Observation of the Resonant Tunneling of Cooper Pairs

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We demonstrate how the Coulomb blockade of tunneling and the coherent Josephson tunneling of electron pairs can coexist in the same experiment. Measurements were made on a circuit consisting of two dc SQUIDs connected in series, with a gate capacitively coupled to the center electrode. Peaks in the current as a function of bias voltage shifted position with gate voltage in agreement with the theory of resonant Cooper pair tunneling.

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A superconducting single electron transistor (S-SET) consists of two nanometer scale superconducting tunnel junctions connected in series so that a small superconducting "island" forms the central electrode. Because of the small capacitance of the island, C_Σ, there is a significant charging energy, $E_C = e^2/2C_\Sigma$ associated with a single excess charge on the island. This charging energy results in a definite number, N, of Cooper pairs on the island and thus the Josephson phase, ϕ, has large uncertainty since $\Delta N \Delta \phi \sim 1$. Despite these large "quantum fluctuations" of the phase on the island, Cooper pairs can tunnel through the island in a phase coherent manner. At certain bias voltages, resonant tunneling is possible, where several Cooper pairs tunnel through the S-SET and the island acquires some excess charge [1]. In this Letter we give experimental evidence for this process of resonant Cooper pair tunneling.

Previous measurements of the current voltage (I-V) characteristics have shown a very rich structure of current peaks at various bias voltages [2–6] but the explanation of these peaks has focused on combined Cooper pair and quasiparticle tunneling [2,4,5,7]. The current peaks can be divided into two groups: those at voltages $V > 2\Delta/e$, where the quasiparticle tunneling is significant, and those at voltages $V < 2\Delta/e$, where quasiparticle tunneling may be neglected. We wish to focus on this latter region where the origin of the current peaks can be of different nature. These have been explained as Cooper pair tunneling when the Josephson frequency, $\omega_J = 2\ \mathrm{eV}/\hbar$ coincides with the resonant frequency of some mode of the electrodynamic environment [3]. This explanation can equally well apply to large capacitance junctions, where charging effects are negligible.

Peaks in the current at $V < 2\Delta/e$ can also be the result of the resonant tunneling of Cooper pairs, which can occur in the absence of quasiparticle tunneling. This process is a sort of internal resonance of the S-SET and will give a peak in the current even if the impedance of the environment is frequency independent. The main signature of the resonant tunneling of Cooper pairs, which distinguishes it from resonance with a particular mode of the environment, is that the voltage position of the associated current peak depends on the gate voltage.

The theory of resonant Cooper pair tunneling has been described by van den Brink *et al.* [1]. They begin with the standard model of an S-SET with a symmetric voltage bias as portrayed in Fig. 1(a). In this model, we imagine that the electrons tunnel through the junctions and that the potential of the leads remains fixed. We consider the change of electrostatic energy of the entire circuit when the charges Q_L and Q_R tunnel through the left and right junctions, respectively,

$$\Delta E = \frac{Q^2}{2C_\Sigma} + \frac{QQ_I}{C_\Sigma} + \frac{QQ_0}{C_\Sigma} - \overline{Q}\,\frac{V}{2}. \qquad (1)$$

Here $Q = Q_L - Q_R$ is the excess island charge due to tunneling, $\overline{Q} = Q_L + Q_R$ is the total charge passing through the voltage sources, and Q_I is the initial excess charge on the island before tunneling. Q_L, Q_R, and Q_I must be integer multiples of the electronic charge. The "charge" $Q_0 = C_g V_g + (C_L - C_R)V/2 +$ "background terms" depends on the potentials of all regions which are capacitively coupled to the island. In the experiment we strive for a symmetric circuit where $C_L = C_R$, and we desire all background potentials to remain fixed. In this case, Q_0 can be continuously varied by changing the gate voltage, V_g. At voltages given by

$$V = \frac{1}{C_\Sigma}\,\frac{Q}{\overline{Q}}\,(Q + 2Q_I + 2Q_0) \qquad (2)$$

a resonant tunneling is possible during which $\overline{Q}$ charges can be transported and $\Delta E = 0$. Hence, Cooper pairs can tunnel at finite bias without dissipation of energy. The energy supplied by the source goes into charging up the island.

