Quantum Jumps between Macroscopic Quantum States of a Superconducting Qubit Coupled to a Microscopic Two-Level System

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We report the observation of quantum jumps between macroscopic quantum states in a superconducting phase qubit coupled to the two-level systems in the Josephson tunnel junction, and all key features of quantum jumps are confirmed in the experiments. Moreover, quantum jumps can be used to calibrate such two-level systems, which are believed to be one of the main decoherence sources in Josephson devices.

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Exploring quantum mechanics in macroscopic artificial quantum systems includes both theoretical interests and application in quantum information [1,2]. Recently, a series of experiments with devices based on Josephson tunnel junctions (JTJ) unambiguously demonstrated the quantum-mechanical behavior of a macroscopic variable [3–6]. The ground state and first excited state, $|0\rangle$ and $|1\rangle$ in Fig. 1(a), of the cubic potential well of a current biased JTJ can be isolated to form an effective two-level superconducting phase qubit whose state can be manipulated by application of microwave pulses [5,7]. The superconducting approach is considered promising for quantum information processing because it is readily to scale up. However, the realization of a superconducting quantum computer is still hampered by decoherence. It is imperative to investigate the decoherence mechanism. Recent experiments have shown that JTJs are ubiquitously coupled to two-level systems (TLS), which are presumably structural defects within the tunnel junction [7]. Such TLS have been identified as one of the dominant sources of decoherence of Josephson phase qubits. Characterizing the TLS, in particular, the effect of an individual TLS on a Josephson junction, is thus critical to the quest to improve the performance of superconducting qubits. The first challenge is to single out a single TLS so that its property can be quantified. The second more fundamental challenge is that in order to study temporal behavior of an individual TLS one need to readout its quantum state. In this Letter, we demonstrate that (1) it is possible to isolate a single TLS from an ensemble and its coupling to Josephson junction can be controlled via frequency selection and (2) the phenomenon known as "quantum jump" in such a coupled TLS-Josephson junction system can be used to readout the quantum state of the TLS, which provides a new approach to calibrate individual TLS and their interaction with the junction.

The concept of quantum jump came from Bohr who suggested that the interaction of light and matter occurs in such a way that an atom undergoes instantaneous transitions of its internal state upon the emission or absorption of a light quantum. These sudden transitions have become known as quantum jumps [8]. Quantum mechanics is originally considered as a statistical theory that makes probabilistic predictions of the behavior of ensembles. Whether it can also be used to describe the dynamics of a single quantum system has been a subject of debate between some founders of quantum mechanics [9]. Observation of quantum jumps in isolated atoms and ions unambiguously settled such dispute as quantum jump is a unique phenomenon displayed only by individual quantum systems that would be totally masked by averaging over an

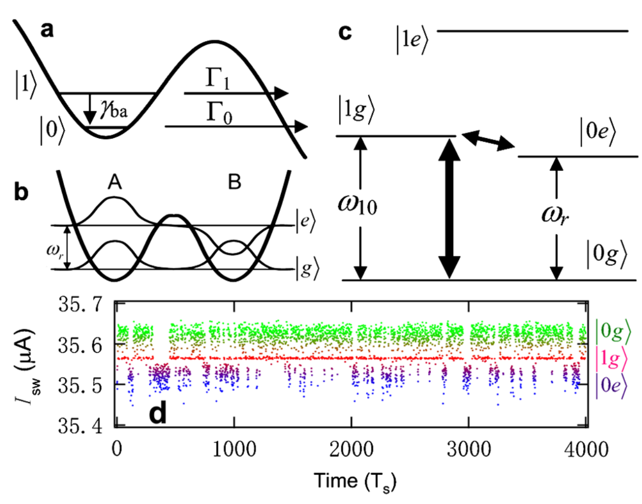

FIG. 1 (color online). (a) Washboard potential of a current biased JTJ. The relaxation and tunneling rates are γ_{ba}, Γ_0, and Γ_1. (b) Double well potential for a TLS. $|g\rangle$ and $|e\rangle$ represent the ground state and the excited state with level spacing ω_r. (c) Energy-level diagram for a junction coupled to a TLS. The energy levels $|0g\rangle$, $|1g\rangle$, and $|0e\rangle$ form the three-level structure used to demonstrate quantum jumps. (d) Simulated I_{sw} trajectory with Hamiltonian (1). The time is in the unit of T_s, the waveform period of I_b. Each point represents I_{sw} obtained in one period of I_b cycle.

ensemble [10]. Quantum jumps in atomic systems also found important applications in quantum measurement, time and frequency standard, and precision spectroscopy [11,12]. In contrast, quantum jumps of a macroscopic system is still an important goal in the field of quantum measurement and its potential application needs to be explored [13].

