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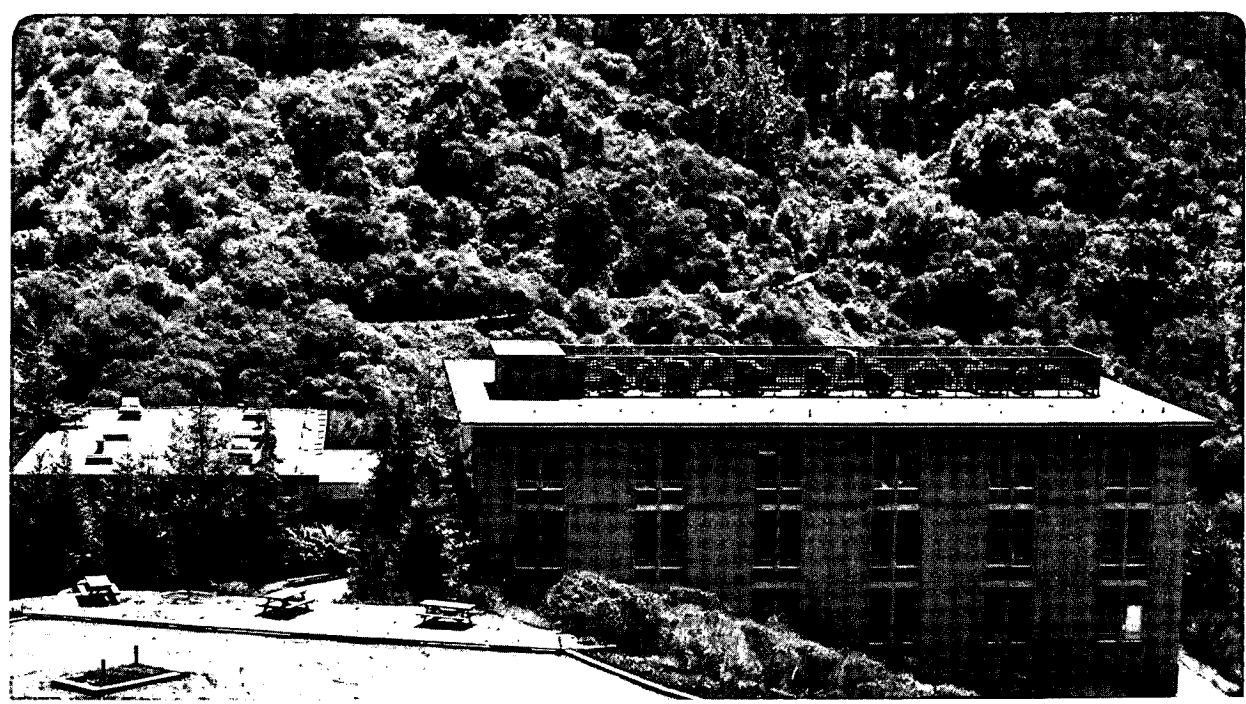
### Quantum Phenomena in Superconductors

J. Clarke

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## Quantum Phenomena in Superconductors

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1. PREAMBLE

I am greatly honored to have been chosen as one of the recipients of the 13th Fritz London Memorial Award. I wish to express my thanks to the committee for selecting me. Much of the work for which you have cited me has been concerned with macroscopic quantum effects in superconductors, the groundwork for which was laid by London in his famous book "Superfluids - Macroscopic Theory of Superconductivity". This book, together with David Shoenberg's "Superconductivity", provided my first introduction to the wonders of superconductivity in my early days as a research student. In this paper I should like to discuss some of those aspects of macroscopic quantum phenomena in which I have been involved, and also to say something about the applications that have resulted from this research. I have decided to write a rather personal and subjective account of this work, trying to give some flavor of how the various topics are related, rather than to produce a detailed scientific document.

