Macroscopic Quantum Tunneling in a *d*-Wave High-T_C $Bi_2Sr_2CaCu_2O_{8+\delta}$ Superconductor

K. Inomata,[1,2,*] S. Sato,[1] Koji Nakajima,[1] A. Tanaka,[2] Y. Takano,[2] H. B. Wang,[2] M. Nagao,[2] H. Hatano,[2] and S. Kawabata[3]

[1]*Research Institute of Electrical Communication (RIEC), Tohoku University, Sendai 980-8577, Japan*
[2]*National Institute for Materials Science (NIMS), Tsukuba 305-0047, Japan*
[3]*National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8586, Japan*
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While Josephson–junction-like structures intrinsic to the layered cuprate high temperature superconductors offer an attractive stage for exploiting possible applications to new quantum technologies, the low energy quasiparticle excitations characteristically present in these *d*-wave superconductors may easily destroy the coherence required. Here we demonstrate for the first time the feasibility of macroscopic quantum tunneling in the intrinsic Josephson junctions of a high temperature superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$, and find it to be characterized by a high classic-to-quantum crossover temperature and a relatively weak quasiparticle dissipation.

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A marked feature characterizing cuprate high temperature superconductors (HTSC) is its strong two dimensionality. In particular the bismuth-based HTSCs, for which this anisotropy is prominent, are best viewed as stacks of superconducting CuO_2 planes weakly linked through intrinsic Josephson junction (IJJ) type couplings [1]. These built-in atomic scale links are tailor-made for technical applications difficult to achieve with artificial Josephson junctions (JJs), and its study has now developed into an active interdisciplinary field. We report below what is to our knowledge the first successful observation of the macroscopic quantum tunneling (MQT) [2–5] of the phase variable of the superconducting order parameter through the potential barrier of an IJJ, opening up an entirely new direction for HTSC applications. While the corresponding phenomena had been observed at around 300 mK in conventional JJs [3,5,6], we have confirmed MQT behavior at approximately 1 K apparently reflecting the characteristically high plasma frequency of IJJs. Our results are highly nontrivial in that they also demonstrate the feasibility of MQT in spite of the presence of dissipative low energy quasiparticles [7–10], which is the other hallmark of HTSCs.

Current-biased JJs offer an ideal stage for realizing a variety of macroscopic quantum phenomena, e.g., energy level quantization within the potential well [4,11,12] and the associated MQT and macroscopic quantum coherence [13,14], all of which have come to be recognized as having immediate implications for qubit applications [13,15–17]. In particular, a phase qubit utilizing MQT has been reported by Martinis and co-workers [15].

Aside from external noises and disorder, a primary source which stands as an obstacle towards observation of MQT is the influence of nonsuperconducting quasiparticle excitations [2]. In conventional *s*-wave superconductors, all quasiparticle states are separated from the superconducting ground state by a finite energy gap and thus become essentially inaccessible upon going to sufficiently low temperatures; hence the observability of MQT. The situation is drastically altered when we turn to HTSCs, which are *d*-wave superconductors. The latter are characterized by four nodes in the order parameter at which the energy gap vanishes [18,19]. HTSCs therefore necessarily sustain a finite population of dissipative quasiparticles down to the lowest temperatures, which would lead one to render MQT unattainable. While this accounts for the absence of previous phase-MQT reports in HTSCs, several theoretical works have recently put this naive view into question by inferring that dissipation due to nodal quasiparticles is not strong enough to totally destroy the coherence required for MQT [7–10]. In addition to the moderately weak influence of quasiparticles, it is also crucial from the experimental point of view to have (1) JJs bearing a high degree of underdamping and hysterics, and (2) a measurement system sufficiently detached from the environment. Devising samples and apparatus fulfilling this prerequisite constituted an integral portion of our project of observing MQT in the IJJs of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212).

