Resonant phase escape in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ surface intrinsic Josephson junctions

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Abstract. We present a study of phase escape in surface Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ intrinsic Josephson junctions in the presence of microwave radiation. The measured switching current distributions display clear double-peak structures in the microwave field, which result from the single- and two-photon resonant escape processes accompanied by microwave-induced potential barrier suppression. We show that these results can be well explained by a quantum-mechanical model proposed by Fistul et al (2003 Phys. Rev. B 68 060504), from which the power and frequency dependences of the switching current distributions can be reproduced.
Josephson devices and circuits behave quantum mechanically at low temperatures. They can be used as artificial atoms for atomic-physics and quantum-optics studies [1] and are promising candidates in superconducting qubit applications [2–5]. Among them, the current-biased Josephson junctions are the simplest, in which rich macroscopic quantum phenomena (MQP), such as macroscopic quantum tunneling (MQT) [6], energy level quantization (ELQ) [7–9] and macroscopic quantum coherence [10, 11], have been demonstrated. In these studies, conventional Josephson junctions made of Al and Nb materials have been mostly used. However, there is a growing interest in other types of junctions, in particular, in the intrinsic Josephson junctions (IJJs) that are fabricated from cuprate Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) superconducting crystals [12–17].

IJJs are distinct in that they are formed within the crystalline Bi2212 superconductor. The superconducting CuO$_2$ double layers in the crystal serve as junction electrodes while the SrO and BiO layers serve as the tunnel barrier, as depicted in figure 1(a) in the case of the mesa-type IJJs used in this work. Both electrodes and the tunnel barrier are smooth on an atomic scale with extremely low defect density. This property is of much interest in qubit applications since previous work shows that defects in amorphous AlO$_x$ tunnel barriers in the Al and Nb junctions act as microscopic two-level fluctuators that cause significant decoherence [18–20].

Interest in IJJs is also due to their very high transition temperature $T_c$, relatively high critical current density $J_c$ and an expected higher classical-to-quantum crossover temperature $T_{cr}$ below which MQP is present. In reported studies by many groups, a $T_{cr}$ as high as 1 K is observed [12–14, 17]. Moreover, the spatial variations of the phase difference and fluxon in the IJJ stacks [12–14, 17] may lead to some interesting physics that is not present in the usual single, small-area (namely the junction size smaller than the Josephson penetration depth $\lambda_J$) Josephson junctions. For example, for the large junctions, $0-\pi$ junctions, and IJJ stacks, a field-theory approach is used to calculate the phase escape rate, which turns out to be many orders of magnitude higher than that in the usual case [21, 22], consistent with the experiment [13]. Recently the theory has been further extended and found to describe excellently the phase diffusion (PD) phenomena in the La$_{2-x}$Sr$_x$CuO$_4$ IJJ stacks [23].

For a junction with critical current $I_c$, capacitance $C$ and effective resistance $R$, $T_{cr}$ can be estimated [24] from $\hbar \omega_p[(1 + 1/4Q^2)^{1/2} - 1/2Q]/2\pi k_B$, where $Q = \omega_p RC$ is the quality factor and $\omega_p = \omega_0(1 - i^2)^{1/4}$, with $\omega_0 = \sqrt{2\pi I_c/C \Phi_0}$ and $i = I/I_c$, is the plasma frequency that depends on the bias current $I$ ($\Phi_0$ being the flux quantum). Since $T_{cr}$ is proportional to $\omega_p$, which depends on the ratio $I_c/C$, it would increase when $I_c$ is increased. However, an increasing $J_c$ also leads to a larger energy-level spacing that scales again with $\omega_p$. This makes it
Since the $I_c$ of the SIJJ is much smaller than that of the inner IJJ (only one is shown for simplicity), the latter only acts as a superconducting lead in the experiment. (b) $I-V$ characteristics at 25 mK for the SIJJ with area $1.4 \times 1.4 \mu m^2$ used in this work.