2. SLUGS

The first experiment to reveal a macroscopic quantum phenomenon in a superconductor was the observation [1] in 1961 that magnetic flux in a superconducting loop was quantized in units of the flux quantum  $\Phi_0 = h/2e$ , a property predicted by London. Shortly after this observation, in 1962, Brian Josephson [2] predicted his famous effect which was observed not too long afterwards by Anderson and Rowell [3]. Early in 1964 Jaklevic and coworkers [4] combined flux quantization and Josephson tunneling to produce the dc SQUID (Superconducting QUantum Interference Device).

This was the situation when I arrived as a new research student at the Royal Society Mond Laboratory in Cambridge in the autumn of 1964. The Mond in those days was a bustling, exciting place, presided over by David Shoenberg. My thesis supervisor was Brian Pippard, who kept a large group of research students and postdocs very busy indeed with a broad miscellany of interesting experiments. My own project was to study transport at the superconductor-normal (SN) metal interface; but to do this I first had to build a more sensitive voltmeter than any then available. Initially, at Brian's suggestion, I designed a galvanometer with superconducting coils which we believed would be sensitive enough to do the trick. However, the first Mond seminar of the term was given by Brian Josephson, just beginning his fourth year as a research student (also under Brian Pippard's supervision), who talked about flux quantization and, rather modestly, about "pair tunneling". The very next morning, Brian

Pippard rushed into my lab in a rather excited state to ask me something like, "How would you like to build a digital voltmeter with a sensitivity of  $2 \times 10^{-15}$  volts and a 1 second measurement time?" He then explained how one could make a galvanometer by passing a current through a coil coupled to a SQUID, and hence a voltmeter by putting a resistor in series with the coil. If one assumes that the SQUID and coil have the same inductance and are perfectly coupled, the voltage required to produce one flux quantum in the SQUID is  $V = R\Phi_0/L$ : if one takes  $L/R = 1$  second, the input voltage to produce one flux quantum is  $2 \times 10^{-15}$  V.

At about this time I discovered a paper by Zimmerman and Silver [5] in which they described simple methods of making weak link junctions and SQUIDS using pieces of niobium and niobium wire. I actually made a working SQUID along these lines, adjusting the force between a niobium wire and the edges of a narrow niobium foil with a rod that extended outside the cryostat. However, I felt that a practical instrument should not have to be adjusted in this way, and looked around for other ways of making junctions.

Among the daily features of life in the Cavendish Laboratory (of which the Mond was part) were the breaks for morning coffee and afternoon tea. One tea-time, Paul Wraight, a fellow research student with whom I shared a lab, suggested that perhaps one could make a junction by dropping a pellet of molten Pb-Sn solder on to a sheet of niobium, which had a native oxide layer. Well, it turned out that we didn't have any niobium sheet, so instead we simply immersed a length of niobium wire in a blob of solder, attached some leads, and dropped the device into liquid helium. To our great joy and amazement, we obtained a current-voltage characteristic with a zero-voltage region -- we had made a Josephson junction.

I then tried for several weeks to make a suitable configuration containing two of these junctions in parallel to form a SQUID. I finally discovered that if I applied a current to a piece of wire passing through a single blob of solder, the zero-voltage current was (often!) modulated. Evidently, the solder made some kind of tunneling contact or weak link to the wire at two (or sometimes three or four) points. The field generated by the current in the niobium wire threaded the one (or more) loops between these junctions to produce quantum interference. Thus, the SLUG (Superconducting Low-inductance Undulatory Galvanometer) was born (Fig. 1), and turned out to be a most useful device for the next 6 or 7 years [6].

I wrote my Ph.D. thesis on the SLUG and its application to the investigation of Josephson

Fig. 1. A SLUG.

tunneling in SNS junctions. At the beginning of 1968 I moved to the University of California Berkeley, where I quickly set up a "SLUG Lab". My first experiment was to show that the constant voltage steps induced in two SNS junctions by rf radiation occurred at the same voltage to 1 part in  $10^8$ , thus helping to resolve some doubts that were being expressed at the time about the accuracy of the Josephson voltage standard.

