

Collapse of thermal activation in moderately damped Josephson junctions

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We study switching current statistics in different moderately damped Josephson junctions: a paradoxical collapse of the thermal activation with increasing temperature is reported and explained by interplay of two conflicting consequences of thermal fluctuations, which can both assist in premature escape and help in retrapping back into the stationary state. We analyze the influence of dissipation on the thermal escape by tuning the damping parameter with a gate voltage, magnetic field, temperature and an in-situ capacitor.

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Decay of metastable states is an important process in many scientific areas [1]. Dissipation plays a crucial role in the decay dynamics. The influence of dissipation on thermal and quantum escape from the superconducting (S) to the resistive (R) state in Josephson junctions has been intensively studied both theoretically [1, 2, 3, 4] and experimentally [5, 6, 7, 8, 9, 10, 11], most recently in connection with the problem of decoherence in quantum systems [11].

So far switching statistics was studied for superconductor-insulator-superconductor (SIS) junctions, while superconductor-normal metal-superconductor (SNS) junctions, which are characterized by stronger dissipation effects, remain, to our knowledge, unstudied. Analysis of dissipation effects in SIS junctions is complicated by ill-defined quality factor Q , which can not be represented by a simple constant [4]. Conflicting reports exist about what kind of resistance R determines the effective damping of SIS junctions: the normal resistance [5], the high frequency impedance of circuitry [6], or the quasiparticle resistance [7]. This is not a problem for SNS junctions, which typically have a resistance R considerably smaller than the open space impedance $\simeq 377\Omega$, and are well described by the RCSJ model with frequency independent Q .

Here we study switching current statistics in moderately damped superconductor-two dimensional electron gas-superconductor (S-2DEG-S) and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi-2212) high- T_c intrinsic Josephson junctions (IJJ's). Being able to tune the damping parameter by a gate voltage, magnetic field, temperature and an in-situ shunting capacitor, we analyze the influence of dissipation on the thermal activation (TA). For both of the *drastically different systems* we observe a sudden collapse of TA with increasing T and explain this paradoxical phenomenon by interplay of two conflicting consequences of thermal fluctuations, which on one hand assist in premature switching and on the other hand help in retrapping back to the S-state. We present numeric and analytic calculations

which are in good agreement with our experimental data.

Fig. 1 shows typical Current-Voltage characteristics (IVC's) for a) a S-2DEG-S (Nb-InAs-Nb) junction #1 and c) a Bi-2212 mesa structure containing nine IJJ's. It is seen that the IVC's are well described by the RCSJ model with frequency independent Q [12]. Details of sample fabrication and characterization can be found in Refs. [13, 14] and [15, 16] for S-2DEG-S and IJJ's, respectively. Measurements were done in a shielded room in a dilution refrigerator for S-2DEG-S, or in a He-4 cryostat for Bi-2212. Switching currents were measured using a sample-and-hold technique.

From Fig. 1 it is seen that the IVC's exhibit hysteresis. Figs. 1 b) and d) show T -dependencies of the switching, I_S , and retrapping, I_R , currents for other Nb-InAs-Nb and Bi-2212 junctions studied here. According to the RCSJ model, Q can be obtained from the magnitude of hysteresis, I_S/I_R . In case of Bi-2212, the experimental I_S/I_R agrees well with the calculated Q using capacitance of IJJ's $C \simeq 68.5 fF/\mu m^2$ [16]. For the unshunted S-2DEG-S #1 from Fig. 1 a) the $I_S/I_R \simeq 1.3$, would correspond to $Q \simeq 1.4$ and $C = 0.11 pF$, consistent with the estimated value of the stray capacitance.

On the other hand, the hysteresis in SNS junctions can be also caused by self-heating [17], non-equilibrium effects [18], or frequency dependent Q [4]. In order to understand the origin of hysteresis, we fabricated an in-situ shunt capacitor, consisting of $\text{Al}_2\text{O}_3/\text{Al}$ double layer deposited right on top of the Nb-InAs-Nb junction. The IVC's of the S-2DEG-S #1 before and after C -shunting are shown in Fig. 1 a). It is seen that the hysteresis increased considerably, while R was little affected by C -shunting. Such behavior is inconsistent with the self-heating scenario. Thus the hysteresis in our junctions is predominantly caused by the finite $Q > 1$. A similar conclusion was made for other planar SNS junctions [19], where it was observed that there is no correlation between the hysteresis and the dissipation power at $I = I_R$.