In what follows, we present experimental evidence for quantum jumps of a single macroscopic quantum system consisting of a current biased JTJ (a phase qubit) coupled to a microscopic TLS, thus demonstrating a fundamental quantum effect in a macroscopic device. Since each TLS has a unique characteristic frequency and the transition frequency ω_{10} between the qubit states $|0\rangle$ and $|1\rangle$ is a smooth function of the bias current I_b, a qubit can be made to couple to a single TLS to form a single composite quantum system by adjusting I_b of the qubit, so that its ω_{10} approaches the level spacing of the target TLS. This system can be tuned to have an effective three-level structure with a strong and a weak transition, as depicted in Fig. 1(c), which is similar to the energy-level scheme utilized to observe quantum jumps in atomic systems [12]. Because occurrence of the weak transition will cause the strong transition to turn on and off abruptly, we denote the strong transition as the "on" state and weak transition as the "off" state, in analogy to the terminology used for atomic systems [12]. A direct consequence of quantum jumps is that the state-dependent switching current $I_{\rm sw}$, at which the junction switches from zero voltage to finite voltage, appears as a random telegraph signal (RTS) [10–12], which is one of the unambiguous signatures of quantum jumps. As for our experiment, we study the trajectory (i.e., time record) of $I_{\rm sw}$ of the phase qubit which showed the predicted RTS when the qubit is irradiated by microwaves with frequency nearly resonating with the TLS. All key features of quantum jumps are confirmed in the experiment. We show that coupling between the qubit and the TLS can be experimentally controlled by adjusting I_b and that the RTS can be used to characterize the property of the TLS. Therefore, the observation of quantum jumps does not only extend the realm of this quantum-mechanical effect to macroscopic quantum systems but also offers an invaluable tool for the study of decoherence in superconducting qubits.

To describe coupling between the TLS and the phase qubit we adopted a model proposed by Simmonds *et al.* [7]. When microwave radiation with frequency ω close to the energy-level spacing of the TLS is applied, an effective three-level system, as depicted in Fig. 1(c), is realized. The two states of the TLS correspond to two different configurations A and B which result in critical currents I_c^A and I_c^B, shown in Fig. 1(b). The interaction Hamiltonian between the TLS and the junction is given by $H_{\rm int} = -\frac{I_c^A\phi_0}{2\pi}\cos\delta \otimes |\Psi_A\rangle\langle\Psi_A| - \frac{I_c^B\phi_0}{2\pi}\cos\delta \otimes |\Psi_B\rangle\langle\Psi_B|$, where $|\Psi_{A,B}\rangle$ represent the two relevant wave functions of the TLS, ϕ_0 is the flux quantum, and δ represents the gauge invariant phase difference across the junction. If we assume a symmetric potential with energy eigenstates separated by $\hbar\omega_r$, the ground and excited states are given by $|g\rangle \simeq (|\Psi_A\rangle + |\Psi_B\rangle)/\sqrt{2}$ and $|e\rangle \simeq (|\Psi_A\rangle - |\Psi_B\rangle)/\sqrt{2}$. Using matrix representation of the phase qubit [14], the Hamiltonian in the basis $\{|a\rangle \equiv |0g\rangle, |b\rangle \equiv |1g\rangle, |c\rangle \equiv |0e\rangle\}$ reads

$$H = \hbar\begin{pmatrix} -i\Gamma_a & \Omega_c - \Omega_m\cos(\omega t) & 0 \\ \Omega_c - \Omega_m\cos(\omega t) & \omega_{10} - i\Gamma_b - i\gamma_{ba} & -\Omega_c \\ 0 & -\Omega_c & \omega_r - i\Gamma_c \end{pmatrix}, \tag{1}$$