We now turn to the description of our samples and measurement setup. In Bi-2212, it is well known that the stacking crystal structure along the *c* axis consists of an alternating array of the superconducting (S) CuO_2 layers and the insulating (I) BiO and SrO layers. The excellent JJ properties exhibited by IJJs in Bi-2212 are by now well established; being ideal atomic sized junctions [1,20], they are, in particular, free of defects and surface roughness of the insulating oxide layers which degrade the quality of artificially made JJs, such as in Al and Nb. To probe the characteristics of the built-in IJJs, it is necessary to construct a pass for the interlayer current flow as illustrated in Fig. 1(a) employing the combination of the double side etching and 3D focused ion-beam etching techniques [21,22]. The junction thus fabricated will generally consist of several layers of IJJs coupled inductively and via charging effects—the number of which is technically difficult to control owing to its minute (Angstrom) scale. Therefore, the IJJs form a 1D-array of S-I-S type JJ. Close to zero bias,

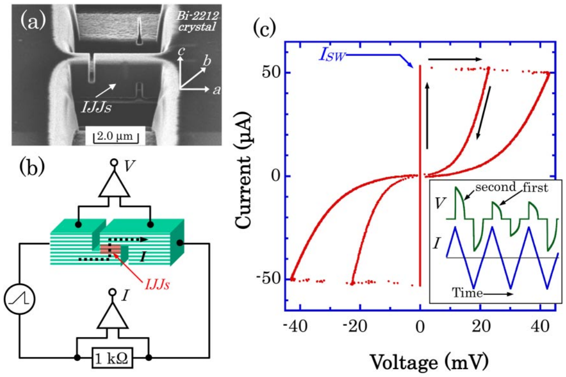

FIG. 1 (color online). (a) Scanning ion-beam micrograph of the IJJs. The critical temperature of the sample is around 90 K. The number of elemental junctions in the IJJs is less than 20 and the junction dimension in the ab plane is $1.76 \times 0.86\ \mu\mathrm{m}^2$. (b) Schematic of the bias lead configuration. Electrical properties of IJJs were measured with the four probes method. (c) I-V characteristic of the IJJs measured at 4.2 K. The I-V curves were measured by ramping a bias current up and down repeatedly. A total of two resistive branches (first and second branches) are exhibited in this figure. The inset shows V or I vs time.

the behavior is nevertheless well captured in terms of a single junction model [23], as evidenced from our experiments detailed below. The IJJs were mounted on the copper-mixing chamber of a ^{3}He/^{4}He Oxford dilution refrigerator with an excellent thermal contact and cooled down from 4.2 K and 40 mK. All cable connections at room temperature were guided through high impedance cupronickel semirigid coaxial cables, which work as a low-pass filter above 1 GHz, to avoid propagating thermal flows and external noises into the sample. Moreover, by using LC low-pass filters along these cables we achieved a strong attenuation of the external noises above 15 MHz. The dilution refrigerator along with the entire analog-measurement system was placed in a shielding room.

The dynamics of a Josephson junction [24,25] is conveniently described as the motion of a fictitious particle in a washboard potential $U(\varphi) = -U_0(x\varphi + \cos\varphi)$, where the phase difference φ is to be viewed as the particle coordinate. Here $U_0 = I_C/2e$ is the Josephson coupling energy and $x = I/I_C$ (I: bias current, I_C: critical current). The particle at the bottom of the potential well oscillates at the plasma frequency defined as $\omega_p = \omega_{p0}(1 - x^2)^{1/4}$, where $\omega_{p0} = (2eI_C/\hbar C)^{1/2}$ is the zero-bias plasma frequency and C is the junction capacitance. In the presence of a bias current, $U(\varphi)$ consists of a periodic potential structure separated by the energy barrier $E(x) = U_0\{-\pi x + 2[x\sin^{-1}x + (1 - x^2)]^{1/2}\}$. Thermal fluctuations at sufficiently high temperatures assist a thermally activated escape of the particle across the barrier whose rate is given by [26]

$$\tau_{\mathrm{TA}}^{-1} = \frac{\omega_p}{2\pi}\exp\left(-\frac{E(x)}{k_B T}\right), \tag{1}$$

where k_B is the Boltzmann constant and T is the temperature. As T is lowered, thermal activation is suppressed exponentially and the escape process eventually gets dominated by MQT events. This crossover takes place at the temperature $T^* \sim \hbar\omega_p/2\pi k_B$ [12,27], and the MQT rate is expressed as [2]

$$\tau_{\mathrm{MQT}}{}^{-1} = 12\omega_p\left(\frac{3E(x)}{2\pi\hbar\omega_p}\right)^{1/2}\exp\left(-\frac{36E(x)}{5\hbar\omega_p}\right). \tag{2}$$