In various qubit MQP studies, the single-photon excitation is more convenient and fundamental. For this purpose, lowering $J_c$ and therefore $\omega_p$ of IJJs is a straightforward solution. One way to do this is to utilize surface IJJs (SIJJs) in mesa-structured samples, as shown in figure 1(a), in which the $T_c$ of the surface CuO$_2$ double layer can be experimentally tuned so that $J_c$ of the SIJJs is adjustable [25]. In our previous works [15, 16], MQT and the sample’s parameter variation suitable for the qubit design have been demonstrated using mesas with sizes ranging from about $2 \mu m$ down to the submicron level [26]. In this paper, we present a study of such an SIJJ with $\hbar \omega_p/2\pi$ below 20 GHz. The single SIJJ has a size comparable to the Josephson penetration depth $\lambda_J$ so the phase difference across the junction can be considered as spatially uniform. Microwave responses are investigated by measuring the junction’s switching current distribution $P(I)$. By varying the microwave frequency and power, single- and two-photon PAT processes accompanied by a slight barrier suppression are observed in the same sample. We will show that these experimental results can be well explained in terms of a quantum model proposed by Fistul et al [27], which demonstrates that the SIJJs are a convenient system for studying the rich MQP in IJJs.

2. Experiment

The IJJ mesa used in this work was fabricated from a near optimally doped Bi2212 single crystal with bulk $T_c = 88$ K. The mesa contained eight IJJs and had a lateral dimension of 1.4 $\mu m$. 
The doping level of the surface CuO$_2$ double layer was carefully adjusted, resulting in a reduced transition temperature of $T'_c = 44$ K. Details of the fabrication process, especially for the surface layer control, are described in [25]. The $I$–$V$ curve measured at 25 mK for the SIJJ is shown in figure 1(b). The sample’s $I_c$ is seen to be less than 3 $\mu$A. Below we will see from the fit that $I_c$ is 2.9 $\mu$A, corresponding to a $J_c$ of 148 A cm$^{-2}$. According to the estimation in [28], this value would lead to a Josephson penetration depth of $\lambda_J \sim 1$ $\mu$m, which indicates that the junction can be roughly considered as in the small-junction limit.

We measured $P(I)$ using the time-of-flight technique, as described in our previous work [15, 16, 29, 30]. The sample was enclosed in a copper box that was anchored to the mixing chamber (MXC) of the dilution refrigerator. To reduce the noise below an acceptable level, a trilayer $\mu$-metal shield was used, and the measurement circuits were filtered by EMI filters at room temperature, RC low-pass filters at the 1 K pot stage and copper powder filters at the MXC temperature [31]. The microwave was coupled to the junction via an electrical dipole antenna at the end of a coaxial cable, along which there were a 20 dB attenuator at the 1 K pot stage, a 10 dB attenuator and a dc block at the still stage. In our measurement, the bias current was ramped up at a constant rate of $dI/dt = 8.93$ mA s$^{-1}$ with a repetition rate of 100 Hz. To reduce statistical uncertainty, each measured $P(I)$ contained $10^4$ escape events. In figure 2(a), the measured $P(I)$ values at some typical temperatures ranging from 25 mK to 4.2 K are plotted.

### 3. Results and discussion

According to the resistively and capacitively shunted junction model [32], the dynamics of a Josephson junction can be described by a fictitious phase particle with position $\varphi$, mass $M = C(\Phi_0/2\pi)^2$ and friction coefficient $1/RC$ moving in a washboard potential

$$U(i, \varphi) = -E_i(i \varphi + \cos \varphi),$$

in which $E_i = I_i \Phi_0/2\pi$. For $i < 1$, the phase particle may escape from the well either by thermal activation (TA) or by MQT through the potential barrier, which corresponds to the junction’s switching from the zero voltage state to the finite voltage state. At temperatures higher than the quantum-classical crossover temperature $T_{cr}$, escape from the potential well is dominated by TA while at temperatures below $T_{cr}$, MQT becomes the dominant escape mechanism. The escape rates for the two processes are given by [33, 34]

$$\Gamma_{TA} = \alpha_t \frac{\omega_p}{2\pi} \exp \left( -\frac{\Delta U}{k_B T} \right),$$

where $\alpha_t = 4/(\sqrt{1 + Q k_B T / 1.8 \Delta U} + 1)^2$ is the damping-dependent factor and $\Delta U(i) = 2E_j [\sqrt{(1 - i^2)} - i \arccos(i)]$ is the barrier height, and

$$\Gamma_{MQT} = \alpha_q \frac{\omega_p}{2\pi} \exp \left[ \left( -\frac{7.2 \Delta U}{\hbar \omega_p} \right) \left( 1 + \frac{0.87}{Q} \right) \right],$$

where $\alpha_q = [120\pi (7.2 \Delta U / \hbar \omega_p)]^{1/2}$.