where $\Omega_c = (I_c^A - I_c^B)\phi_0\delta_{10}/4\pi$, $\Omega_m = \frac{\phi_0\delta_{10}}{2\pi}I_m$, I_m is the amplitude of the microwave, and $\delta_{01} = \delta_{10} = \frac{2\pi}{\phi_0} \times \sqrt{\hbar/2\omega_{10}C}$ is the coupling matrix element, C is the capacitance of the junction. Here Γ_i ($i = a, b, c$) is the escape rate from the level $|i\rangle$ out of the potential and γ_{ba} is the rate of energy relaxation from $|b\rangle$ to $|a\rangle$. Ω_c is the energy splitting caused by the TLS which can be determined from the spectroscopy [7]. The Hamiltonian (1) determines the evolution of the joint state of the phase qubit and the TLS which can be solved without further approximation through numerical simulation. However, before presenting the results of simulation, we briefly discuss the underlying physics that governs the dynamics of the system. In the interaction picture and choosing a rotating frame of the frequency ω, the Hamiltonian (1) can be simplified to

$$H' = \hbar\begin{pmatrix} -i\Gamma_a & -\Omega_m/2 & 0 \\ -\Omega_m/2 & \Delta - i\Gamma_b - i\gamma_{ba} & -\Omega_c e^{-i\Delta t} \\ 0 & -\Omega_c e^{i\Delta t} & \Delta_r - i\Gamma_c \end{pmatrix}, \tag{2}$$

where $\Delta \equiv \omega_{10} - \omega$ and $\Delta_r \equiv \omega_r - \omega_{10}$ are the detunings. Disregarding all decay terms, the coupling between the states $|1g\rangle$ and $|0e\rangle$ is the result of a competition between the diagonal terms $\{\Delta, \Delta_r\}$ and the off-diagonal term $\Omega_c\exp(\pm i\Delta t)$. When the detunings are relatively large, this three-level system has a weak transition between the states $|0e\rangle$ and $|1g\rangle$ and a strong transition between $|0g\rangle$ and $|1g\rangle$. This configuration is similar to that used to observe quantum jumps in atomic systems [10–12].

The evolution of the system can be modeled using a standard Monte Carlo simulation developed specifically for quantum jumps [12]. In the simulation, in accordance with the experimental procedure, we sweep the bias current I_b linearly from an initial value $\ll I_c$ to a value slightly larger than I_c within time T_0. We divide T_0 into N intervals for sufficiently large N and calculate the evolution trajectory of the coupled system described by Eq. (1). In each interval, we compare the probability p of the qubit switching to the finite voltage state within the interval with a random number r uniformly distributed between zero and one. A switching event is assumed to occur if $p > r$ and the bias current at this interval is then the switching current $I_{\rm sw}$. Otherwise the process is repeated in the next interval until a switching event finally occurs. Figure 1(d) shows a simulated $I_{\rm sw}$ trajectory using parameters appropriate for our qubit. I_{sw} is clearly clustered around three values. The upper, middle, and lower values correspond to the junction escaped to the finite voltage state from the states $|0g\rangle$, $|1g\rangle$, and $|0e\rangle$, respectively. Since the coupling between $|0g\rangle$ and $|1g\rangle$ is much stronger than that between $|1g\rangle$ and $|0e\rangle$, the system undergoes frequent transitions between $|0g\rangle$ and $|1g\rangle$ and infrequent jumps between $|1g\rangle$ and $|0e\rangle$. The abrupt changes in I_{sw} of the qubit mark the occurrence of quantum jumps between the three levels of the system. The parameters used in the simulation are $\omega/2\pi = \omega_{10}/2\pi = 9.02$ GHz, $\omega_r/2\pi = 8.7$ GHz, $\Omega_c/2\pi = 200$ MHz [Fig. 2(c)], $\Omega_m/2\pi \sim 2$ MHz, and $\gamma_{ba} = 0.6\ \mu\mathrm{s}^{-1}$ [15]. All parameters, except coupling strength between the junction and the microwave field Ω_m, were determined from independent measurements and are consistent with the previous reports [5]. From the simulation we found that $\Omega_m/2\pi \sim 2$ MHz, which is consistent with our experimental setup.