3. CHARGE IMBALANCE

During the autumn of 1971 I became rather intrigued by a paper by Rieger *et al.* [7] dealing with nonequilibrium superconductivity. They considered a current flowing through a superconductor of volume  $\Omega$  in such a way that quasiparticles were injected and pairs extracted, and proposed that an observable electrochemical potential should be created between the quasiparticles and the pairs. I decided to test this idea experimentally, using the configuration shown in Fig. 2. After depositing an

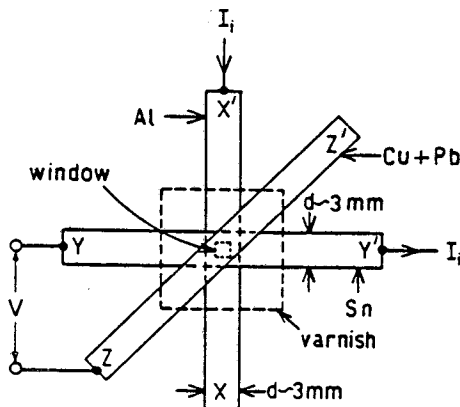


Fig. 2. Configuration for detection of charge imbalance. In order of deposition the films are Al (XX'), Sn (YY'), varnish, Cu (ZZ'), and Pb (ZZ').

Al-Al<sub>2</sub>O<sub>3</sub>-Sn tunnel junction, I painted on a layer of varnish, leaving a window in the middle of the junction. I then evaporated a diagonal

strip of Cu (ZZ') to form a normal probe coupled to the Sn via a second tunnel junction. To reduce the series resistance of this probe and thus enable me to make very sensitive voltage measurements I evaporated a Pb film over the Cu.

In the experiment, a current was passed through the Al-Al<sub>2</sub>O<sub>3</sub>-Sn tunnel junction. I could detect any voltage developed in the Sn strip with a SLUG in series with a resistor R connected between the Sn and Cu films. Since the electrochemical potential  $\mu_p$  of the pairs had to be constant in the Sn strip, the SLUG voltmeter measured the voltage relative to  $\mu_p$ . Much to my delight, a voltage did indeed appear on the normal probe in the presence of a current in the injector junction. I obtained a good deal of data from several samples on the dependence of this voltage on injection current and temperature, measuring the voltage in a null-balancing mode with zero current in the SLUG. I then flew off to Cambridge for a 6-month leave of absence, clutching my precious notebook of yet-to-be-analyzed data.

In the New Year of 1972, I analyzed my results. The data were self-consistent, but not in agreement with the theory that had prompted the experiment. Now by a remarkable stroke of good fortune, I happened to be sharing an office in the Mond with Mike Tinkham, who was spending a sabbatical year in Cambridge to write his now-famous book on superconductivity. Mike kept insisting that he was supposed to write a book and not become involved in any new physics, but, fortunately for me, scientific curiosity finally overcame his eagerness to finish his book! Aided by numerous tea-time discussions, particularly with Brian Pippard who had worked on a closely related topic in connection with the resistance of the NS interface, we finally arrived at a theory for the effect, which we called "branch imbalance".

In essence, the idea is as follows [8]. A tunnel current I passed through a NS junction, with the superconductor (for definiteness) positively biased at a voltage greater than  $\Delta/e$ , injects electronlike excitations into the superconductor throughout the volume overlaying the normal electrode ( $\Delta$  is the energy gap). To conserve charge, a corresponding number of Cooper pairs must flow out of this region into the surrounding superconducting film. Thus, there is a steady-state number imbalance Q between the electronlike and holelike branches of the excitation spectrum that is proportional to the branch relaxation time  $\tau_Q$ . When one couples this nonequilibrium superconductor to a normal probe via a second tunnel barrier, a current flows unless one applies a voltage to prevent it: this is precisely the voltage detected in the experiment. It turns out that this voltage is proportional to the charge imbalance between branches, which we called  $Q^*$ , rather than Q. Mike showed that the detector voltage near the transition temperature  $T_c$  should scale as  $I\tau_Q/\Omega$ , where  $\tau_Q = [\Delta(0)/\Delta(T)]\tau_E$  and  $\tau_E$  is the inelastic scattering time at the Fermi energy. My data were in excellent accord with this prediction.