In figure 2(b), we show the temperature dependence of the mean $\langle I_{SW} \rangle$ and width $\sigma$ of the experimental $P(I)$ (symbols), together with the results calculated from the TA and MQT theories (solid lines) using the standard conversion between $\Gamma_{TA,MQT}$ and $P(I)$ [35]. We can see that $\sigma(T)$ has three distinctive regimes that are separated by two characteristic temperatures $T_{cr}$ and $T_0$. Below $T_{cr} \sim 125$ mK, $\sigma$ saturates at $\sim 10$ nA and becomes independent.
Figure 2. (a) Measured $P(I)$ at the temperatures indicated. (b) Temperature dependence of the mean $\langle I_{SW} \rangle$ and standard deviation $\sigma$ of $P(I)$ (symbols). The MQT to thermal activation (TA) crossover temperature $T_{cr} \sim 125 \text{ mK}$ and the temperature $T_0 \sim 2.5 \text{ K}$ above which PD occurs are indicated. Solid lines are predictions from the TA and MQT theories.

of temperature, suggesting that the escape mechanism of the phase particle is dominated by MQT. For $T_{cr} < T < T_0 \sim 2.5 \text{ K}$, $\sigma \propto T^{2/3}$, which indicates that TA dominates. For $T > T_0$, $\sigma$ decreases with increasing temperature, indicating that the PD process sets in [15]. In this process, the particle escapes from one well in the washboard potential and is retrapped in the subsequent wells before finally switching to the running state. In fitting the experimental data with the TA and MQT theories, we are able to determine the junction’s $I_c$ to be 2.9 $\mu$A and $C$ to be 260 fF. The results are found to change only slightly when the junction’s $R$ varied in a typical range from a few hundred to a few thousand ohms. The obtained parameters are listed in table 1. Using these parameters, we calculate the crossover temperature $T_{cr}^{\text{cal}}$ to be $\sim 130 \text{ mK}$, which agrees well with the experimental result of $\sim 125 \text{ mK}$ as shown in figure 2.

In the measurement of $P(I)$, we increase the bias current, so the junction’s plasma frequency and the energy spacing between the ground and excited levels decrease continuously.
When the microwave is applied and its frequency $\nu$ matches a fraction of the level spacing and satisfies the condition $2\pi \nu m = \omega_0 n$, where $\hbar \omega_0 = E_n - E_0$ is the level spacing between the ground state and the $n$th level ($m$ is a small positive integer), the particle will be excited from the ground to the excited level, resulting in escape from the level and a resonant peak in $P(I)$ appears [7–9]. However, for this process to happen, the microwave-induced excited-level population times the escape rate of the level should be large. Explicitly, one can consider the exponent in equation (3) to be of the order of unity, which leads to the condition

$$
(2\pi \nu / \omega_0)^5 \lesssim \hbar \omega_0 / E_1
$$

required for the resonant escape to appear.

Figure 3(a) shows the density plot of $P(I)$ versus power in the presence of $\nu = 17.9$ GHz microwave radiation. It can be seen that $I_{SW}$ decreases slightly with increasing power before resonant escape occurs, which results in a double-valued structure in a narrow microwave power range. After that $I_{SW}$ becomes single valued again and is seen to decrease at a faster rate with further increasing power. The slight decrease of the switching current with microwave power should result from an effective barrier suppression; hence the observed resonant escape is not the simple situation described above. In fact, taking the junction’s parameters in table 1, we find $(2\pi \nu / \omega_0)^5 \sim 0.085$ and $\hbar \omega_0 / E_1 \sim 0.02$ so equation (4) is clearly not satisfied.