The resonant tunneling itself is not enough to sustain a current in the S-SET because it results in a charging of the island with charge Q. The excess Cooper pair charge Q must tunnel off the island before the next resonant tunneling can occur. When Q tunnels off, energy must be absorbed, and the rate of this process depends critically on the electrodynamic environment of the S-SET. The electrodynamic environment can be modeled by the impedance $Z_e(\omega)$. In the limit that $\mathrm{Re}[Z_e(\omega)] \ll R_Q = h/4e^2 = 6.45\ \mathrm{k}\Omega$, simulations [1] for the case that $\mathrm{Re}[Z_e(\omega)] =$ const show a rich structure of current peaks

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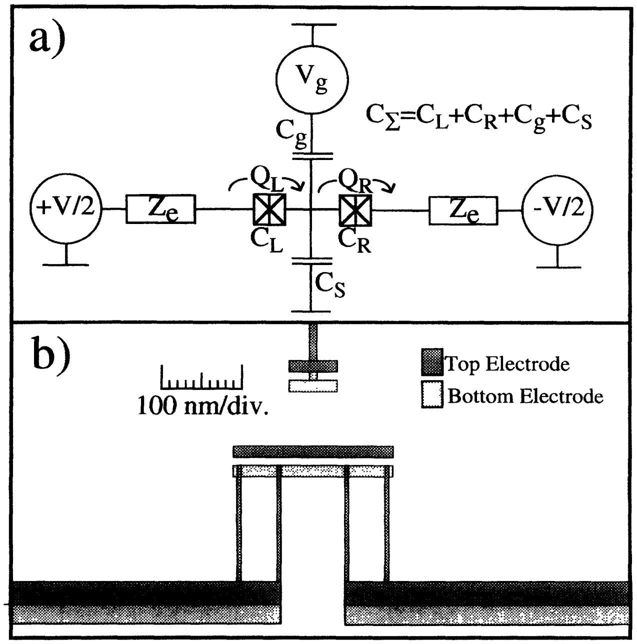

FIG. 1. (a) A schematic of the S-SET. (b) A sketch of the layout for sample 1. For both samples, the single tunnel junction in the schematic (a) was replaced by two junctions in parallel, to form a dc-SQUID.

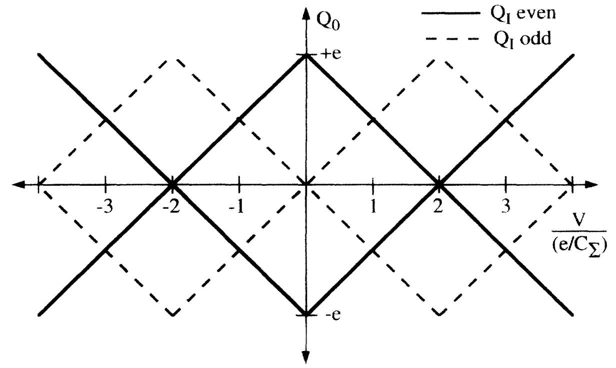

FIG. 2. A plot of Q_0 vs V showing the condition for the simplest resonant tunneling, $\{Q = \pm 2e, \overline{Q} = 0\}$ or $\{Q = 0, \overline{Q} = \pm 2e\}$, for both odd and even initial charge Q_I on the island.

whose positions depend on bias voltage as in (2). In this Letter we show quantitative agreement with the predicted position of the current peaks, and their dependence on gate voltage.