Later that spring, Mike Tinkham wrote a classic paper [9] on the theory. Charge imbalance has subsequently been studied in a wide variety of different physical phenomena, and it has proved a useful means of measuring  $\tau_E$  in a number of superconductors [10].

#### 4. CYLINDRICAL DC SQUIDS

In the latter part of my stay in Cambridge in 1972 I wrote a review paper on SQUIDS. At that time the rf SQUID (a single junction interrupting a superconducting loop) was becoming much more popular than the dc SQUID: not only was it more sensitive, but it required only one junction! However, in thinking about the article I became convinced that the relatively poor performance of the dc SQUID achieved hitherto was mostly due to the non-optimum coupling of the cold, low resistance SQUID to the room-temperature amplifier. I carried out some preliminary experiments in the Mond using a point contact SQUID coupled to an amplifier via a tuned circuit, and achieved greatly improved sensitivity.

Early in 1974 Wolf Goubau arrived at Berkeley to begin a postdoctoral fellowship. Wolf and a new graduate student, Mark Ketchen, produced the cylindrical dc SQUID -- a series of films deposited on a 3-mm diameter quartz tube [11]. This device involved Josephson tunnel junctions, shunted with normal metal films, and was optimally matched to the room-temperature amplifier via a tuned circuit, so that the sensitivity was limited by intrinsic noise. At the time this SQUID was the most sensitive available, with a noise energy of about  $3 \times 10^{-30}$  JHz<sup>-1</sup>. The "flux noise energy" is defined at  $\epsilon/1\text{Hz} = S_\phi/2L$ , where  $S_\phi(f)$  is the spectral density of the equivalent flux noise and  $L$  is the SQUID inductance. This device became our "in-house SQUID" for a number of years, and proved very rugged and easy to use.

#### 5. GEOPHYSICS

The development of the cylindrical SQUID gave us a magnetometer with a sensitivity of about  $10^{-14}$  THz<sup>-1/2</sup> ( $10^{-10}$  gauss Hz<sup>-1/2</sup>) at frequencies above about  $10^{-2}$  Hz (at lower frequencies the spectral density of the noise scaled as  $1/f$ ). In 1975 I gave a talk on SQUIDS at a small geophysics conference held in Berkeley that led to some ongoing discussions about the possibility of using SQUIDS for geophysical measurements. Frank Morrison in the Engineering Geoscience Department at Berkeley suggested that we look into a technique known as magnetotellurics ("magnetism of the earth"). The essential idea is that low frequency electromagnetic waves ( $< 100$  Hz) generated in the ionosphere and magnetosphere propagate down to the earth's surface. The earth, being a relatively good electrical conductor, reflects these waves. We define an impedance tensor  $Z(\omega)$ , via the relation  $\vec{E}(\omega) = Z(\omega)\vec{H}(\omega)$ , where  $\vec{E}(\omega)$  and  $\vec{H}(\omega)$  are the Fourier components of the fluctuating horizontal electric and magnetic fields at the surface. Thus, by measuring two orthogonal components of the magnetic field and the corresponding components of the electric field, one can determine  $Z(\omega)$ . The impedance tensor is averaged over a skin depth at frequency  $\omega$ , typically 1 km at 1 Hz. If one measures the fields as a function of frequency one can build up an impedance profile of the earth, at depths down to 10's of kilometers if one is patient enough.

Although the principle is splendid, the practice at the time was less sanguine. The electric field measurement was fine -- one simply measured the fluctuating voltage between two electrodes buried in the ground a few

hundred meters apart. The magnetic field measurements, on the other hand, were often very heavily contaminated by spurious noise that gave a hopelessly biased  $Z(\omega)$ . It was generally believed that the noise arose in the magnetometers. Thus, by using a SQUID magnetometer, which had a very low intrinsic noise level, one might hope to make a substantial improvement in the accuracy of magnetotellurics (MT).