To further verify the situation, we calculate the energy levels, and the level escape and transition rates of the junction using an approach described in [36]. The total escape rate $\Gamma_{LO}$ is then obtained from the stationary solution of the master equation first considered by Larkin and Ovchinnikov [36, 37]. In figure 4, we show the switching current distribution $P(I)$ taken from figure 3(a) at three microwave powers of $-4$ (squares), 0.6 (circles) and 3 (triangles) dBm. The result at the power of 0.6 dBm displays a clear double-peak structure with two peaks located at bias currents of $I_1 = 2.69$ $\mu$A and $I_2 = 2.53$ $\mu$A. If we assume unsuppressed potential barriers, the calculated energy level numbers within the potential well are 3 and 7 for $I = I_1$ and $I_2$, respectively, which are shown in the upper and lower insets. The calculated escape rate $\Gamma_{LO}$ is found to be dominated by the phase particle’s escape from the ground state; thus estimation using $\Gamma_{MQT}$ is convenient. For $I_1 = 2.69$ $\mu$A, we have $\Gamma_{MQT} \sim 50$ s$^{-1}$, which is about two to three orders of magnitude smaller than the value expected from the $P(I)$ data measured using the present current sweeping rate. This indicates that a slight barrier suppression must occur. The barrier suppression becomes more significant at a lower $I_2 = 2.53$ $\mu$A where the resonant peak locates, since assuming an unsuppressed potential barrier we have seven energy levels in the potential well and $\Gamma_{MQT}$ will be of the order of $10^{-9}$ s$^{-1}$.

In order to explain the results in figures 3(a) and 4, we use a model proposed by Fistul et al [27], in which barrier suppression is taken into account and the system is treated quantum
Figure 3. (a) Density plot of $P(I)$ versus microwave power for single-photon absorption at $v = 17.9$ GHz and $T = 25$ mK. The plot is color coded according to the bar on the right-hand side. (b) Switching current $I_{SW}$ versus microwave power at $v = 17.9$ GHz for three fixed $Q(=\omega^2/\alpha^2)$ values as calculated from equation (7). The red line with $Q = 100$ matches fairly well the experimental result in (a), which is shown as solid dots with the horizontal axis converted to the linear power dependence. The result leads to $R = 2090 \Omega$ if $\omega_0$ is used for $\omega_p$. It can be seen that the double-peak feature starts disappearing for $Q < 50$.

mechanically. According to this model, the normalized switching current $i_{SW} = I_{SW}/I_c$ versus the applied microwave strength can be written as

$$i_{SW} = 1 - \frac{\eta^2}{2} \sum_{nm} \frac{|\langle n|\phi|m \rangle|^4}{[\hbar^{-1}E_{nm}(I_{SW}) - \omega]^2 + \alpha^2}, \quad (5)$$

where $E_{nm}(I_{SW}) = E_n(I_{SW}) - E_m(I_{SW})$, $\eta$ is the normalized ac current amplitude induced by the microwave field, $\omega = 2\pi v$ is the circular frequency of the microwave, $\langle n|\phi|m \rangle$ is the matrix element and $\alpha^2 = \omega^2/Q$ is the damping parameter of the junction. In this work, we only take the ground state and the first excited state into account so the harmonic oscillator consideration
Figure 4. $P(I)$ taken from figure 3(a) at three microwave powers of $-4$ (squares), 0.6 (circles) and 3 (triangles) dBm. The upper and lower insets show the energy levels at bias currents of $I_1 = 2.69\,\mu\text{A}$ and $I_2 = 2.53\,\mu\text{A}$ as indicated on the $P(I)$ curve with the power of 0.6 dBm displaying the double-peak structure.