The current-voltage (I-V) characteristic of the IJJs measured by biasing along the c axis [see Fig. 1(b)] at 4.2 K is displayed in Fig. 1(c). The typical I-V characteristic of IJJs exhibiting a multibranch structure was observed. The total number of branches corresponds to the number of elemental junctions in the IJJs as one can confirm by applying a larger bias. When biased, a switching to a finite voltage state takes place at a random value of the switching current I_{SW} and the I-V curve shows a hysteresis. The zero-bias Josephson current is slightly larger than the first branch of IJJs, which indicates that the noise level of our system is quite low. In addition, the McCumber parameter $\beta_C = 2eI_C CR_q^2/\hbar$ and the damping parameter $Q^{-1} = (\omega_{p0}CR)^{-1}$ were $\sim 10^5$ and $\sim 10^{-2}$, respectively. R is the effective shunt resistance, and R_q is the quasiparticle resistance which is estimated from the slope of the first branch of an I-V curve at zero bias. This high degree of hysteresis and the underdamping are crucial for detecting the MQT.

The physical nature of the escape process in JJs can be elucidated by analyzing the statistics of the stochastic switching [6,12,26] from a zero-voltage state to a finite voltage state. To this end measurement of I_{SW} was repeated for 2000 times at each temperature with a current resolution ΔI of 20 nA, which we checked were sufficient to determine the switching current distribution $P(I_{\mathrm{SW}})$. Figure 2(a) shows the temperature dependence of $P(I_{\mathrm{SW}})$. The measurements were performed for the first branch of IJJs. In this experiment a ramp-shaped waveform was used with the constant bias speed dI/dt. Histograms of $P(I_{\mathrm{SW}})$ were calculated against the bias current and the bin width corresponds to the current resolution ΔI of the measurement setup. As T is lowered, $P(I_{\mathrm{SW}})$ narrows and shifts to higher currents. The $P(I_{\mathrm{SW}})$ measured at 4.2 K are fitted with the thermal activation theory proposed by Kramers [28,29], and the zero-noise critical current obtained from the fitting is $I_C = 48.54 \pm 0.02\ \mu$A. This value gives a practical estimate of I_C at 0 K. The results exhibit good agreement with the Kramers theory at 4.2–1.1 K, but deviates substantially below 1 K. Note also that below 1 K, the amount of shift of $P(I_{\mathrm{SW}})$ along the current axis reduces considerably. These findings strongly imply that quantum tunneling takes over and the escape process is essentially T independent in this regime as verified below. We also expect that the good fitting of $P(I_{\mathrm{SW}})$ in the thermally activated regime to conventional theories is an indicator that the weakest link in our IJJs effectively be-