S-2DEG-S junctions provide a unique opportunity to

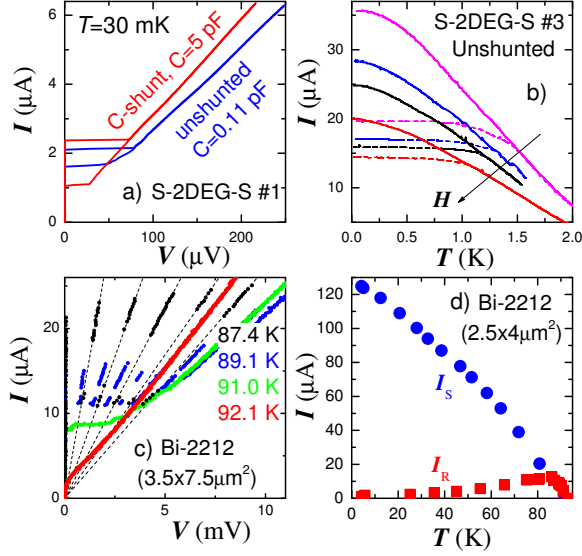


FIG. 1: a) IVC's of a Nb-InAs-Nb junction #1 at $T = 30\text{ mK}$ before and after deposition of an in-situ shunting capacitor; b) Measured switching (solid lines) and retrapping (dashed lines) currents of another Nb-InAs-Nb #3 at four magnetic fields. c) IVC's of a Bi-2212 mesa containing nine stacked IJJ's at four different $T < T_c \simeq 93\text{ K}$. Multibranch structure is due to one-by-one switching of IJJ's. d) Measured switching I_S and retrapping I_R currents of another mesa.

tune the Josephson coupling energy E_{J0} and Q by applying gate voltage V_g [13, 14]. For this purpose a thin gate electrode was deposited on top of the InAs. Fig. 3 a) shows switching current histograms at $T = 37\text{ mK}$ for S-2DEG-S #2 at different V_g . The inset shows the width at the half-height of the histograms ΔI vs. the most probable switching current I_{Smax} . It is seen that initially histograms are getting wider with increasing negative V_g , consistent with the increase of TA with decreasing E_{J0}/T . However, at $V_g < -0.35\text{ V}$ a sudden change occurs and ΔI starts to rapidly collapse.

Fig. 2 b) shows ΔI vs. T for the S-2DEG-S junction #3 at four magnetic fields, the same as in Fig. 1 b). In all cases we can distinguish three T -regions:

(i) At low T the histograms are independent of T , indicative for the Macroscopic Quantum Tunnelling (MQT) regime [3, 4, 5, 6]. The decrease of ΔI with H leaves no doubts that we observe for the first time the MQT in SNS junctions (details will be published elsewhere).

(ii) At intermediate T , ΔI increases in agreement with the TA calculations, shown by dashed lines in Fig. 2 c), for which the escape rate from S to R state is given by

$$\Gamma_{TA} = a_t \frac{\omega_p}{2\pi} \exp \left[-\frac{\Delta U}{k_B T} \right]. \quad (1)$$

Here ΔU is the barrier height, and $\omega_p = \omega_{p0}(1 - (I/I_{c0})^2)^{1/4}$ is the Josephson plasma frequency, $\omega_{p0} =$

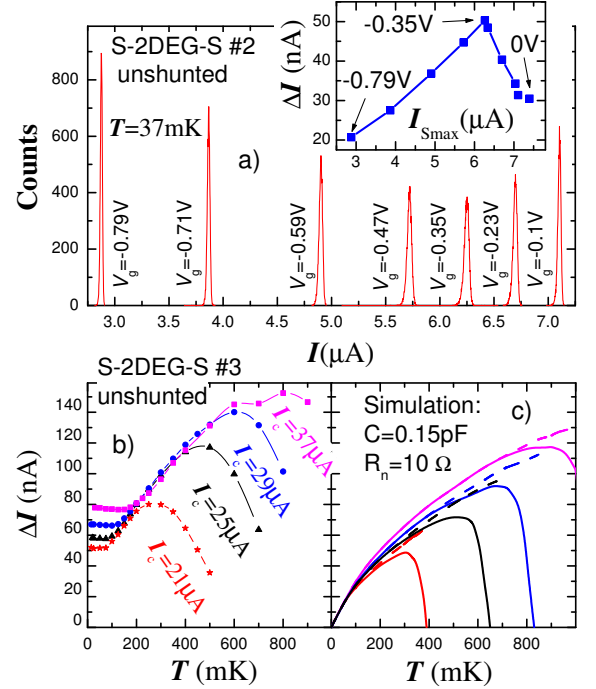


FIG. 2: Switching statistics of S-2DEG-S junctions: a) histograms at different gate voltages for junction #2. Inset shows the width vs. the most probable switching current I_{Smax} . A sudden collapse of ΔI occurs at $V_g < -0.35\text{ V}$. b) The width of histograms vs. T for the junction #3 at four magnetic fields, the same as in Fig. 1 b). Three T -regions can be distinguished: the MQT region at low T , the TA region at intermediate T , and collapse of histograms at higher T . c) Numerical simulations for the case of Fig. 2b). Dashed and solid lines represent ΔI for classical thermal activation disregarding and taking into account retrapping, respectively.