We consider the simplest resonant Cooper pair tunneling $Q = \pm 2e$, $\overline{Q} = \pm 2e$ (i.e., $\{Q_R = \pm 2e, Q_L = 0\}$ or $\{Q_L = \pm 2e, Q_R = 0\}$), where one Cooper pair tunnels onto or off of the island. Figure 2 shows a diagram of Q_0 vs V where the resonant condition (2) is fulfilled. We see from the diagram that the gate voltage dependence is e periodic in Q_0 if the initial excess charge Q_I is allowed to be both even and odd, and $2e$ periodic if Q_I restricted to either even or odd integer multiples of e. As the bias voltage is decreased to zero the pattern in gate voltage is much more complex than that of Fig. 2 due to the resonant tunneling of many charges (large $\overline{Q}$) which describes the buildup of the supercurrent.

In order to determine the phase coherent nature of the electric current in the S-SET, we performed experiments in a dc-SQUID-like geometry. We have previously reported experimental results on a geometry which consisted of two S-SET's connected in parallel to form *one* loop [8]. These experiments showed that at voltages $V < 2\Delta/e$, the height of the current peaks could be modulated with magnetic field, having period corresponding to one flux quantum $\Phi_0 = h/2e = 20.7$ G μm^2, in the single loop. This behavior verifies that there is a phase coherent component to the current in the S-SET for $V < 2\Delta/e$, arising from Cooper pair tunneling through both tunnel junctions, without significant quasiparticle tunneling.

In the experiments reported in this Letter we have studied the circuit geometry shown in Fig. 1(b), where each junction was replaced by two junctions in parallel so as to form a dc-SQUID. Replacing the simple junction by a SQUID allowed modulation of the Cooper pair current by application of a magnetic field. The mean area of the loop, given by one half the sum of the areas defined by the inner and outer perimeters, $A = 0.81 \pm 0.04$ μm^2. Thus Cooper pair current could be suppressed with magnetic fields the order of $\Phi_0/2A = 13$ G. At these small magnetic fields we can neglect effects due to suppression of the superconducting gap Δ.

The small tunnel junctions were formed by the overlap of the bottom and top electrodes, which were made by evaporation through the same mask at two different angles. Both the bottom and top electrodes were Al and the tunnel barrier was formed by thermal oxidation of the Al. The sample was cooled in a dilution refrigerator and measurements were made at $T \sim 50$ mK. The dc I-V curves were measured with battery powered electronics and the leads to the junction were filtered to attenuate high frequency noise. The bias circuit employed feedback to keep the dc voltage across the sample constant, independent of the differential resistance of the sample. The current was measured as a voltage drop across a 2×10^8 Ω resistor.

We show data for a sample where the resistance of the S-SET was 32 kΩ. Assuming a symmetric circuit, we can consider each dc SQUID as an effective single junction with $R_N = 16$ kΩ, from which we can calculate a coupling energy of $E_J = (R_Q/R_N)\Delta 2 = 42$ μeV. We find that $E_C = e^2/2C_\Sigma \approx 58 \pm 3$ μeV which will be discussed below. Therefore, the ratio $E_J/E_C \approx 0.72$, and the temperature $k_B T \sim 4.3$ μeV $\ll \min[E_J, E_C]$.

The I-V characteristic of the sample is shown in Fig. 3. In Fig. 3(a) we see the dominant Josephson-quasiparticle peak [2] beginning at $V = 2\Delta/e$, and the sharp gap edge at $V = 4\Delta/e = 840$ μV. Figure 3(b) shows an enlargement of the region $V < 2\Delta/e$, where peaks in the current can be seen at specific bias voltages. In contrast to previous experiments [2,4,5] we would like to focus on this region of the I-V curve where the resonant tunneling of Cooper pairs occurs.

All structure in the I-V curve can be modulated periodically by magnetic field with period $B = 24.6 \pm 0.8$ G, which is within experimental error of the calculated value $\Phi_0/A = 25.6 \pm 1.3$ G. By applying a flux of $(n + 1/2)\Phi_0$ (n an integer), all peaks in the current could be suppressed as can be seen by comparing the curves in Figs. 3(a) and 3(b). The current suppression shown in Fig. 3 is not complete, in part due to the coarse stepping interval in flux ($\approx\Phi_0/25$). A small asymmetry in the two junctions of the SQUID would also result in incomplete suppression of the Cooper pair current.

