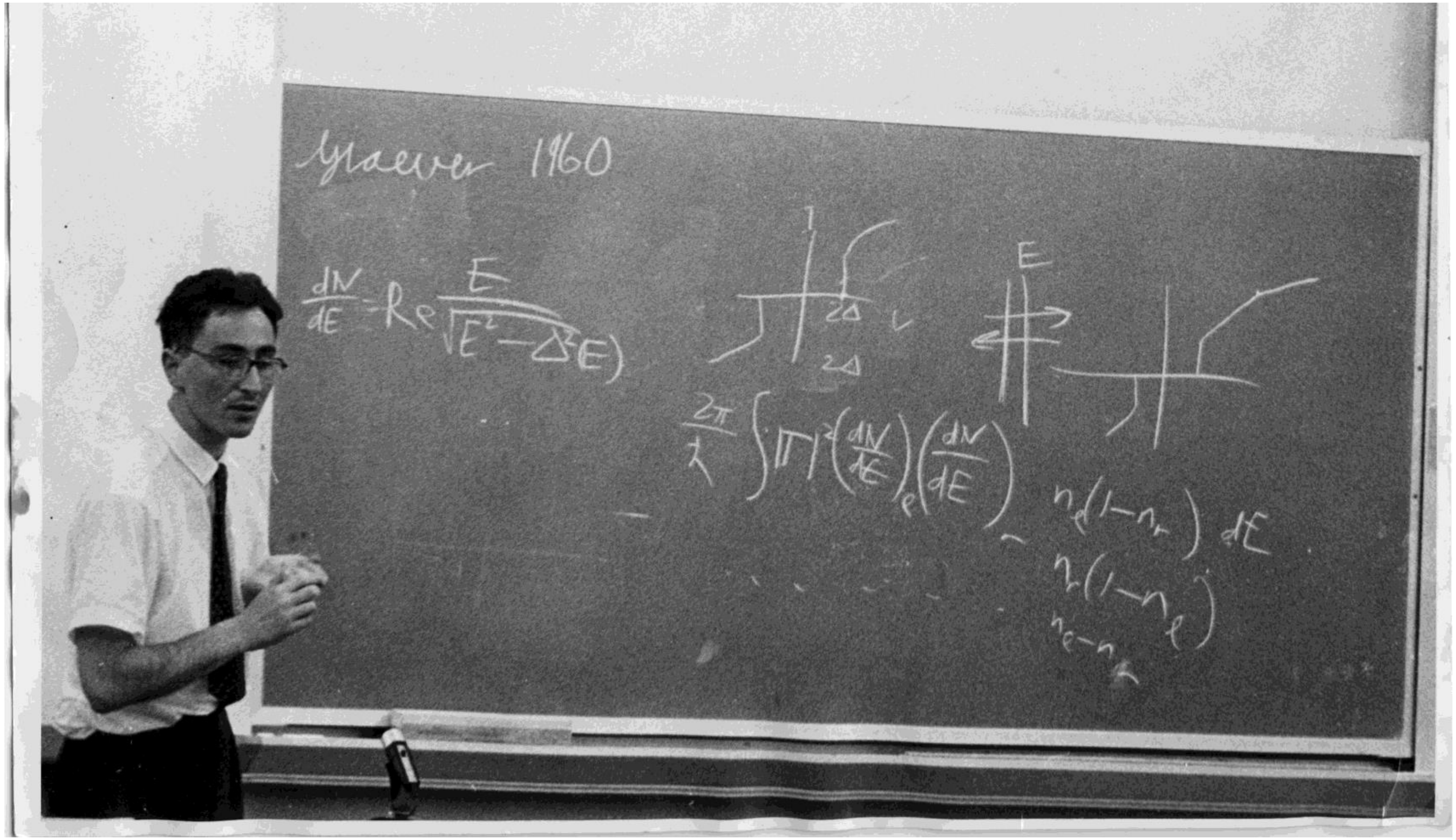


Thesis advisor: Brian Pippard

My thesis research required measuring voltages of 10^{-12} to 10^{-13} volt

State-of-the-art 10^{-9} volt

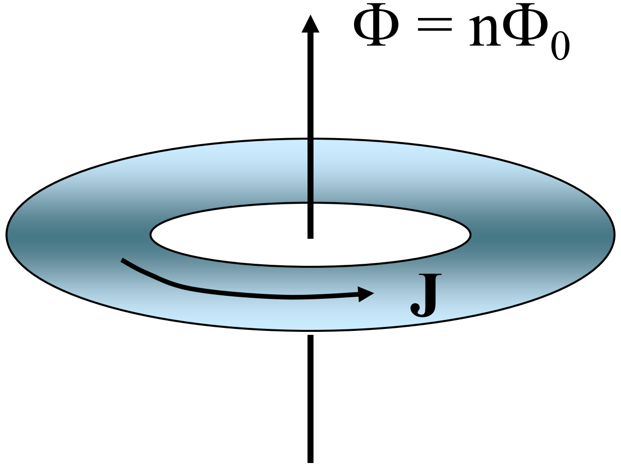
Brian Josephson Explains Josephson Tunneling



November 1964

Courtesy Brian Josephson

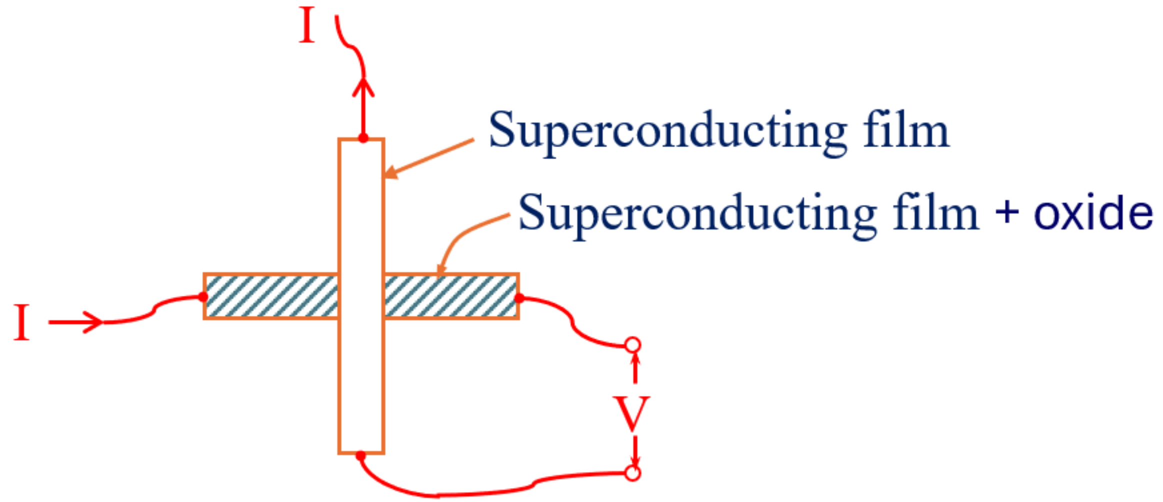
Flux Quantization



$\Phi = n\Phi_0$ ($n = 0, \pm 1, \pm 2, \ldots$)
where $\mathbf{\Phi_0 \equiv h/2e} \approx 2 \times 10^{-15}$ Tm^2
is the **flux quantum**

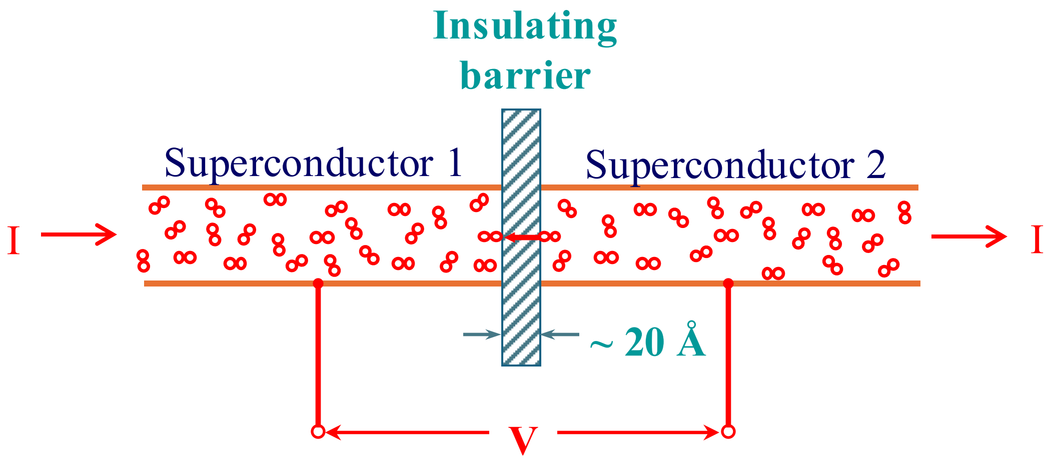
Experimental observation 1961: Deaver and Fairbank
Doll and Näbauer