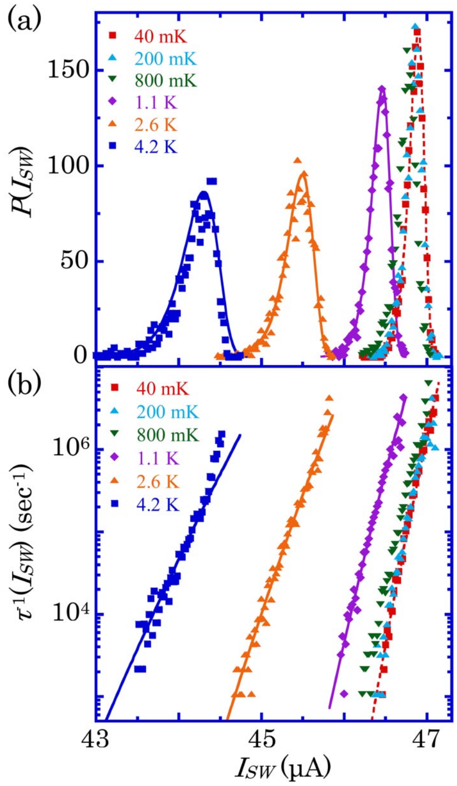

FIG. 2 (color online). (a) Switching current distribution $P(I_{\rm SW})$ of IJJs. The solid and dashed lines are the fitting [28,29] in the thermal and MQT regions, respectively, and the zero-noise critical current I_C was extracted from these fittings. The measurement condition and the junction parameters were the following: $dI/dt = 42.4$ mA/sec, $\Delta I = 20$ nA, $I_C = 48.54 \pm 0.02$ μA, $C = 76.26$ fF, $\omega_{p0}/2\pi = 221.3$ GHz. The junction capacitance C was estimated by $C = \varepsilon_r \varepsilon_0 S/d$, where $d = 15$ Å [1,20] is the c-axis lattice constant of Bi-2212, S is the junction area, $\varepsilon_r = 10$ [20] and ε_0 are the relative permittivity and the vacuum permittivity, respectively. (b) Escaping rate $\tau^{-1}(I_{\rm SW})$ of IJJs. The theoretical thermal rates calculated by Eq. (1) are shown as solid lines, and MQT rate without dissipation, which was calculated by Eq. (2), is exhibited as a dashed line.

haves like a single Josephson junction. Figure 2(b) shows $\tau^{-1}(I_{\rm SW})$ calculated from the experimental data in Fig. 2(a) [12,26]. As T is lowered, the slope of $\ln[\tau^{-1}(I_{\rm SW})]$ increases and $\tau^{-1}(I_{\rm SW})$ shifts to higher $I_{\rm SW}$ similar to the behavior of $P(I_{\rm SW})$. One observes from a comparison of the two figures that below 1 K, where the amount of shift of $P(I_{\rm SW})$ gets smaller and saturates, the rates $\tau^{-1}(I_{\rm SW})$ overlap with each other. This implies that $\tau^{-1}(I_{\rm SW})$ is also independent of T in this regime. Using the value of I_C obtained from the fitting of $P(I_{\rm SW})$, the tunneling rates are estimated from Eqs. (1) and (2). The fitting of $\tau^{-1}(I_{\rm SW})$ agrees with the experimental data.

The standard deviation $\sigma(T)$ of $P(I_{\rm SW})$ is plotted against T on a double logarithmic scale in Fig. 3. In the high T region (1–4.2 K), $\sigma(T)$ is proportional to $T^{2/3}$ as expected, and decreases with decreasing T owing to the suppression of thermal activation. But below 1 K it is saturated and independent of T in accordance with Fig. 2. $T_{\rm esc}$ [4] also exhibits a T-independent behavior. (see the inset of Fig. 3) Actually, we have also observed this kind of saturating behavior of $\sigma(T)$ in the IJJs fabricated in Bi-2212 whisker single crystals. It is also worth mentioning that the two sets of data shown in Fig. 3 were taken from the same sample, where the low-I_C system was obtained by reducing the oxygen content of the original sample. The decrease of T^* with this reduction of I_C, akin to the behavior seen upon applying a magnetic field in low-T_C materials, serves as a check that the MQT event observed is genuine. These phenomena agree with the tendencies which have been reported for low-T_C JJs [3,6]. To check that the observed saturation is not due to external noise, we confirmed that connecting LC low-pass filters in series does not effect the value of $\sigma(T)$. Moreover, an intermittent ramp bias was applied to the sample in order to avoid heating. We are thus led to conclude that the experimental results presented here are direct consequences of MQT of the macroscopic junction phase of IJJs fabricated in HTSC Bi-2212. The effect of MQT appears below the crossover temperature T^*, which we estimate from the data to be 0.75 K for $I_C = 48.54$ μA and 0.95 K for $I_C = 84.92$ μA, and which are shown in Fig. 3 by the open and filled arrows, respectively. Meanwhile, based on the uncertainties of I_C and C, and the bias dependence of T^* as obtained from the formula $T^* \sim \hbar\omega_p/2\pi k_B$ [12,27] is 0.75–0.80 K for $I_C = 48.54$ μA and 0.85–1.0 K for 84.92 μA. These results agree well with the experimental values of T^*'s.