With this background, Wolf Goubau and a graduate student, Tom Gamble, built a 3-axis SQUID magnetometer with its accompanying electronics, at the time by far the most ambitious SQUID project we had undertaken. We also had to put together a computer to take data. After a long spell of construction we finally took the equipment to the field, collected a good deal of data, and returned to Berkeley to analyze them.

To our considerable disappointment, we found that our MT data looked no better than most other data that we had seen previously: for example,  $Z(\omega)$  showed unphysically large variations with frequency. No amount of "data massaging" could eliminate the large levels of spurious noise that contaminated the MT signal. However, we did have one advantage in our favor: we were sure that the noise could not have arisen from our magnetometers, and it must therefore have had an external origin. We then began to worry about spurious noise generated, for example, by distant traffic or by motion of the magnetometer in the earth's static field.

Solid state physicists have known for a long time that lock-in detection is an excellent way to lower the noise in their experiments. With this idea in mind, we borrowed a second 3-axis magnetometer (with rf SQUIDS), bought some data telemetry equipment, and set up our MT experiment with the two magnetometers about 5 km apart, each with a nearby electric field array. The basic idea was to use the magnetic fields from one magnetometer as a "remote reference" for the magnetic and electric fields at the other site. Thus, one retains only those components of the H- and E-fields that are correlated with the remote H-field. This procedure eliminates any local noise sources provided the coherence length of the noise is appreciably less than 5 km and one averages for a sufficiently long time. To cut a long story short, this technique worked wonderfully well, and produced very high quality data [12].

The development of the remote reference technique coincided with a major boost in funding for oil, gas and geothermal exploration. Any of these natural resources can produce an apparent resistivity anomaly below the surface of the earth, and under appropriate circumstances can be located using MT. We carried out a number of such surveys, including a particularly successful one at Cerro Prieto, in Mexico in which we located a source of geothermal energy rather precisely. Almost all MT, I believe, is now carried out with a remote reference.

#### 6. NOISE THEORY

The development of the cylindrical SQUID with well-characterized parameters and performance prompted the need for a detailed noise theory. For her thesis work, Claudia Tesche performed a very careful and detailed computer simulation of the SQUID. The basic assumption

was that the noise originated as two independent Nyquist noise sources in the shunt resistors. One then had to compute the interplay of this noise with the highly nonlinear dynamics of the SQUID. The essential result of the simulation was that, for a properly optimized SQUID, the noise energy is given approximately by [13]

$$\epsilon/1\text{Hz} = 10(\text{LC})^{1/2}k_B T, \quad (1)$$

where C is the capacitance of each tunnel junction. This formula says, in essence, that "smaller is better" -- by reducing the area of the junctions and the inductance of the SQUID loop one improves the sensitivity of the SQUID. Numerous SQUIDS were subsequently fabricated by a variety of groups who used photolithography or electron-beam lithography to reduce the dimensions of the thin films. Several types of SQUID have been made with noise energies as low as a few  $\mu\text{V}$ , including one at Berkeley made by Roger Koch and Dale Van Harlingen [14]. More recently, Fred Wellstood and Cristian Urbina [15] have shown that the temperature dependence of the noise energy predicted by Eq. (1) is correct for temperatures as low as 0.1 K.

The noise theory leading to Eq. (1) is of course classical, but the fact that noise energies approaching  $\mu\text{V}$  are achievable naturally leads one to consider the limitations on the performance imposed by quantum mechanics. To investigate this problem in 1980 Roger, Dale, and I first studied the noise in single, resistively shunted Josephson junctions in the limit in which  $M\omega_J \gg k_B T$ , where  $\omega_J$  is the Josephson frequency. Using a quantum Langevin equation we calculated the noise generated at relatively low frequencies, much less than  $\omega_J$ . Over an appropriate range of voltage we found that the noise originated in the zero point fluctuations in the shunt resistor at frequency  $\omega_J$ ; these fluctuations are generated by an ensemble of harmonic oscillators, representing the resistor, with random phases. We then carried out a series of measurements on resistively shunted junctions and verified the theory in some detail [16].