At magnetic fields corresponding to $n\Phi_0$, Fig. 3(b) shows a set of peaks which are particularly sensitive to gate voltage. Arrows in the figure indicate the positions $m \times 117\ \mu$V (m an integer) where these peaks were maximum at different values of the gate charge as given in the figure. At intermediate values of the gate charge, the peaks shift in position as seen in a 3D plot of current vs voltage vs gate voltage (Fig. 4). The shifting of these peaks with gate voltage forms a checkerboard pattern on the surface of Fig. 4, which corresponds exactly to the

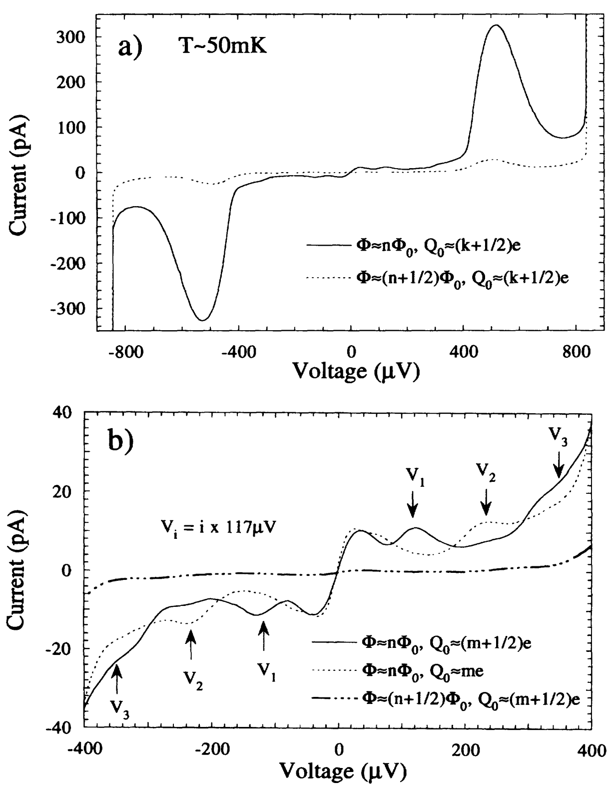

FIG. 3. (a) The I-V curve of a S-SET with parameters $E_J = 42\ \mu$eV and $E_C = 58\ \mu$eV, showing the Josephson-quasiparticle peak and its suppression with magnetic field. (b) The same curves at scale $V < 2\Delta/e$, showing the peaks due to resonant tunneling of Cooper pairs, and their suppression with magnetic field.

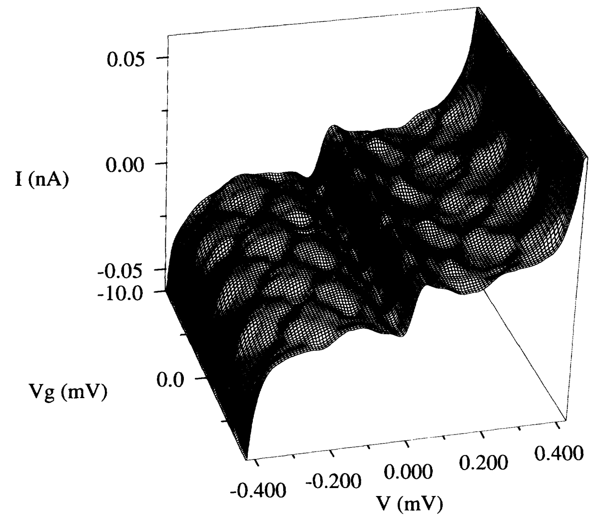

FIG. 4. A 3D plot of I vs V vs gate voltage at $B = 0$ G. Resonant tunneling of Cooper pairs causes peaks in the current which shift position with gate voltage. These form a checkerboard pattern on the surface corresponding to the resonant conditions mapped out in Fig. 2.

resonance conditions mapped out in Fig. 2. In order to make the plot such as in Fig. 4, it was necessary that the background charge remain stable on the time scale of $\frac{1}{2}$ h. From Figs. 3(b) and 4 we see that no significant asymmetry in the S-SET is present, otherwise the 3D plot of Fig. 4 would be skewed, with the peaks shifting in gate voltage as one moves to higher bias voltage, and the peaks in Fig. 3(b) would not appear all at the same gate voltage. Also seen in Figs. 3(b) and 4 is a peak closer to the origin which shows a weaker dependence on gate voltage but develops some structure as gate charge is varied. This peak can be explained by higher order resonant processes.