$(2eI_{c0}/\hbar C)^{1/2}$ and I_{c0} is the fluctuation-free critical current. Dissipation enters only into the prefactor of Eq.(1), which for our moderately damped junctions is $a_t = (1 + 1/4Q^2)^{1/2} - 1/2Q$ [3], where $Q = \omega_p RC$.

(iii) At higher T , the histograms start to rapidly collapse leading to a downturn of ΔI . This paradoxical phenomenon is the central observation of this work.

Fig. 3 c) shows that a similar collapse occurs in IJJ's at $T^* \sim 75\text{ K}$. Here we show the effective escape temperature T_{esc} , which indicates how much the *relative* width $\Delta I/I_{c0}$ differs from the TA prediction, Eq.(1). Figs. 3 a) and b) show switching current histograms of a *single* IJJ just before and after the collapse. As reported previously [16], at $T < T^*$ the histograms are perfectly described by TA, shown by the dashed lines. However, at $T > T^*$ the histograms become narrower and loose the characteristic asymmetric shape, as seen from comparison with the TA simulation in Fig. 3b).

We start discussing the observed phenomenon by excluding scenarios which can not explain it. First, it can not be due to T -dependence of the damping parameter

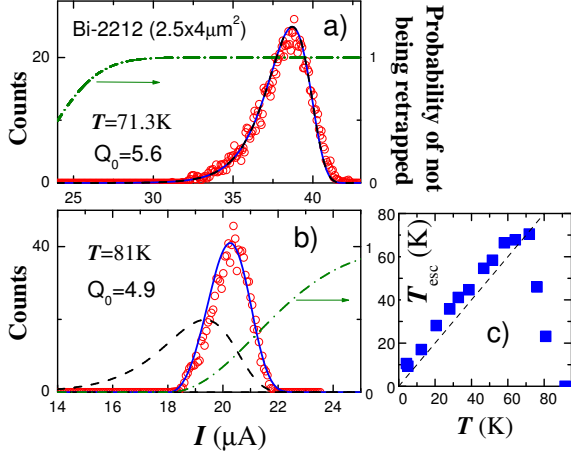


FIG. 3: Switching histograms of a *single* IJJ at a) $T < T^*$ and b) $T > T^*$: circles represent experimental data, dashed lines - TA simulations, Eq.(1), and dashed-dotted lines - probabilities of not being retrapped, Eq(3). Solid lines show the conditional probability of switching without being retrapped (the product of dashed and dashed-dotted lines). Note that both the width and the shape of the histograms change at $T > T^*$ c) The effective escape temperature for the same IJJ. A sudden collapse of T_{esc} at $T^* \simeq 75\text{K}$ is seen.

since $Q(T)$ changes only gradually through T^* and since we did take into account the Q -dependence of the TA prefactor a_t in our simulations. Second, it can not be caused by frequency dependent damping due to shunting by circuitry impedance. Indeed, we also observed a similar collapse for planar SNS junctions [19] with $R \simeq 0.2\Omega$, for which such shunting plays no role.

To explain the phenomenon we first note that T^* is close to the temperature at which hysteresis in IVC's vanishes (cf. Figs. 3c,1d and 2b,1b), indicating that retrapping plays a role in the observed phenomenon. The rate of TA retrapping from R to S state is known only for strongly underdamped junctions $Q \gg 1$ [2]:

$$\Gamma_R = \frac{I - I_{R0}}{Q_0} \sqrt{\frac{E_{J0}}{2\pi k_B T}} \exp \left[-\frac{E_{J0} Q_0^2 (I - I_{R0})^2}{2k_B T} \right], \quad (2)$$

where $Q_0 = \omega_{p0} RC$. Note that unlike the TA escape, the TA retrapping depends strongly on dissipation [10], due to the Q_0^2 factor under the exponent in Eq.(2).

The probability to measure the switching current I is a conditional probability of switching $P_S(I)$ from the S to the R-state *and not being retrapped back* during the time of the experiment:

$$P_{nR} = 1 - \int_I^{I_{c0}} P_R(I) dI / \int_0^{I_{c0}} P_R(I) dI, \quad (3)$$

where $P_R(I) = \frac{\Gamma_R(I)}{dI/dt} \left[1 - \int_I^{I_{c0}} P_R(I) dI \right]$ is the retrapping probability.