We next applied the same approach to the sensitivity of the dc SQUID. The situation here is more complicated, because the SQUID has two noise contributions: a voltage noise at the output and a current noise around the SQUID loop. Furthermore, these noises are partially correlated. The presence of the two noise terms, incidentally, implies that  $\epsilon/1\text{Hz}$  is not a complete specification of the sensitivity, although it remains a valuable figure-of-merit for comparing different SQUIDS. A practicable way of completely specifying the performance is to couple an input circuit to the SQUID to make an amplifier. For a high-Q tuned input circuit consisting of a capacitor in series with a coil weakly coupled to a quantum-limited SQUID, the optimized room temperature [17] is  $hf/k_B \ln 2$  ( $f$  is the signal frequency). This is the general result for any quantum-limited amplifier. To date, nobody has achieved this limit for a practical SQUID, although there are some intriguing applications, notably as the transducer in a gravity wave antenna.

## 7. MAGNETIC RESONANCE WITH SQUIDS

The dc SQUIDS we currently use are based on the design of Ketchen and Jaycox [18] at IBM. The body consists of a square washer, overlaid with a spiral input coil. Claude Hilbert carried out a very thorough and detailed investigation of this kind of SQUID as a radiofrequency amplifier. For a SQUID at 4.2 K and an input circuit tuned to the signal frequency of 93 MHz, the measured gain of about 19 dB and noise temperature of between 1 and 2 K were both in good agreement with predictions [19]. The noise temperature compares very favorably with that achieved with other types of amplifier.

Having developed this low noise amplifier, Claude and I collaborated with Erwin Hahn and his student Tycho Sleator to exploit it in nuclear magnetic resonance experiments. Of the several experiments we have carried out, one of the more intriguing is the detection of nuclear quadrupole resonance using noise.

The sample used in the first experiments [20] in 1984 was  $\text{NaClO}_3$ , in which the  $^{35}\text{Cl}$  nucleus has two doubly degenerate energy levels with a transition frequency of 30.6857 MHz at 1.5 K. The sample is contained in a superconducting coil connected in series with the input coil of a SQUID and a capacitor. Current fluctuations in the input circuit produce a magnetic flux in the SQUID loop and hence an output voltage. In the absence of the sample, the spectral density of the noise is a Lorentzian, centered at the resonant frequency of the tuned circuit, arising from the Nyquist noise generated in the resistive components of the circuit (chiefly dielectric losses in the capacitor and contact resistances to the capacitor). We carried out two separate experiments in which we measured the departures from this Lorentzian lineshape induced by the presence of the  $\text{NaClO}_3$ .

In the first experiment, the sample is in thermal equilibrium. When the resonant frequency of the tuned circuit is equal to the Larmor frequency  $f_L$  the major effect of the sample is to introduce an additional "spin resistance" into the tuned circuit, thereby lowering its Q over a frequency range equal to the linewidth of the quadrupole resonance ( $1/\pi T_2$ , where  $T_2$  is the transverse relaxation time). Thus, one is able to determine the nuclear quadrupole resonant frequency and linewidth with the sample in thermal equilibrium, with no rf pulse applied to align the spins.

In the second experiment, the populations of the two nuclear levels are equalized by means of a continuous rf excitation at resonance. After the excitation is turned off, the spectral density of the noise is measured in a time much less than the longitudinal relaxation time,  $T_1$  (~ days). In this case there is no net absorption of energy from the tank circuit; rather, one observes noise emitted into the circuit as the population of the upper level decays via spontaneous emission. Figure 3 shows a typical bump produced on top of the Lorentzian by this "spin noise". It is somewhat amusing to note that the lifetime against spontaneous emission involving the flipping of one spin is  $10^6$  centuries, and that the total spin noise power detected is  $5 \times 10^{-21}$  W, about 5% of the Nyquist noise power generated in the bandwidth  $1/\pi T_2$ .