Josephson Tunnel Junction



- Junction has intrinsic capacitance C

Josephson Tunneling

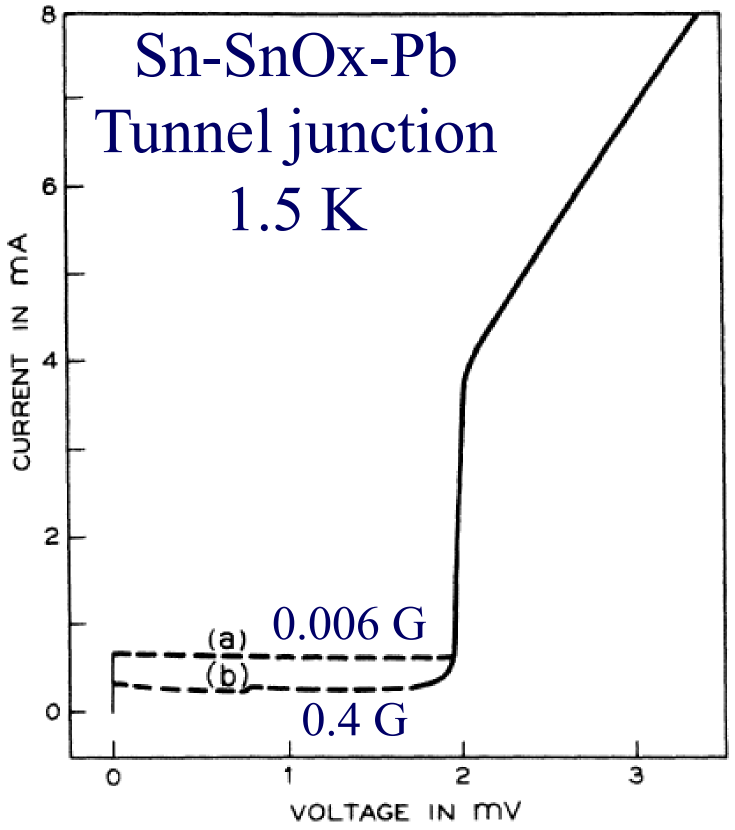


Cooper pairs tunnel through the barrier

δ Is the phase difference across the barrier

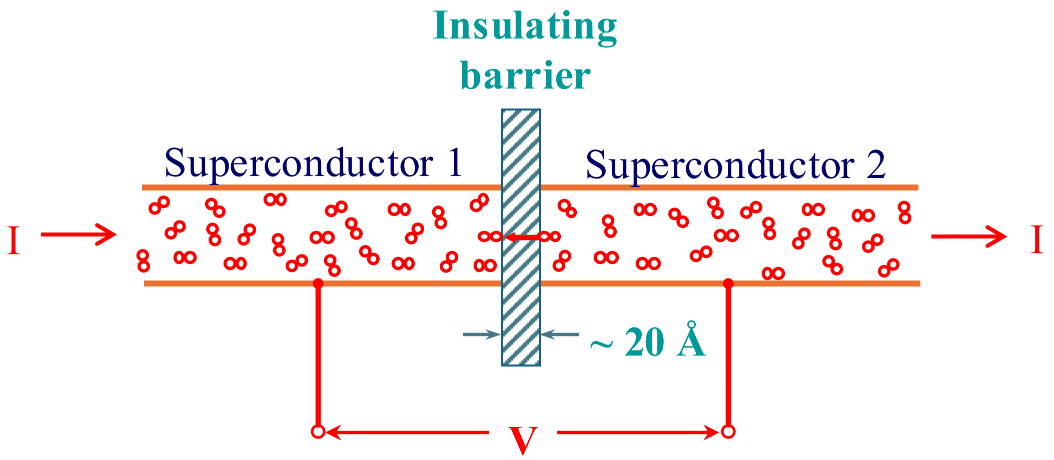
$$I = I_0 \sin\delta$$
$$\delta = \phi_1 - \phi_2$$
$$d\delta/dt = 2eV/\hbar$$
$$= 2\pi V/\Phi_0$$

Josephson 1962



Anderson and Rowell 1963
Bell Labs

Josephson Tunneling



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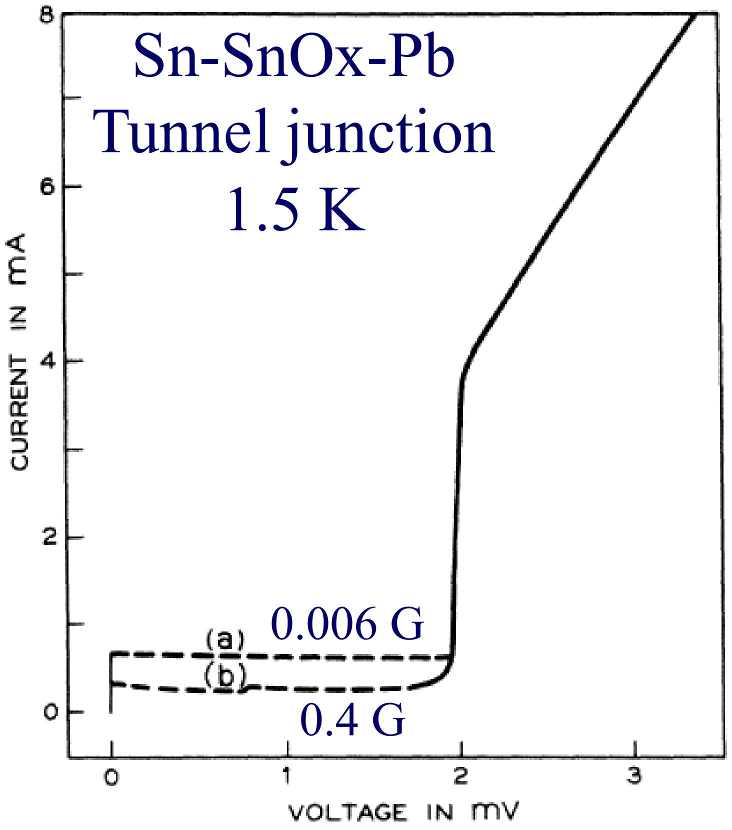
Josephson 1962