We can compare the shape and magnitude of the observed peaks in Fig. 3(b) with that of simulations [1]. The simulations assume Z_e = const, independent of ω, in which case the current is proportional to Z_e. For the sake of comparison, we estimate $Z_e = 50\ \Omega$, for which the simulations give the current value $I \approx 23$ pA for the peak at $V = 2e/C_\Sigma$, $Q_0 = 0$, and $E_J/E_C = 0.7$. The observed value is $I = 13$ pA for this peak which is of the correct order of magnitude.

The observed peak is broader than that of the simulations, consistent with its lower amplitude. The discrepancy between simulation [1] and experiment may be accounted for by the ideal assumption of the simulations that Z_e = const. In fact, the impedance of the environment is frequency dependent and is in general not trivial to model accurately. The leads to the S-SET were not designed with a geometry which was conducive to an exact solution for their impedance. Furthermore, the simulations do not take into account any quasiparticle tunneling. Even a very small amount of quasiparticle tunneling $I \sim 100e$/sec will tend to smear the observed current peaks. These quasiparticle tunneling events are continually resetting the initial charge Q_I as the gate voltage is slowly changed. Hence, the observed I-V curve is e/C_g periodic in gate voltage, resulting from the averaging of two, $2e/C_g$ periodic curves, shifted one to another by e/C_g.

Our interpretation of the data means that the charging energy of the S-SET is given by the peak spacing, $2E_C = e/C_\Sigma = 117 \pm 5\ \mu$V. The experimental error in determining the peak spacing is due to the coarse stepping interval in gate voltage ($\sim 0.1e/C_0$) as well as a background current at voltages closer to $2\Delta/e$ which washes out the third peak. To verify this interpretation, we would like to have an independent measure of C_Σ. According to theory of the Coulomb blockade in the voltage biased SET [9], valid in the limit $R_N \gg R_Q$, there is a threshold voltage for the onset of tunneling which has the maximum value $V_t = e/C_\Sigma$. This results in a voltage offset of the normal I-V curve which is usually used in the experimental literature to determine e/C_Σ.

We have experimentally determined an offset voltage by making a linear extrapolation of the slope of the normal state I-V curve to find the intercept with the voltage axis. The normal state I-V curve is measured in a large magnetic field $B \approx 1$ T. We find that for our samples no constant offset voltage can be defined over any range of the bias voltage. The offset voltage rises rapidly at low voltages ($0 < V < 10e/C_\Sigma$) and begins to increase more gradually at higher voltages ($V > 10e/C_\Sigma$), with a crossover between these two behaviors occurring around $V_{\rm off} \approx 120\ \mu$eV. Another sample which had a value of $e/C_\Sigma = 65\ \mu$eV, determined from the resonant peak spacing, showed similar behavior of the offset voltage, with the crossover occurring at $V_{\rm off} \approx 70\ \mu$eV. A detailed description of the offset voltage will be the subject of a future publication.