Experimentally, we implemented the three-level system using a 10 μm $\times$ 10 μm Nb/AlO$_x$/Nb junction. The parameters of the junction are $I_c \approx 36\ \mu$A and $C \approx 4$ pF, respectively. The device was thermally anchored to the mixing chamber of a dilution refrigerator with a base temperature of about 18 mK. As schematically shown in Fig. 2(a), the switching current of the junction was measured by the four-probe method. The measurement lines were composed of twisted wires, *RC* filters, and copper powder filters [16]. The center conductor of an open-ended coaxial cable was placed above the junction for application of microwave. This arrangement resulted in $>$110 dB attenuation between the end of the coaxial cable and the junction. A sawtooth bias current was applied with a repetition rate of 100 Hz [Fig. 2(b)]. The junction voltage was amplified by a differential amplifier and the switching current was recorded when a voltage greater than the threshold was first detected during every ramp. In the experiment, we first spectroscopically examined the phase qubit by measuring ω_{10} as a function of I_b [Fig. 2(c)] in the region slightly below I_c. The measured $\omega_{10}(I_b)$ agreed well with the theoretical prediction of the $|0\rangle$ to $|1\rangle$ transition [5,7]. An energy-level repulsion caused by coupling to a single TLS in the junction was observed in the spectrum when the frequency of the microwave $\omega/2\pi$ was about 8.7 GHz. In the vicinity of this anticrossing the TLS and qubit formed an effective three-level system which was utilized to observe the aforementioned quantum jumps. The quantum states of the system were determined from the values of I_{sw}.

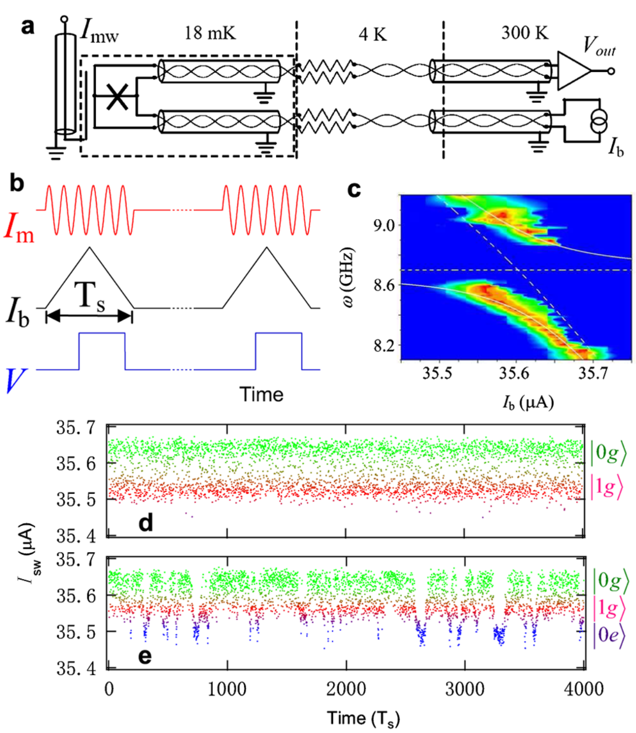

FIG. 2 (color online). (a) Schematic drawing of the measurement circuit. X represents a junction. (b) The time profile of microwave signal, bias current, and voltage signals. (c) Avoided crossing on the qubit spectroscopy caused by the coupling between the qubit and TLS. (d) I_{sw} trajectory with off resonant, $\omega/2\pi = 9.2$ GHz $> \omega_r/2\pi$, and (e) on resonant, $\omega/2\pi = 9.02$ GHz, microwave irradiation at 18 mK.

Figures 2(d) and 2(e) show the measured I_{sw} trajectory as a function of time. When the microwave source is not resonant with the level spacing of the TLS [Fig. 2(d)] the junction and TLS are effectively decoupled. However, the interaction between the junction and the microwave field could still generate transitions between the qubit states $|0\rangle$ and $|1\rangle$. In this case the junction could tunnel out of the potential well either from $|0\rangle$ or $|1\rangle$. Note that I_{sw} of $|0\rangle$ state is slightly higher than that of $|1\rangle$ state. In Fig. 2(d) the trajectories are clustered around 35.63 and 35.55 μA, corresponding to I_{sw} for qubit states $|0\rangle$ and $|1\rangle$, respectively. Here, only the strong transition between $|0g\rangle$ and $|1g\rangle$ was observed because only these two levels were involved in the dynamics of the system. When a microwave field with $\omega/2\pi = 9.02$ GHz was applied [Fig. 2(e)], coupling between the qubit and TLS was turned on. In this case I_{sw} trajectory jumped randomly between three distinctive bands: the upper (35.63 μA), middle (35.55 μA), and lower (35.50 μA) bands, corresponding to the coupled qubit-TLS system being in the states $|0g\rangle$, $|1g\rangle$, and $|0e\rangle$, respectively [17]. Such RTS is the fingerprint of quantum jumps.