First year as a graduate student

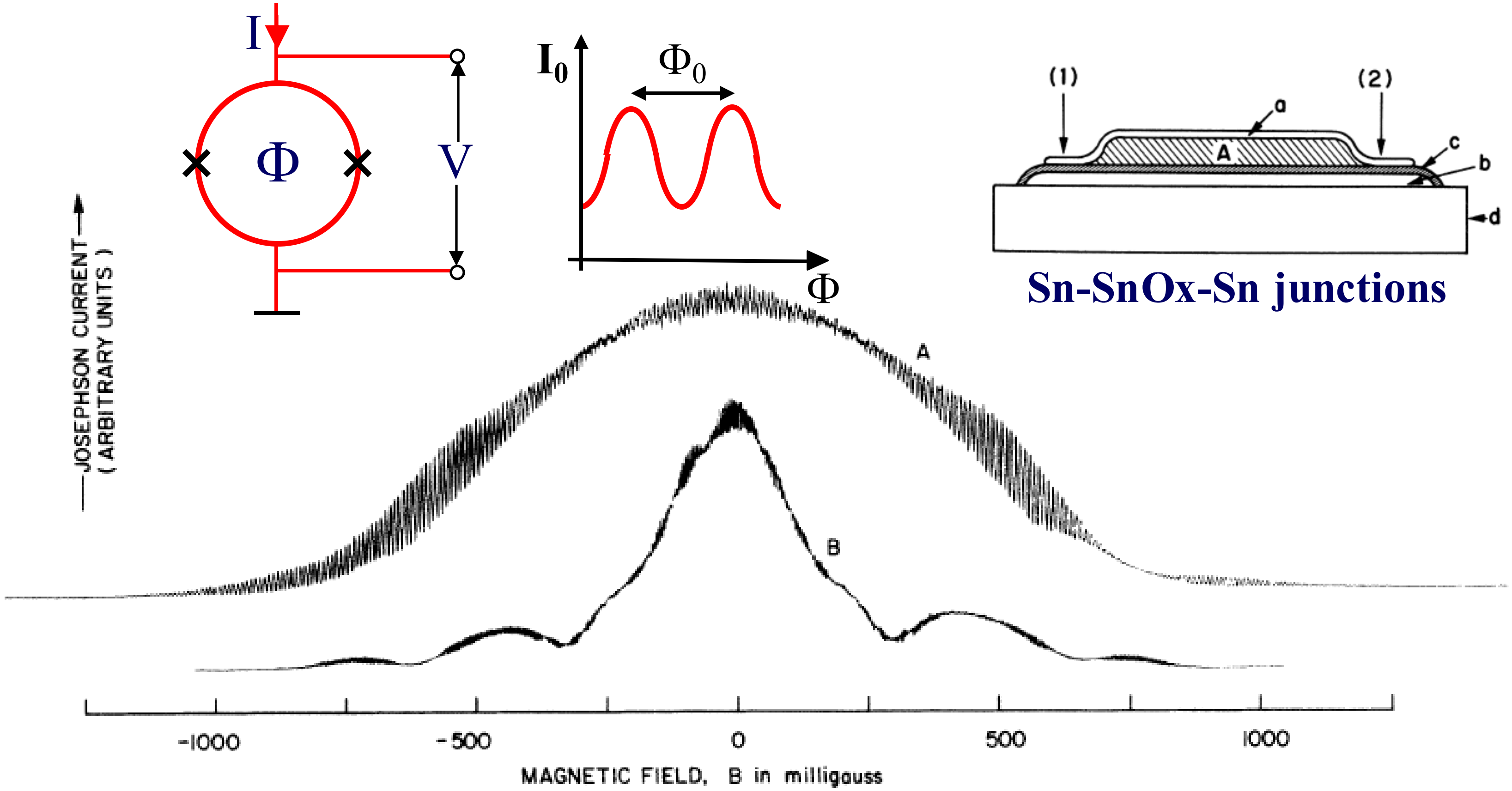
[Nobel Prize 1993]



Anderson and Rowell 1963

Bell Labs

Birth of the Superconducting Quantum Interference Device (SQUID)



Sn-SnOx-Sn junctions

- Critical current versus applied magnetic field for two different junction spacings
- Rapid oscillations due to interference, slow oscillations due to diffraction
- *Essential physics analogous to two-slit interference in optics*
- Sensitive detector of magnetic field

Jaklevic, Lambe, Silver and Mercereau (Ford Motor Company Laboratory, Dearborn, MI) 1964

The Very Next Day

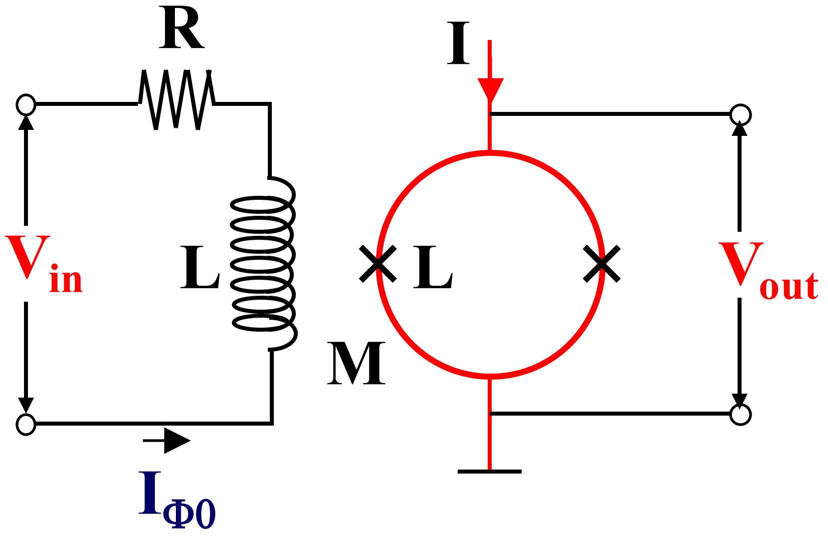
Brian:

“John, How would you like a voltmeter with a resolution of 2×10^{-15} V in 1 second?”

Brian Pippard

November 1964

Brian's Idea



$M = L$

$\tau = L/R$

Digital voltmeter: $I_{\Phi 0} = \Phi_0/M = \Phi_0/L$

Voltage resolution: $V_{in} = I_{\Phi 0}R = (\Phi_0/L)R = \Phi_0/\tau = 2 \times 10^{-15}$ V
for $\tau = 1$ s

Six order of magnitude improvement over the state of the art!

Problem

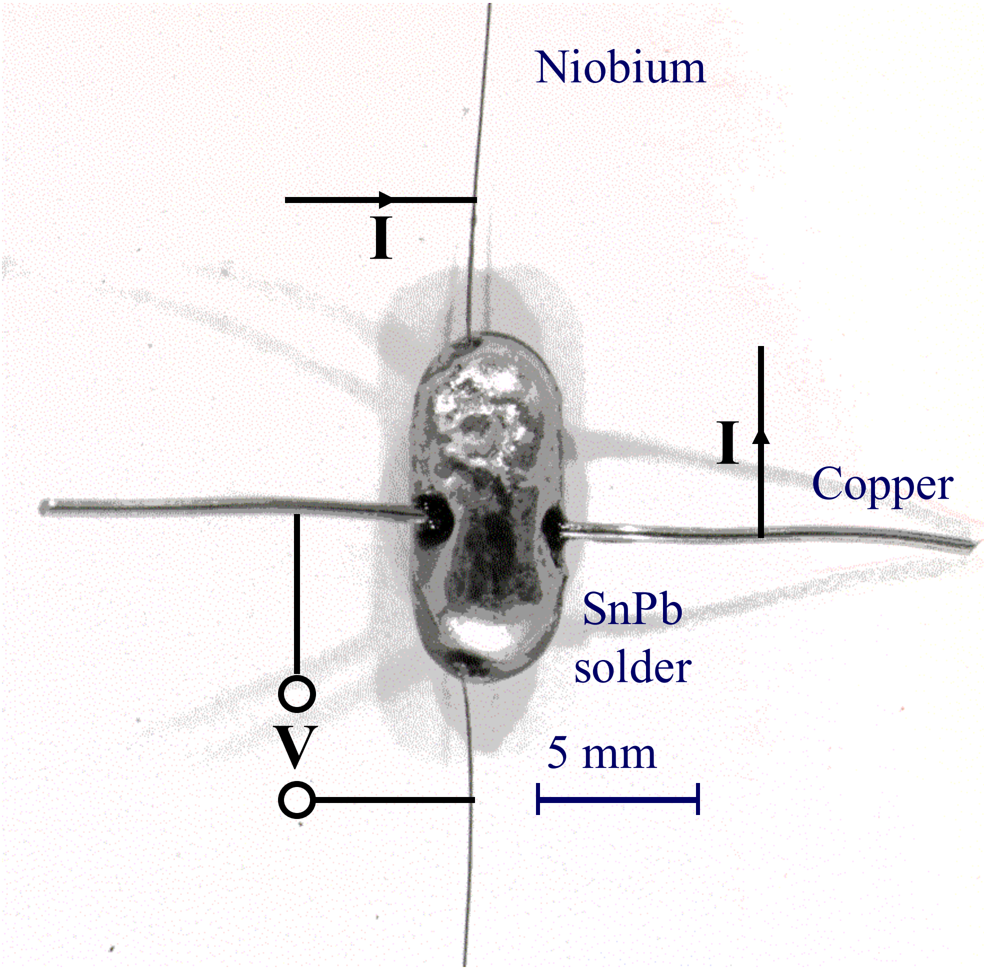
The Mond Laboratory did not possess the equipment to deposit thin films.

I spent several weeks trying to fabricate a Josephson junction from pieces of niobium foil and niobium wire, sometimes soldered together with PbSn solder. None of my attempts was successful.

My problem was solved one day during our tea break when I was expressing my frustration at not being able to make a Josephson junction.

At Tea

- Paul Wraight, a fellow research student, pointed out that Nb has a surface oxide layer and PbSn solder is a superconductor. Why don't you put a blob of solder on a piece of Nb wire?