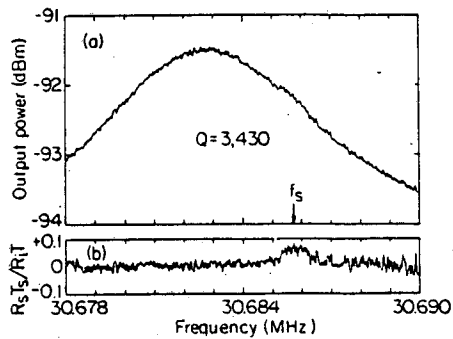


Fig. 3. Spin noise: spectral density of (a) noise current for a  $\text{NaClO}_3$  sample with saturated spins, and (b) nuclear-spin noise obtained from (a).

### 8. MACROSCOPIC QUANTUM TUNNELING

As a final topic, I'd like to touch on a subject where the word "macroscopic" has a quite different meaning. When we talk about superconductivity or flux quantization or Josephson tunneling being a macroscopic phenomenon in the sense that Fritz London so clearly understood, we refer to effects arising from the coherent superposition of a large number of microscopic variables each governed by quantum mechanics. On the other hand, Tony Leggett, in a series of elegant papers [21] beginning with an invited talk at LT-15, has discussed a second type of macroscopic behavior, namely that displayed by a single macroscopic degree of freedom -- for example, the center-of-mass motion of a pendulum bob. He has raised the issue of whether or not macroscopic systems like this exhibit quantum mechanical behavior, for example, zero point motion or quantization of energy. The prototypical system for studying macroscopic quantum behavior of this kind is the Josephson tunnel junction, where the macroscopic degree of freedom is the phase difference  $\delta$  across the junction, or a Josephson junction incorporated into a superconducting loop (a rf SQUID), where the macroscopic degree of freedom is the flux in the SQUID loop. I shall say a little about the former configuration.

A current-biased Josephson junction is analogous to a particle moving on a tilted washboard potential. The zero voltage state of the junction corresponds to the trapping of the particle in one of the wells, where it oscillates at the plasma frequency  $\omega_p/2\pi$ , with  $\langle \delta \rangle = 0$ . The transition of the junction to a nonzero voltage corresponds to the escape of the particle from the well to a state in which it rolls down the washboard with  $\delta = 0$ . In the classical limit  $\hbar\omega_p \ll k_B T$  the escape process is via thermal activation. In this limit, the particle is a point-like mass with continuous energy and escapes over the top of the barrier separating the potential well from the free-running state. In the quantum limit  $\hbar\omega_p \gg k_B T$ , however, the particle is no longer point-like but, because of its zero point motion, must be described by a wave packet. The energy of the particle is now quantized. The particle escapes from the well by macroscopic quantum tunneling (MQT), which occurs because the tail of the wave function describing the particle extends under the barrier. To demonstrate the quantum

behavior of  $\delta$  therefore, one would like to demonstrate the existence of both MQT and the quantization of energy.

There have been a number of experiments to investigate MQT. Most of them showed that as the temperature was lowered the lifetime of the zero voltage state tended to flatten out as the escape process crossed over from the thermal to the quantum regime. However, a persistent experimental difficulty has been the determination of the capacitance of the junction and of the resistance shunting it. In an attempt to overcome this problem, Michel Devoret and John Martinis undertook a series of experiments at Berkeley [22] in which these parameters and the critical current  $I_0$  were determined in the classical regime. Thus, we were able to compare experimental results in the quantum regime with theoretical predictions with no adjustable parameters. We first studied junctions in which the damping was small ( $Q = 30$ ) and had a negligible effect on the escape rate. To characterize the escape rate  $\Gamma$  from the zero voltage state we introduced the escape temperature  $T_{esc}$  via the relation

$$\Gamma = (\omega_p/2\pi)\exp(-\Delta U/k_B T_{esc}), \quad (2)$$

where  $\Delta U$  is the barrier height. At high temperatures  $T_{esc}$  was very close to  $T$ , as we expect from the Kramers' result for thermal activation. At low temperatures, however,  $T_{esc}$  flattened off. In one particular experiment, the low temperature value of  $T_{esc}$  was  $37.4 \pm 4.0$  mK, in very good agreement with the predicted value of  $36.0 \pm 1.4$  mK.