One of the prominent signatures of quantum jumps is the exponential decay of the dwell time between the jumps [12]. To analyze our data we borrow from the general methods used to study quantum jumps in atomic systems. We hereafter group the two states $\{|0g\rangle, |1g\rangle\}$ coupled by the strong transition as one state (denoted as "on") and $|0e\rangle$ as the other state (denoted as "off"). Then the system can be fully characterized by the dwell times in the "on" and "off" states and the upward (downward) transition rate $R_{\rm on}$ ($R_{\rm off}$). We extracted distributions of the "on" and "off" time intervals from the experimental data. In each case the results were binned and fit to ex-

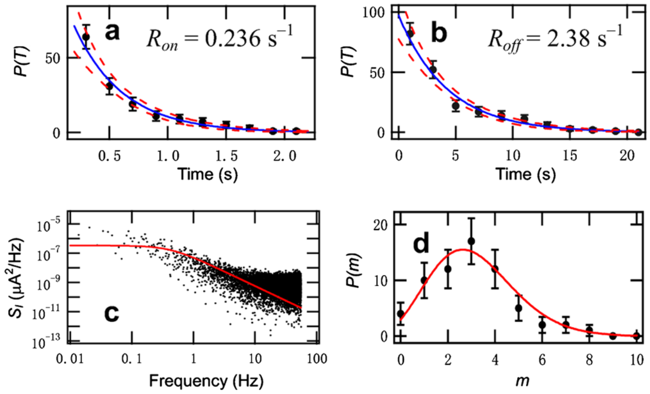

FIG. 3 (color online). The distribution of the length of (a) "on" time intervals and (b) "off" time intervals obtained from experimental data. The solid lines are best fits to exponential decay, and the dashed lines indicate the corresponding 90% confidence bands. (c) Power spectrum of $I_{\rm sw}$ trajectory at $\omega/2\pi = 9.02$ GHz. Solid line was calculated by inserting $R_{\rm on}$ ($R_{\rm off}$) obtained from the fits in (a) and (b) into $S_I(f)$ equation and scaling by κ^2. (d) The distribution of "off" to "on" jumps. m is the events of "off" to "on" jumps in 6 s. The solid line is a fit to a Poisson distribution.

ponential decays [Figs. 3(a) and 3(b)]. The transition rates for the "on" and "off" states obtained from the best fits are $R_{\rm on} = 0.236 \pm 0.036$ s^{-1} and $R_{\rm off} = 2.38 \pm 0.45$ s^{-1}, respectively. The uncertainties of R's were determined following the standard procedure with 90% confidence level. Note that $R_{\rm off}$ is the relaxation rate of the state $|e\rangle$ of the TLS, an important property that otherwise is very difficult to measure. Thus the method presented here enables further investigation of $R_{\rm off}$ as a function of relevant parameters, which is crucial to understand the role of TLS in qubit decoherence.

It is also predicted [11] that the power spectrum of $I_{\rm sw}$ trajectory is a Lorentzian with half-width $2\pi\Delta f = R_{\rm on} + R_{\rm off}$, $S_I(f) = [\kappa^2 R_{\rm on}R_{\rm off}/(R_{\rm on} + R_{\rm off})]\{1/[(2\pi f)^2 + (R_{\rm on} + R_{\rm off})^2]\}$, where κ has the dimension of current. To verify that the observed RTS is indeed due to coupling to a single TLS, we digitized $I_{\rm sw}$ in the "on" and "off" states to obtain its power spectrum using Fourier transformation. As shown in Fig. 3(c), the shape of the power spectrum of RTS agrees well with the theoretical result.

Another verifiable feature of quantum jumps is the functional form of jump history versus time. It is predicted that the distribution of "off" to "on" jumps follows the Poisson statistics [12]. This Poisson distribution is confirmed by the data presented in Fig. 3(d). Therefore, both experiments and simulations showed that $I_{\rm sw}$ trajectory jumps exactly between three distinctive states. Since these macroscopic quantum states represent the motion of about 10^9 electrons, this suggests that 10^9 electrons jump simultaneously to another state in absorption or emission of a single photon. We emphasize that when temperature was increased to 0.2 K, which is above the quantum-to-classical crossover temperature, RTS in $I_{\rm sw}$ disappeared. Hence, our result cannot be explained by a non-quantum-mechanical mechanism.

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