December 1964

At Tea

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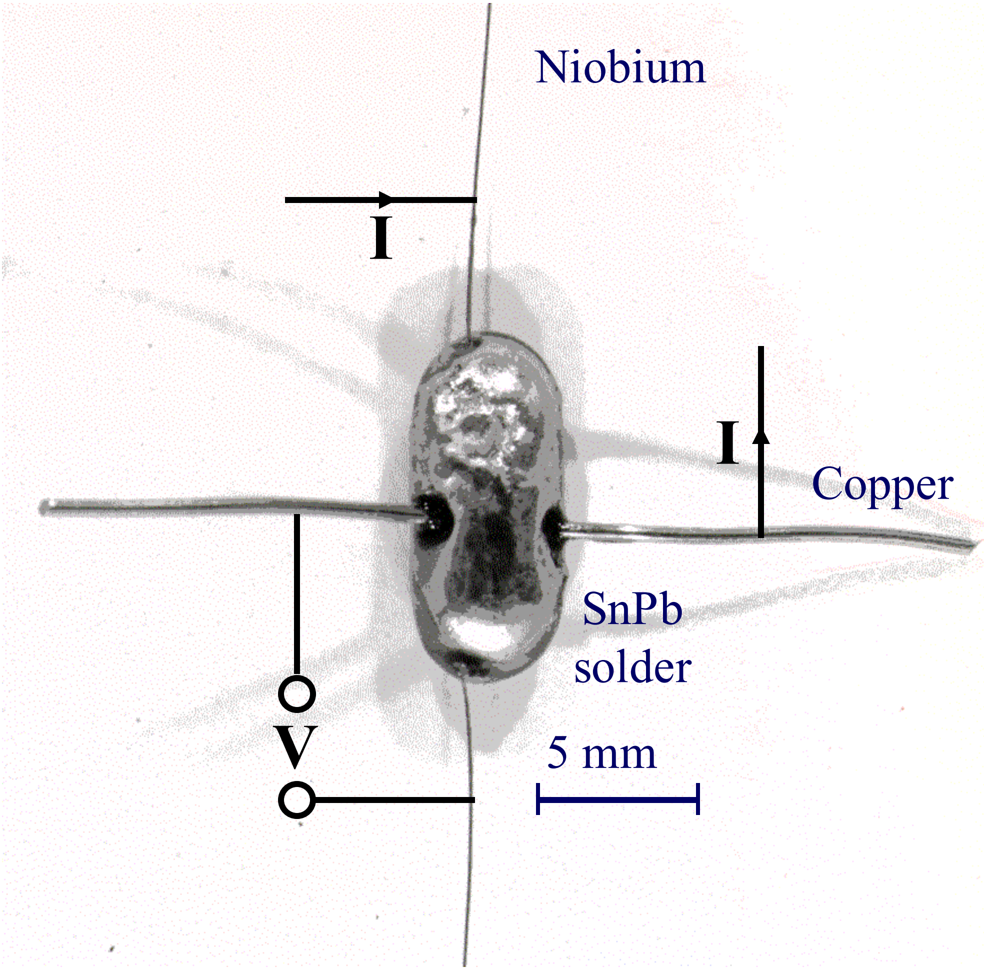
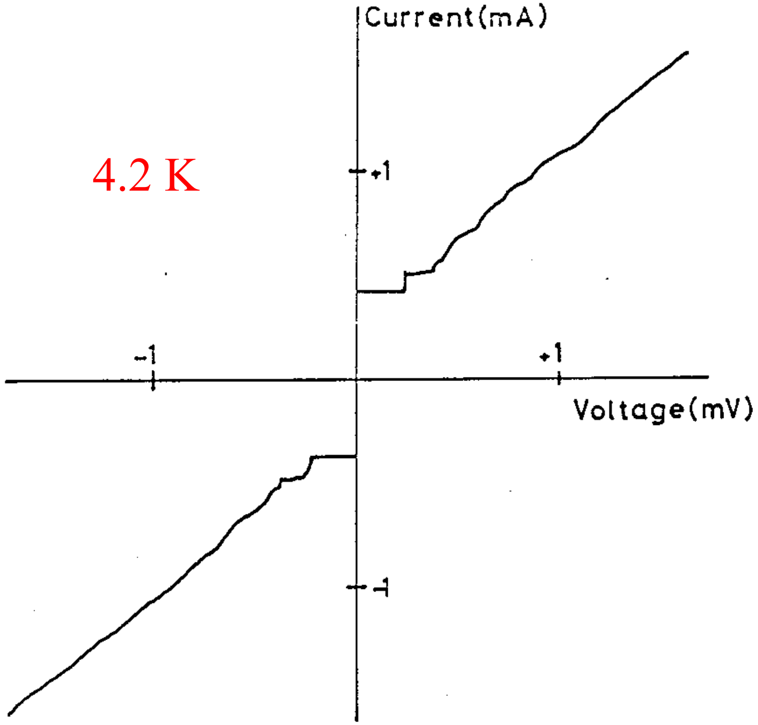
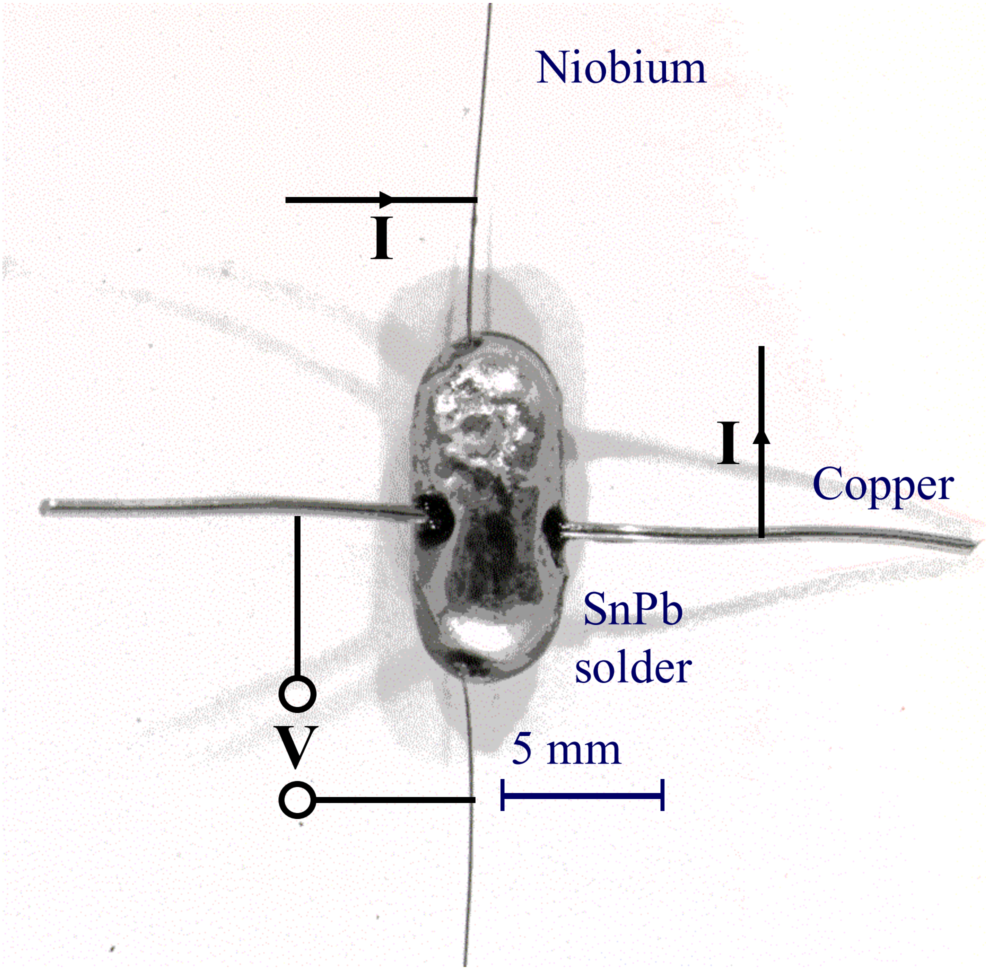