We would like to make two points concerning recent experiments on similar circuits. The first point to make is that in the measurements described here the I-V curve is periodic in gate voltage with period e/C_g. As these data demonstrate, the e-periodic behavior in gate voltage occurs even when the charge transport mechanism is overwhelmingly due to Cooper pair tunneling, where charge is transferred in units of $2e$. In some experiments $2e$-periodic behavior of the I-V curve has been observed for $V < 2\Delta/e$ [3,6,10,11]. The $2e$ periodicity has been explained as arising from the lower free energy [6] of the state with even parity, due to the extra energy Δ, required to create one unpaired quasiparticle in the island [12]. Although some samples exhibit this parity effect, the lack of it seems to be the norm in many experiments. We presume that this parity effect is not present in our samples due to single electron tunneling through impurity states, e.g., a trap in the oxide barrier. Excess charge on the island can then fill these impurity states one by one, and the charge Q_I can be of both even and odd parity, even if the condensate may have even parity.

A second related experiment was the recent report of the observation of the Aharonov-Casher effect [13]. Although the circuit studied in their experiment had more connections than ours, it can be reduced to a circuit where one island is weakly connected to the leads. An analysis similar to the one we presented here will give a periodic gate voltage dependence of the I-V curve. In the analysis presented here, we consider the island charge to be a well defined quantity. The phase of the island has large uncertainty ("quantum fluctuations"), which is to say that the measurement cannot determine whether the vortex went to the left or to the right of the island. In this spirit, the gate voltage oscillations of the S-SET's I-V curve might be visualized as the quantum interference of vortices due to the Aharnov-Casher effect. Such a description is dual to the one which we have presented.

In summary, we have observed the resonant tunneling of Cooper pairs in the superconducting single electron transistor. In this process, Cooper pairs tunnel at finite voltages which are resonant with the charging of the island by some discrete amount of change. The voltage position of the resulting peaks in the current, depend on the gate voltage in agreement with theory.

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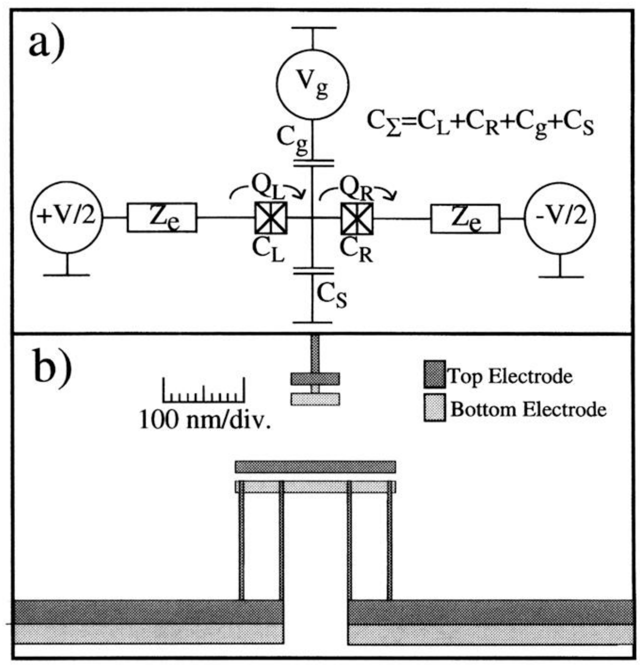

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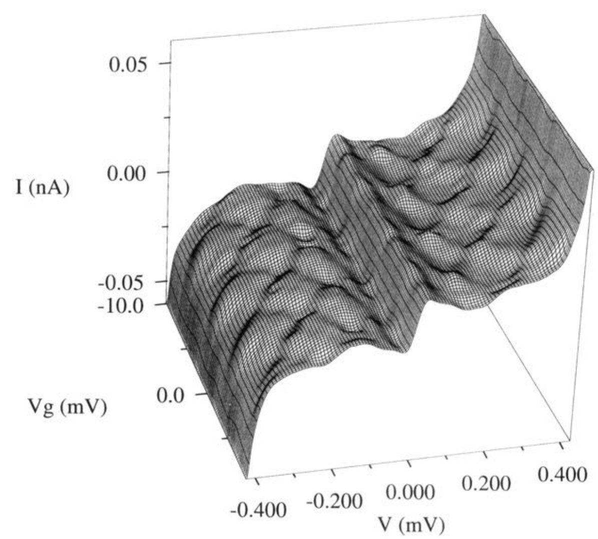

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