Having established the occurrence of MQT, let us briefly account on its physical implications. We begin by mentioning two factors essential to our findings, i.e., (1) the large

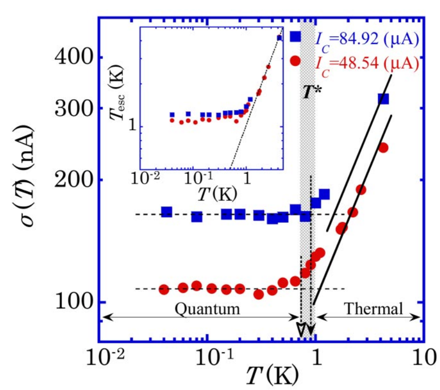

FIG. 3 (color online). Standard deviation $\sigma(T)$ of $P(I_{\rm SW})$. $\sigma(T)$ were calculated by $\sigma = (\langle I_{\rm SW}{}^2\rangle - \langle I_{\rm SW}\rangle^2)^{1/2}$. The two sets of data were taken from the same sample by reducing the oxygen content. The solid lines show the theoretical fitting of the thermal region. $\sigma(T)$ starts to saturate below the crossover temperature T^* [12,27]. The experimental T^*'s of the measured samples are around 1 K, falling within the shaded crossover region calculated theoretically. The inset shows the escape temperature $T_{\rm esc}$ vs T. The dotted line corresponds to $T = T_{\rm esc}$.

magnitude ω_p of the overall energy scale involved, and (2) the relatively weak form of dissipation with which the quasiparticle transport affects the system. The former aspect is apparently reflected in the thermal-to-quantum crossover temperature, which to the best of our knowledge is the highest reported to date. Though the temperature itself is not the main emphasis here, it does expose a potential advantage enjoyed by HTSC materials, which deserves to be explored further. Meanwhile the latter factor concerns the much more subtle issue of ''taming'' the nodal quasiparticles mentioned earlier, which bring us back to the *I-V* characteristics displayed in Fig. 1(c). In general, the quasiparticle dynamics in a JJ is manifested in the *return curve* (the low-voltage subgap portion of the curve following the jump to the first branch, obtained upon switching off the bias current), a regime where Cooper pairs cannot participate in the charge transport. In JJ stacks artificially fabricated using conventional superconductors, this curve exhibits an abrupt drop to nearly zero current at low temperatures [20], signaling a strong suppression of quasiparticle excitations. Meanwhile, the resistively shunted junction model widely employed in quantum mechanical treatments of dissipation in JJs [2] can lead to the dominance of ohmic behavior and decoherence when the resistance becomes a relevant perturbation. The power--law-like tail seen in our data falls into a novel class of behavior termed the *superohmic* dissipation [30], which is intermediate between these two cases. That this subtle form of dissipation should play a crucial role in our observations is in accord with some of the recent theories on d-wave JJs [7–10].

Our study sheds new light on a number of fundamental questions, which reside on the intersection of two major areas of current research: HTSC physics and future quantum technology. For example, it provides a fresh perspective on the issue of differentiating between very distinct forms (e.g., transverse-momentum conserving and nonconserving processes) of quasiparticle tunneling between d-wave superconductors, several of which may account for *superohmic* dissipation. Another related problem—with direct implications to optimizing device geometry—is to resolve how the differences between generic d-wave JJs and the interlayer IJJs would influence MQT experiments. For instance, the absence of zero-energy bound states [10] and the presence of a bilayer tunneling matrix element suppressing nodal quasiparticle tunneling [31] the latter can both be considered advantages peculiar to the IJJs.

In summary, we have successfully observed phase MQT in the IJJs of HTSCs, inviting further investigation on coherence-dissipation competition in these systems. Though only an initial step towards applications, we anticipate that efforts along this line may lead to a rich cross-fertilization between the fields of HTSC science and quantum information.

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Note added.—After completion of this work, we learned that Bauch *et al.* have also observed the MQT at around 40 mK in an HTSC $YBa_2Cu_3O_{7-\delta}$ grain boundary Josephson junction [32].

*Current address: Frontier Research System, RIKEN, 34 Miyukigaoka, Tsukuba 305-0841, Japan.
Email address: inomata@frl.cl.nec.co.jp

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