Before dinner



December 1964

The Day After

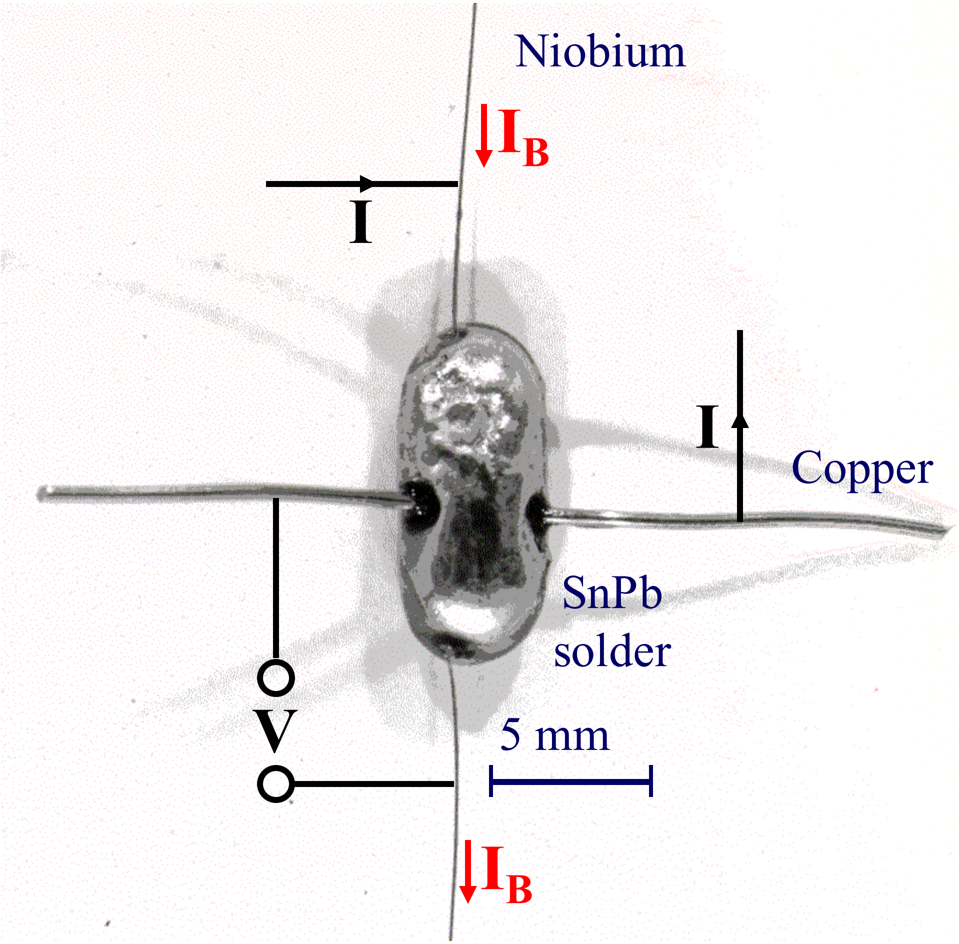


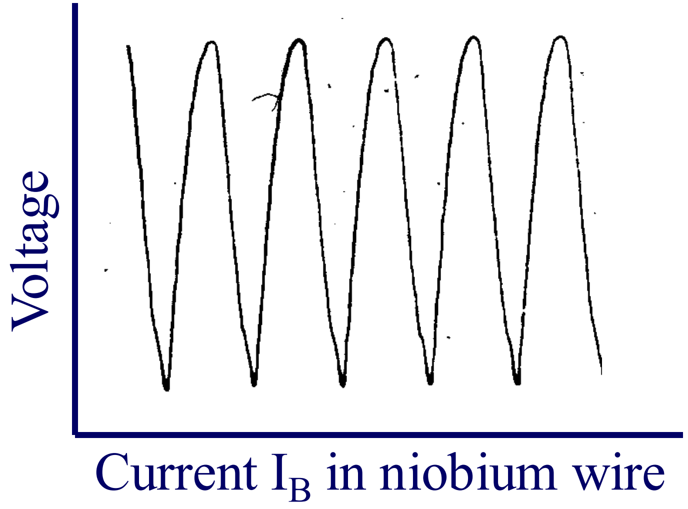
Brian Pippard: “It looks as though a slug crawled through the window last night and expired on your desk!”

SLUG

The SLUG

Superconducting Low-Inductance Undulatory Galvanometer





Analog voltmeter
Voltage noise
(10^{-14} $VHz^{-1/2}$)
February 1965

Paul L. Richards

Some months before I graduated, Paul Richards, a faculty member of the Physics Department at UC Berkeley, came to visit my lab in Cambridge. We had a very long conversation (and lunch) about my research and his research. I really enjoyed meeting him. I had been pondering where to go as a postdoctoral scholar and realized that UC Berkeley would be a great choice. As a result, I ended up there. Paul was the main reason I came to Berkeley. He was a wonderful mentor. He and his family became my close friends. Very sadly, he is no longer with us.

Courtesy Audrey Richards

On January 6, 1968 I moved to the Physics Department at the University of California, Berkeley as a postdoc for one year.

On July 1, 1969 I became a Faculty Member and a Senior Scientist at Lawrence Berkeley National Laboratory, and started my research group.

Research at UC Berkeley

New Group Members

In 1980 John Martinis, who had just received his B.A. at UC Berkeley, joined my group as a Graduate Student.

In 1982 Michel Devoret, who had just received his Ph.D. in France from the University of Orsay, joined my group as a Postdoctoral Scholar.

Tony Leggett’s Question

Do macroscopic variables obey quantum mechanics?

We decided to investigate his intriguing question using a current-biased Josephson junction. The macroscopic variable is the phase difference δ between the superconducting order parameters on either side of the barrier.

Experimental Environment

Our experiment was cooled in a dilution refrigerator to temperatures as low as 18 mK.

We invested a great deal of time adding copper shielding to minimize the level of electrical and magnetic noise reaching the experiment.

Cold end of dilution refrigerator

Superconducting circuit

VOLUME 55, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1985

Energy-Level Quantization in the Zero-Voltage State of a Current-Biased Josephson Junction

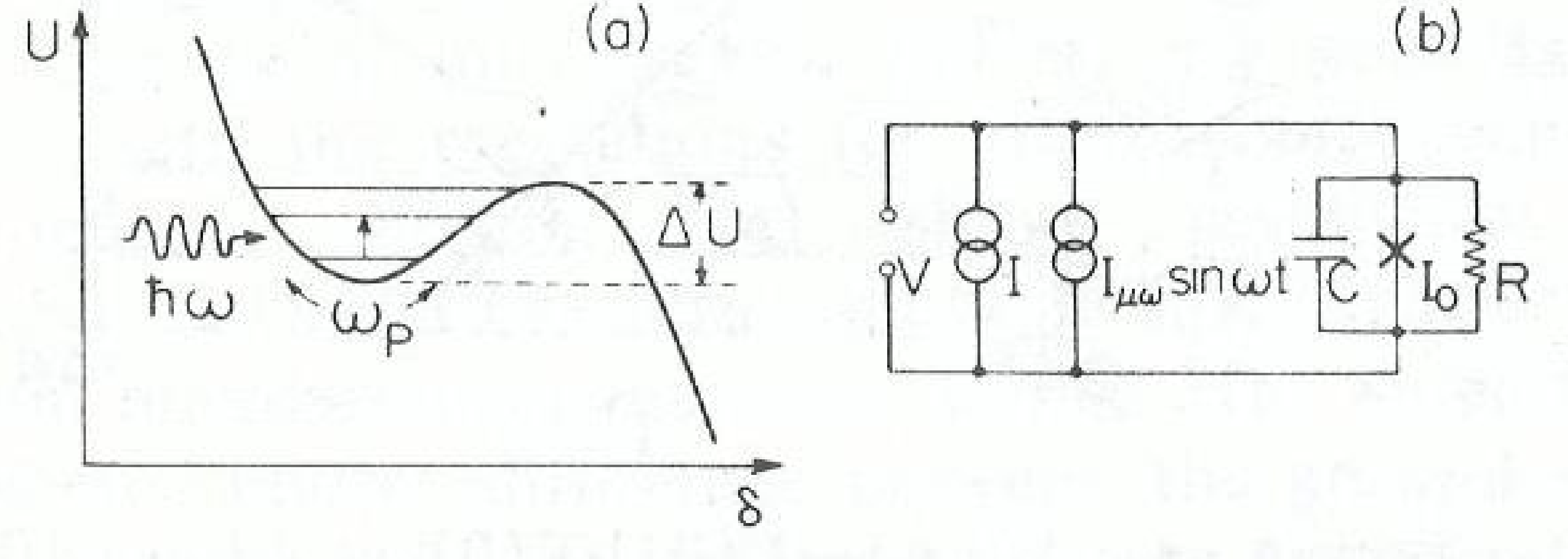
John M. Martinis, Michel H. Devoret,(a) and John Clarke
Department of Physics, University of California, Berkeley, California 94720, and Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720

(Received 14 June 1985)

We report the first observation of quantized energy levels for a macroscopic variable, namely the phase difference across a current-biased Josephson junction in its zero-voltage state. The position of these energy levels is in quantitative agreement with a quantum mechanical calculation based on parameters of the junction that are measured in the classical regime.