is a good approximation. In this case, we have $E_{01} = \hbar\omega_p$ and

$$|\langle 0 | \hat{\phi} | 1 \rangle|^2 = |\langle 0 | \sqrt{2m\omega_p}(a + a^\dagger) | 1 \rangle|^2 = \frac{2e^2}{\hbar \omega_p C},$$ \hspace{1cm} (6)

in which $e$ is electronic charge. Replacing $\eta^2/2$ with $W/k$, where $W$ is the microwave power and $k$ the coupling coefficient, equation (5) can be written as

$$i_{SW} = 1 - \frac{4e^4}{C^2\hbar^2} \frac{W/k}{\omega_p^2[(\omega_p - \omega)^2 + \omega^2/Q]},$$ \hspace{1cm} (7)

where $\omega_p = \omega_0(1 - i_{SW}^2)^{1/4}$ is a function of $i_{SW}$. In figure 3(b), we show the calculated $I_{SW}$ versus $W$ for three fixed $Q$ values using the junction parameters in table 1. The red line calculated with $Q = 100$ shows good agreement with the experimental result in figure 3(a), which is plotted as solid dots from the peak positions of the switching current distributions. This $Q$ value leads to a damping parameter of $\alpha = 0.06\omega_0$ and an effective junction resistance of $R = 2090\,\Omega$ if we take $Q = \omega_0 RC$. For comparison, we also show in figure 3(b) the results with $Q = 50$ and 200. We see that the blue line with $Q = 50$ decreases monotonously with increasing microwave power, which means that there would be no double-peak structure in $P(I)$ if the quality factor is less than 50. On the other hand, the green line with larger $Q = 200$ shows that a double-peak feature with larger peak separation and wider microwave power range would appear.

The junction’s quality factor $Q$ can be estimated in an alternative way from the microwave enhancement of the phase escape rate $\Gamma$ converted from the switching current distributions [7, 9]. In figure 5, we plot the experimental results (dots) together with a Lorentzian fit (solid line) taking into account two power levels of $W_1 = -0.8\,\text{dBm}$ and $W_2 = 0.6\,\text{dBm},$ just before
Figure 5. Microwave enhancement of the escape rate $\Gamma$ converted from the data in figure 3(a) at two power levels of $W_1 = -0.8$ dBm and $W_2 = 0.6$ dBm, just before and at which the double-peak structure appears (see figure 4), respectively. Dots represent the experimental result and the line is a Lorentzian fit. The full-width at half-maximum corresponds to $\Delta \nu = 512$ MHz, giving rise to a quality factor $Q$ of $\nu / \Delta \nu = 35$.

and at which the double-peak structure appears (see figure 4), respectively. When the full-width at half-maximum $\Delta I_{SW}$ is converted to the width in the frequency domain, we find $\Delta \nu = 512$ MHz, which leads to a quality factor $Q$ of $\nu / \Delta \nu = 17.9$ GHz/512 MHz = 35. This value compares to the above fitted result considering that the present experiment involves a relatively strong microwave drive that results in noticeable barrier suppression. In this case, the escape rate enhancement in figure 5 is evaluated relative to the value just before the double-peak structure appears, not to that in the absence of the microwave drive.

Equation (5) or (7) thus captures the basic feature of the experimental switching current distributions and can provide a useful way for the estimation of the damping parameter $\alpha$ and the effective resistance $R$ of the junction by model fitting to the experimental data. However, in figures 3(b) and 4, one would expect the resonant condition $\omega_p = \omega$ to be satisfied at $I_{SW} = I_2 = 2.53$ $\mu$A. Nevertheless, from simple calculations we find that $\omega_p / 2\pi = 20.5$ GHz at $I_2$ or $\omega_p = 19.6$ GHz at $I'_2$ in figure 3(b), which is 2.6 (or 1.7) GHz higher than the applied microwave frequency of 17.9 GHz. We suspect such discrepancies to be caused by two factors that are not considered in equation (5) or (7). Firstly, equation (5) is derived considering that the effective potential barrier has no extreme points (or $\Delta U = 0$) [27]. This condition seems over-restricted since the phase particle will escape out of the potential well via the MQT process at certain $\Delta U > 0$. Secondly, there may exist suppression of energy level separation when the microwave power becomes stronger.

In figure 6, we show the measured $P(I)$ versus the applied microwave power at $T = 25$ mK for different frequencies around $\nu = 17.9$ GHz. A distinct feature of these results is that the peak separation of the double-peak structure increases with increasing $\nu$, which we find to be also explainable within the model of Fistul et al. In figure 7, we show the calculated results from
Figure 6. Density plot of the measured $P(I)$ versus applied microwave power at $T = 25$ mK for (a) $\nu = 17.7$ GHz, (b) $\nu = 17.9$ GHz and (c) $\nu = 18.1$ GHz. The plot is color coded according to the bar on the right-hand side.