Subsequently, Andrew Cleland [23] made measurements on junctions with thin-film resistive shunts that provided moderate damping ( $Q \geq 1$ ) and that, according to the Caldeira-Leggett theory, should substantially reduce the escape rate. For a junction with  $Q = 1.8$  the measured value of  $T_{esc}$  extrapolated to  $T = 0$  was  $45 \pm 2$  mK, in very good agreement with the predicted value of  $43 \pm 2$  mK. These results strongly support the correctness of the Caldeira-Leggett treatment of the effects of dissipation on MQT, even to the accuracy of the prefactor term.

To demonstrate the quantization of energy in the well, John and Michel also measured the escape rate in the quantum limit in the presence of a microwave current [22]. Because the well is anharmonic, the energy level separations decrease with increasing energy, thus allowing one to detect the energy levels spectroscopically. Since the microwaves induce transitions from one state to another of higher energy, and the escape rate increases when the population of higher energy states increases, we expect a resonant enhancement of the escape rate when the microwave photon energy corresponds to an energy level spacing. We varied the spacings by adjusting the static bias current, keeping the microwave frequency  $\Omega/2\pi$  and power  $P$  fixed. In Fig. 4(a) we show the change in escape rate  $[\Gamma(P) - \Gamma(0)]/\Gamma(0)$  vs. bias current in the presence of 2 GHz microwaves. The temperature was high enough for the thermal population of the lower lying excited states to be substantial. The three peaks correspond to the transitions shown in the inset. Figure 4(b) shows the calculated level spacings for three transitions as a function of bias current  $I$ . The



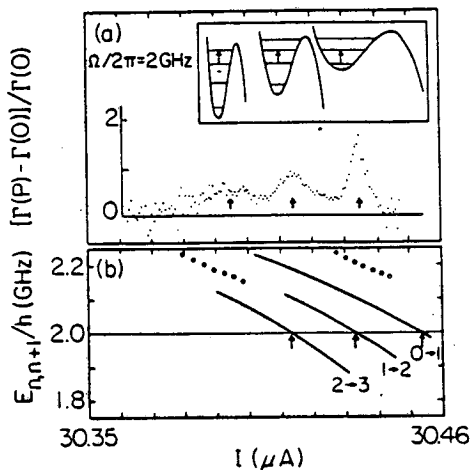


Fig. 4. (a)  $[\Gamma(P) - \Gamma(0)]/\Gamma(0)$  vs.  $I$  for  $80 \times 10 \mu\text{m}^2$  junction at 28 mK in presence of 2 GHz microwaves. Inset shows transitions between energy levels corresponding to peaks indicated with arrows. (b) Calculated energy level spacings for  $I_0 = 30.572 \pm 0.017 \mu\text{A}$  and  $C = 47.0 \pm 3.0 \text{ pF}$ . Dotted lines indicate uncertainties in the  $0 \rightarrow 1$  curve due to uncertainties in  $I_0$  and  $C$ . Arrows indicate values of bias current at which resonances are predicted.

intersections of these curves with the 2 GHz frequency line predict the values of  $I$  at which the peaks should occur. The absolute positions of the measured peaks are shifted from the predicted positions by about 2 parts in 3000, an error that lies within the uncertainties; the relative positions of the experimental and predicted peaks are in very good agreement.

These two experiments, demonstrating that  $\delta$  exhibits zero point motion and that the energy in the well is quantized, provide overwhelming evidence that  $\delta$  is a quantum variable. Thus, it is possible to isolate and study a single degree of freedom in a system that is certainly macroscopic enough for us to "get our grubby fingers on".

#### 9. ACKNOWLEDGMENTS

I wish to thank, in particular Brian Pippard, who introduced me to the subject of superconductivity and who started me off in such a fascinating direction of research.

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