Microwave Irradiation in the Quantum Limit

a) Cubic potential *U* vs phase difference δ showing three energy levels. The transition from the ground state is induced to the first excited state by a photon of frequency ω/2π. (b) Model of current-biased Josephson junction shunted by capacitor *C* and resistor *R* and irradiated by external microwaves.



In the zero-voltage state, the plasma frequency $\omega_p/2\pi$ of small oscillations is given by $\omega_p = (2\pi I_0/C\,\Phi_0)^{1/2}[(1 - (I/I_0)^2]^{1/4}$, where $\Phi_0 = h/2e$ is the flux quantum.

We control energy level spacings by adjusting the bias current *I*.

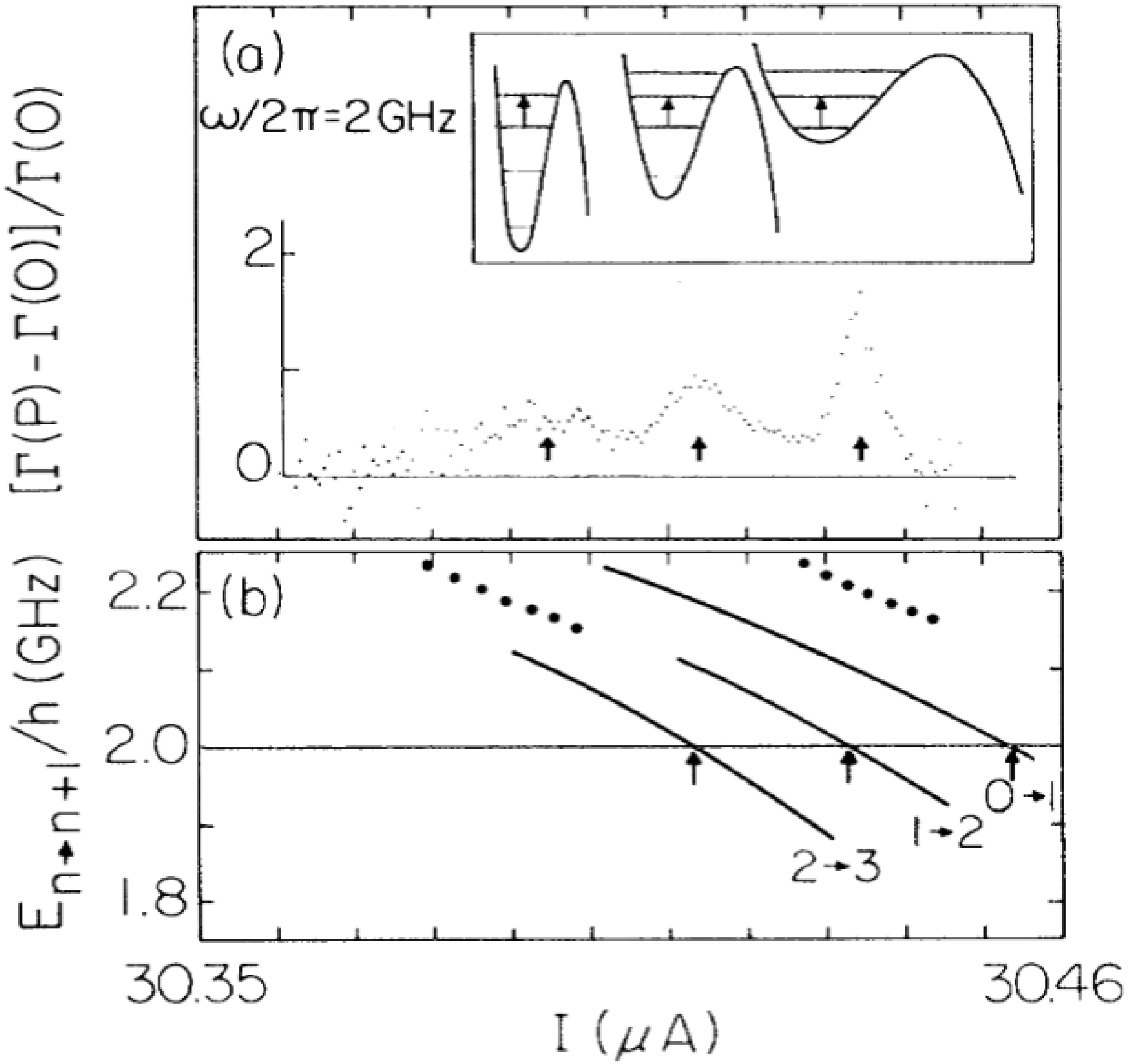
Escape Rate Enhancement by Microwaves

- The escape rate Γ out of the well in the presence of microwaves of power P is resonantly enhanced over that in the absence of microwaves when the microwave frequency corresponds to the spacing between two energy levels.
- Change in the escape rate $[\Gamma(P) - \Gamma(0)]/\Gamma(0)$.

Escape Rate vs. Bias Current

(a) $[\Gamma(P) - \Gamma(0)]/\Gamma(0)$ vs I at 28 mK in the presence of 2.0 GHz microwaves. Arrows indicate the positions of resonances. Inset represents the corresponding transitions between energy levels.

(b) Calculated energy level spacings $E_{n \rightarrow n+1}$ vs I. Dotted lines indicate uncertainties in the $E_{0 \rightarrow 1}$ curve due to errors in I_0 and C. Arrows indicate values of bias current at which resonances are predicted.

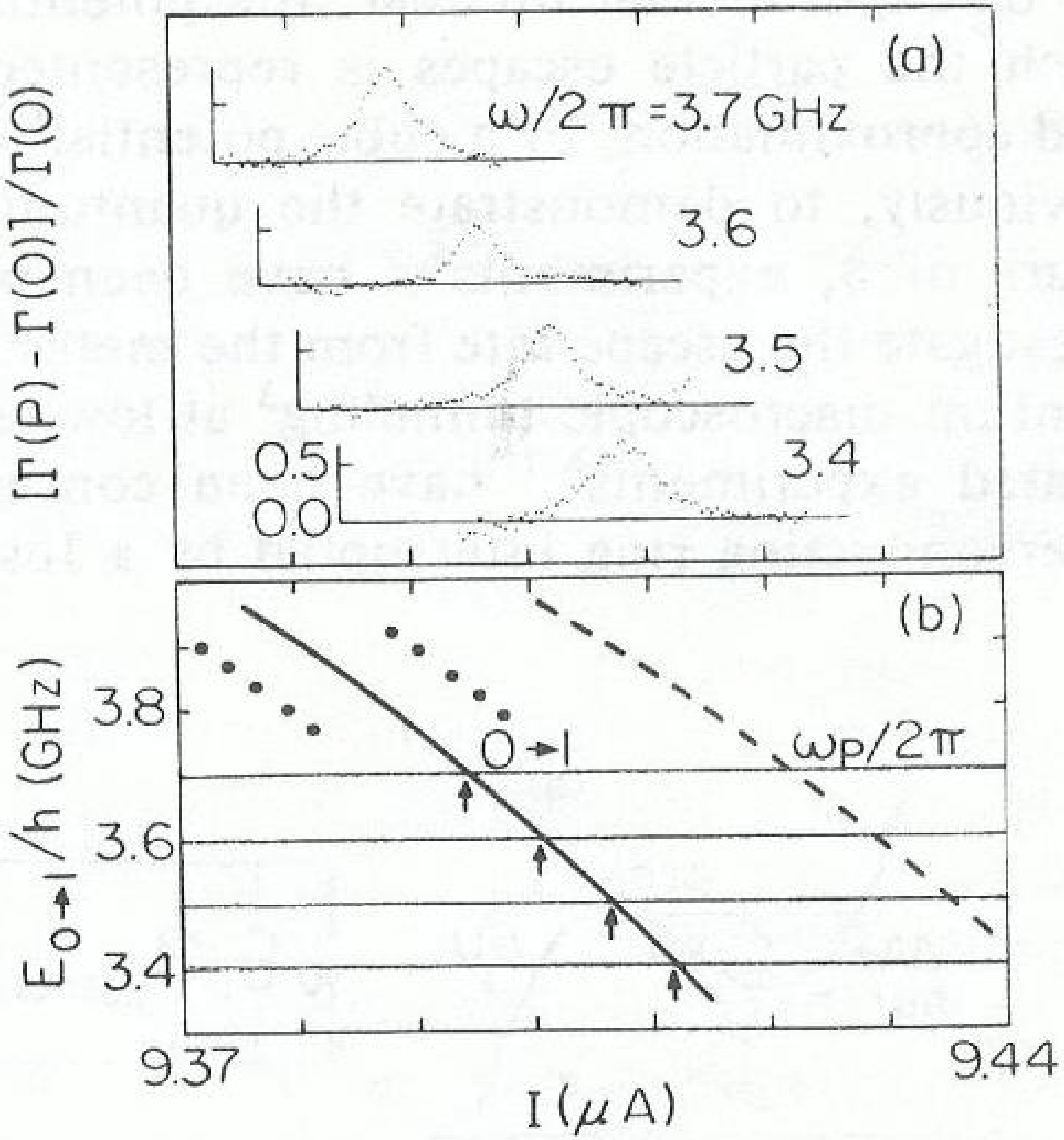


Microwave Frequency Dependence

(a) $[\Gamma(P) - \Gamma(0)]/\Gamma(0)$ vs I for a junction at 28 mK in the presence for four microwave frequencies.