Figure 7. Calculated switching current $I_{SW}$ versus microwave power using the junction’s parameters in table 1 and $Q = 100$ for three frequencies $\nu$ indicated. Three vertical arrows are guides showing that the peak separation of the double-peak structure increases with increasing $\nu$ as observed experimentally (figure 6).

the model using the junction’s parameters in table 1 for the same microwave frequencies as in figure 6. Three downward arrows are guides showing that the peak separation of the $P(I)$ double-peak structure increases with increasing $\nu$, in agreement with the experimental results in figure 6.

Similar to the single-photon process, the phase particle may also undergo resonant escape by absorbing more than one photon. Figure 8 shows the measured $P(I)$ versus the applied microwave power at $T = 25$ mK for three frequencies of $\nu = 8.9, 9.0$ and 9.1 GHz, which correspond approximately to half of the frequency values in figure 6. The results show a clear $I_{SW}$ drop as the microwave power increases, which is seen again to increase with increasing microwave frequency, as is the case in figure 6. In the present case, the results are relatively
Figure 8. Density plot of the measured $P(I)$ versus applied microwave power at $T = 25$ mK for (a) $\nu = 8.9$ GHz, (b) $\nu = 9.0$ GHz and (c) $\nu = 9.1$ GHz demonstrating a two-photon PAT process. The plot is color coded according to the bar on the right-hand side.

smeared, showing gradually with increasing frequency a broadened peak in $P(I)$ to a clear double-peak structure, indicating that the two-photon PAT process is present.

The above results demonstrate that the quantum picture of the resonant phase escape with barrier suppression well interprets the experimental observations in figures 3, 4, 6 and 8 for the Bi2212 SIJJ. These results are similar to those observed previously in both the conventional Josephson junctions [27, 29, 38] and the IJJs [14, 17], and differ from the reports in [7–9] in that they are accompanied by certain barrier suppression and equation (4) is not satisfied.

We note that similar double-peak features in $P(I)$ at temperatures above $T_{cr}$ in the classical regime have been observed and explained within a classical nonlinear theory [39]. Furthermore, pseudo-Rabi oscillations in the classical regime have also been discussed extensively [40–43]. Theoretical studies have suggested several key experimental tests [41, 42] in order to distinguish the quantum effect from a classical one: (a) the resonances appear only at the subharmonics, not at the overtones; (b) the resonances have Lorentzian shape in contrast to the classical asymmetric shape; and (c) with increasing driving, the resonances shift to the higher frequencies. It will be interesting to use these tests to clarify the quantum or classical nature of the SIJJ systems. From the present results, we see that when the SIJJ is placed at temperatures well below the classical-to-quantum crossover temperature $T_{cr}$ and only a few energy levels are involved in the microwave excitation process [43], it behaves quantum mechanically, with its response to the microwave field well described by the quantum PAT process. In addition, our experimental observations at higher temperatures are also consistent with the quantum picture. We find that when the temperature is increased above $T_{cr}$, the double-peak structure in $P(I)$ usually disappears. According to the discussion in [27], thermal fluctuation will lead to the smearing of the $I_{SW}$ drop and therefore to the disappearance of the resonant peak at higher temperatures. Also, from our calculations using the approach of Larkin and Ovchinnikov [36, 37], we find that at temperatures well above $T_{cr}$, the phase particle is mainly populated at higher excited energy levels and thus the usual PAT process will not occur even when the microwave frequency $\nu$ matches energy level spacing $E_{01}$.
4. Summary

We presented a systematic study of the phase escape and switching current distribution for a Bi2212 surface IJJ in the microwave field. Compared with the usual inner IJJs, the surface IJJ had a reduced and controllable Josephson current density and the energy level spacing was adjusted below 20 GHz allowing convenient single- and two-photon excitation measurements in the presence of microwave radiation. The switching current distributions under microwave driving with various power and frequency were measured, which display clear double-peak features resulting from the single- and two-photon resonant phase escapes with microwave-induced potential barrier suppression. We showed that these results can be well explained by a quantum-mechanical model proposed by Fistul et al in [27].

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