(b) Calculated energy level spacing $E_{0\rightarrow1}$ vs I. Dotted lines indicate uncertainties due to errors in I_0 and C.
Arrows indicate values of bias current at which resonances are predicted.
Dashed line indicates plasma frequency.

The shift in the positions of resonances as the microwave frequency is changed is in excellent agreement with predictions.

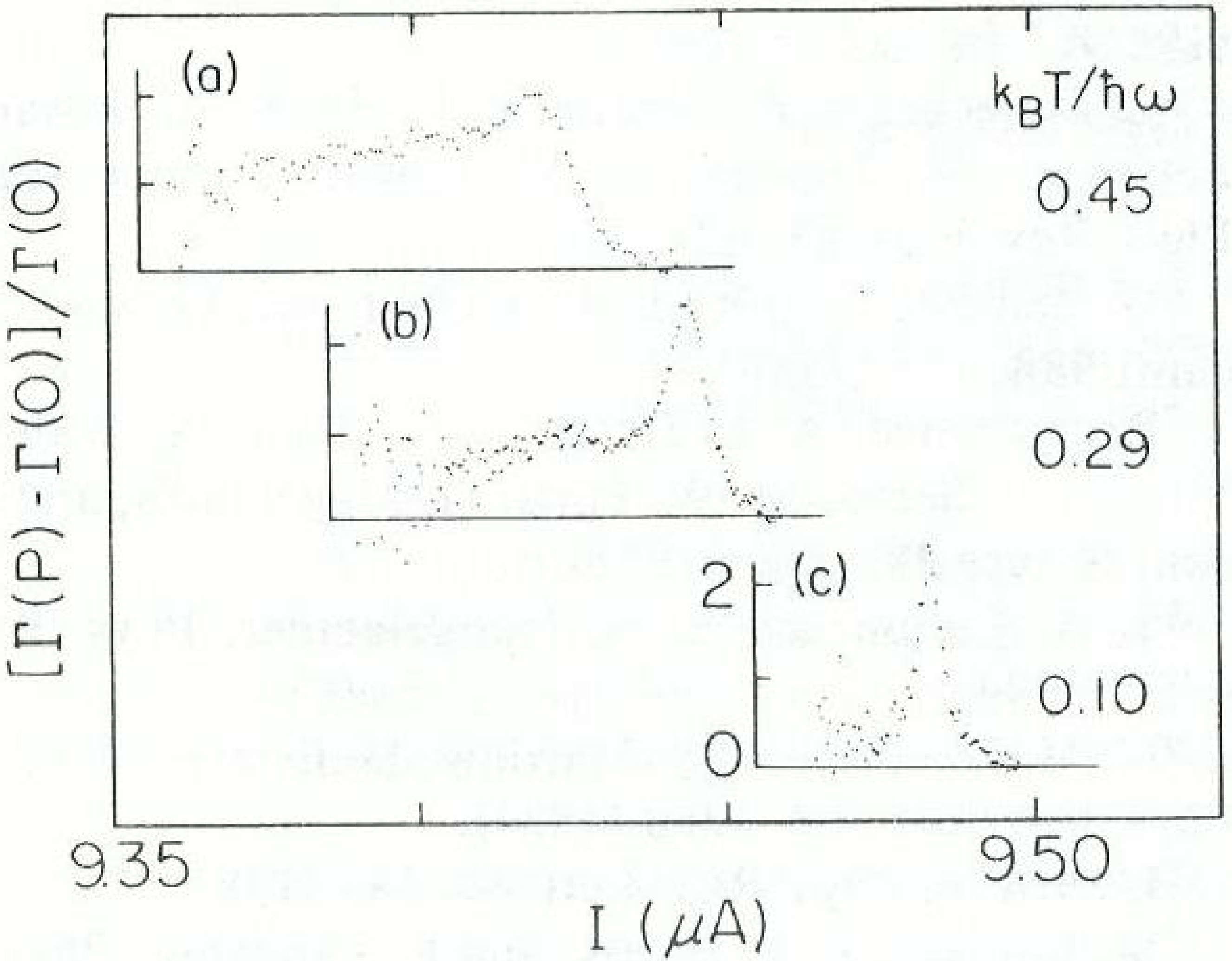


Evolution from Quantum to Classical Behavior

At the lowest temperature (c) the junction was firmly in the quantum limit. We see a single resonance.

At the intermediate temperature (b) an additional shoulder begins to appear.

At the highest temperature (a) the response is a continuum, characteristic of classical behavior.



Summary

- We observed microwave-induced resonant enhancement of the rate at which a current-biased Josephson tunnel junction escapes from the zero-voltage state. The positions of these resonances are in excellent agreement with the predictions of a model in which the energy levels are quantized, with no fitting parameters.
- These results provide very strong evidence for the quantum behavior of the macroscopic variable δ.

VOLUME 55, NUMBER 18 PHYSICAL REVIEW LETTERS 28 OCTOBER 1985

Measurements of Macroscopic Quantum Tunneling out of the Zero-Voltage State of a Current-Biased Josephson Junction

Michel H. Devoret,[a] John M. Martinis, and John Clarke
Department of Physics, University of California, Berkeley, California 94720, and Materials and Molecular Research Division,
Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 26 July 1985)

The escape rate of an underdamped ($Q \approx 30$), current-biased Josephson junction from the zero-voltage state has been measured. The relevant parameters of the junction were determined *in situ* in the thermal regime from the dependence of the escape rate on bias current and from resonant activation in the presence of microwaves. At low temperatures, the escape rate became independent of temperature with a value that, with no adjustable parameters, was in excellent agreement with the zero-temperature prediction for macroscopic quantum tunneling.

Escape of the particle from the quantum well

In the thermal regime ($k_B T >> \hbar\omega_p$), the particle escapes from the well via thermal activation at a rate

$\Gamma_t = a_t(\omega_p/2\pi)\exp(- \Delta U/k_B T)$.

Here, $a_t = 4/[(1 + Qk_B T/ 1.8\,\Delta U)^{1/2} + 1]^2$, where $Q = \omega_p RC$ is the damping factor.

In the quantum regime ($k_B T << \hbar\omega_p$), the escape is predicted to occur via macroscopic quantum tunneling at a rate

$\Gamma_q = (a_q\omega_p/2\pi)\exp[(-7.2\,\Delta U/ \hbar\omega_p)[1 + 0.87/\mathrm{Q}]]$ at $T = 0$.

Here, $a_q = [120\pi(7.2\,\Delta U/\hbar\omega_p)]$.

The crossover temperature at which the escape rate changes from thermal (temperature dependent) to quantum (temperature independent) is predicted to be $\hbar\omega_p/2\pi k_B$ in the limit $\mathrm{Q} >> 1$.

Escape Temperature T_{esc}

To express the experimental measurements of the escape rate in a way that is as independent as possible of the parameters of the junction, we introduce the "escape temperature" T_{esc} defined through the relation

$\Gamma = (\omega_{\mathrm{p}}/2\pi)\exp(-\Delta U/k_{\mathrm{B}}T_{\mathrm{esc}})$.

In the thermal regime, the theoretical prediction is $T_{\mathrm{esc}} = T/(1 - p_t)$,

where the magnitude of $p_t = (k_{\mathrm{B}}T/\Delta U)\ln a_t$, is small compared with unity.

In the quantum regime at $T = 0$, the prediction is

$T_{\mathrm{esc}} = (\hbar\omega_{\mathrm{p}}/k_{\mathrm{B}})/7.2(1+ 0.87/Q)(1- p_q)$ where $p_q = (\hbar\omega_{\mathrm{p}}/7.2\Delta U)\ln a_q$.

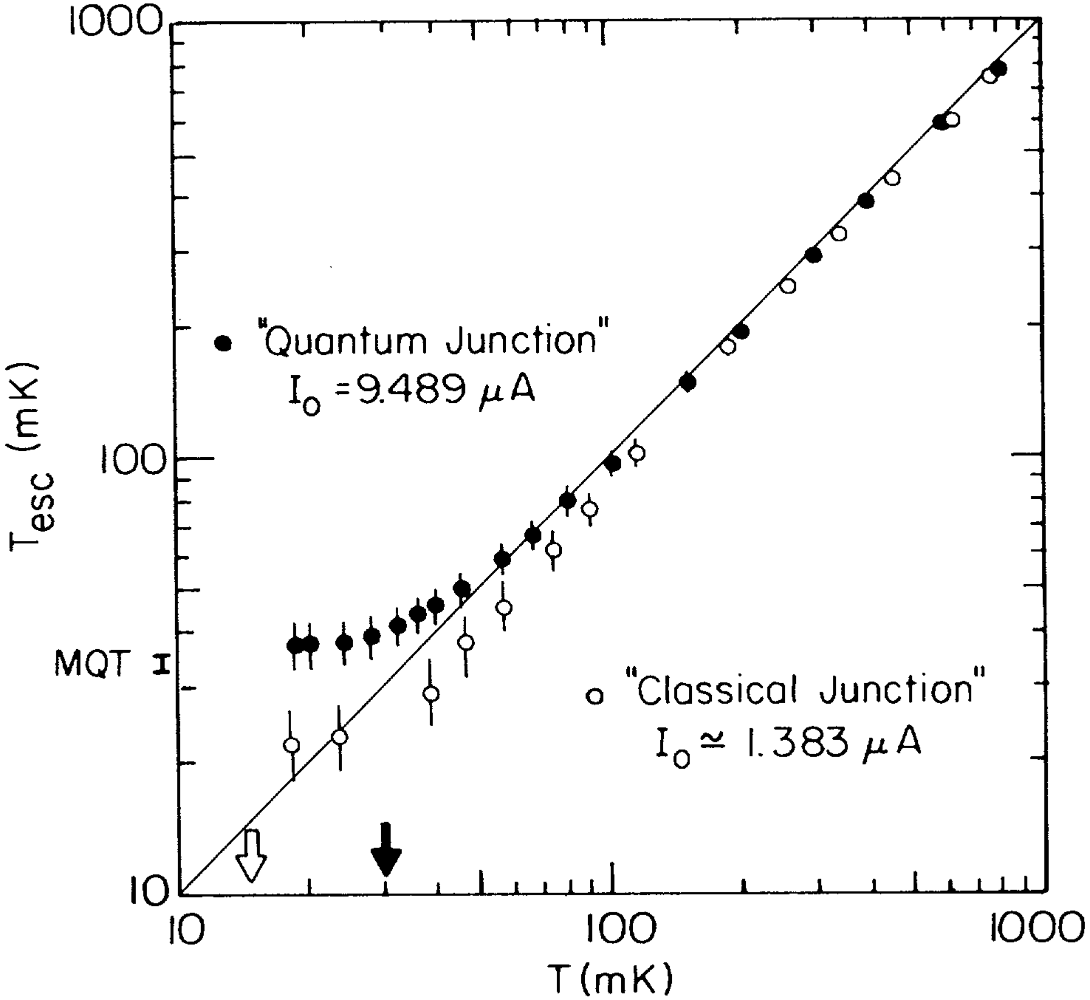
The crossover temperature at which the escape rate changes from thermal (temperature dependent) to quantum (temperature independent) is predicted to be $\hbar\omega_{\mathrm{p}}/2\pi k_{\mathrm{B}}$ in the limit $Q >> 1$.

T_{esc} vs T for two values of critical current for $\ln(\omega_p/2\pi\Gamma) = 11$.

The solid and open arrows indicate the predicted crossover temperature for the higher and lower critical currents, respectively.

The predicted value of T_{esc} for the higher critical current is indicated on the left.

The low temperature values of T_{esc} are in good agreement with the $T = 0$ predictions.



Dependence of T_{esc} on bias current I

In the figures, points are experimental data and solid lines are theoretical predictions. Vertical lines are error bars.

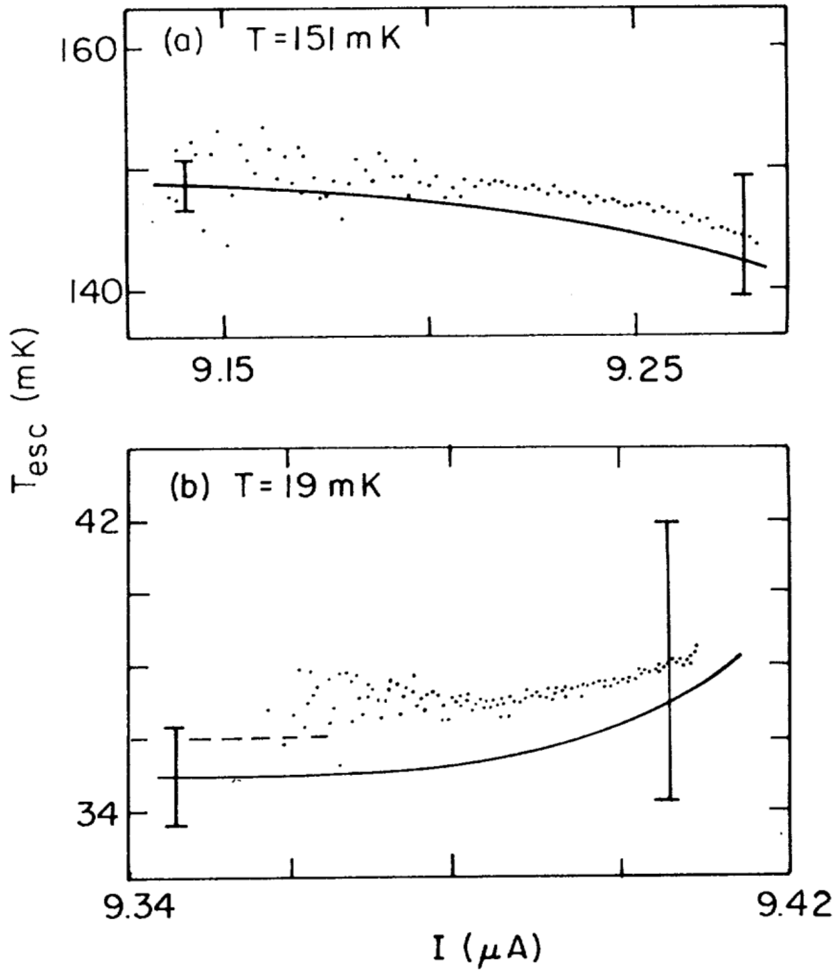
In (a) (T = 151 mK) T_{esc} decreases with increasing bias current because $a_t < 1$.

In (b) (T = 19 mK) T_{esc} increases with increasing bias current through the current dependence of ΔU because $a_q \gg 1$. The current dependence of ω_p is relatively unimportant. The horizontal dashed line is the prediction for zero damping.

Within the experimental uncertainties, the data are in good agreement with theory.

The very different dependence of T_{esc} on bias current in (a) and (b) demonstrates that the escape mechanisms are different in the classical and quantum regimes.

T_{esc} vs I for a junction (a) in the classical regime and (b) in the quantum regime. I_0 = 9.489 μA.



Summary

We measured the escape rate of a current-biased Josephson junction from the zero-voltage state for two values of critical current. For the lower critical current, T_{esc} followed the classical prediction to within experimental error. For the higher critical current, T_{esc} was equal to T at higher temperatures but began to flatten off at temperatures below 50 mK, becoming temperature independent below 25 mK. Within the experimental uncertainties, the low-temperature value of T_{esc} was in excellent agreement with the zero-temperature theoretical prediction for macroscopic quantum tunnelling, with all relevant parameters measured *in situ* in the classical limit.

The combination of the results from these two publications provided very strong evidence for the existence of energy quantization and macroscopic quantum mechanical tunnelling in an electrical circuit.

The combination of the results from these two publications provided very strong evidence for the existence of energy quantization and macroscopic quantum mechanical tunnelling in an electrical circuit.

Nobel Citation:

"for the discovery of macroscopic quantum mechanical tunnelling and energy quantization in an electrical circuit"

References to competing research on MQT

1. R.V. Voss and R.A. Webb, Phys. Rev. Lett. 47, 265 (1981).

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