Dashed-dotted lines in Fig. 3 a,b) show the calculated P_{nR} . It is seen that at $T < T^*$ the $P_{nR} = 1$ in the

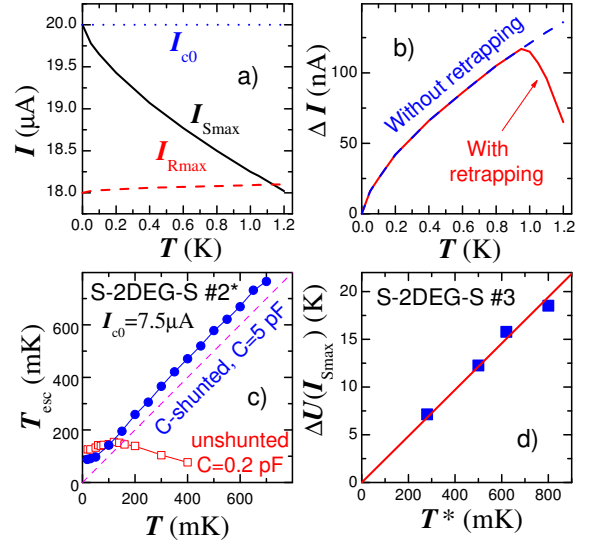


FIG. 4: Numerical simulations for S-2DEG-S #3: a) T -dependence of the fluctuation free $I_{c0} = 20\mu\text{A}$ (dotted line), the most probable switching current I_{Smax} (solid line) and the most probable retrapping current I_{Rmax} (dashed line). b) The width of switching histograms disregarding retrapping (dashed line) and taking into account retrapping (solid line). c) T_{esc} vs. T for S-2DEG-S #2* before and after in-situ C-shunting. d) The height of escape barrier (at the most probable switching current I_{Smax}) vs T^* : symbols represent experimental data from Fig. 2b), the solid line corresponds to the simulation in Fig. 4 b).

region where $P_S > 0$, therefore retrapping is insignificant. However, at $T > T^*$, retrapping becomes significant at small currents. The resulting conditional probability of measuring the switching current, $P(I) = P_S(I)P_{nR}(I)$, normalized by the total number of switching events, is shown by the solid line in Fig.3 b). It is seen that it explains very well both the reduced width and the almost symmetric shape of the measured histogram.

Figs. 4 a,b) show results of simulations, in which we intentionally disregarded the T -dependence of I_{c0} , keeping Q_0 and E_{J0} constant. In the simulations we used the parameters of S-2DEG-S #3. It is seen that the most probable retrapping current I_{Rmax} has a weak T -dependence, consistent with the experiment, see Fig. 1 b). On the other hand, I_{Smax} decreases approximately linearly with T and eventually crosses I_{Rmax} . Fig. 4 b) represents the width of histograms. It is seen that within the TA model ΔI continuously increases with T . However, retrapping reduces ΔI as soon the switching and retrapping histograms start to overlap.

The T^* can be estimated from the system of equations:

$$\Gamma_{TA}(I_{Smax}) \simeq (dI/dt)/I_{c0}, \quad (4)$$

$$\Gamma_R(T_{down}) = \Gamma_{TA}. \quad (5)$$

Here the first equation is the condition for I_{Smax} , which states that the junction should switch into the R-state

during the time of experiment. From Eqs.(1,4) it follows that $\Delta U(I_{Smax})/k_B T \simeq \ln \left[\frac{a_t \omega_p I_{c0}}{2\pi d I/dt} \right] \equiv Y$, which agrees with experiment, as shown in Fig. 4d). Taking $\Delta U \simeq (4\sqrt{2}/3)E_{J0} [1 - I_S/I_{c0}]^{3/2}$, and neglecting T -dependence of I_{c0} , we reproduce the linear T -dependence $I_{Smax}/I_{c0} \simeq 1 - (3Yk_B T)/(4\sqrt{2}E_{J0})$, seen in Fig.4 a). Substituting this expression into Eqs.(5,2) and assuming $I_{R0} \simeq \frac{4I_{c0}}{\pi Q_0}$ (valid for $Q_0 > 2$), we obtain:

$$T^* \simeq \frac{16E_{J0}}{9Q_0^2 Y^{\frac{1}{3}} k_B} \left[\sqrt{1 + \left(1 - \frac{4}{\pi Q_0}\right) \frac{3Q_0^2}{\sqrt{8}Y^{\frac{1}{3}}} - 1} \right]^2. \quad (6)$$

From Eq.(6) it follows that T^*/E_{J0} depends almost solely on Q_0 . Fig. 4 c) shows T_{esc} vs T for a S-2DEG-S #2* (similar to #2) before and after C -shunting. A dramatic difference in the behavior of TA is obvious. As shown in Fig. 1a) the C -shunting affects almost solely Q_0 . Therefore, switching from S to R state is not strongly affected by C -shunting. On the contrary, retrapping is affected considerably because $I_{R0} \sim 1/Q_0$. Under these circumstances, higher T is required to reduce I_{Smax} to the level of I_R , resulting in the increase of T^* .

To get an insight into the phase dynamics at $T > T^*$, we show in Fig. 4 d) the dependence of $\Delta U(I = I_{Smax})$ vs. T^* for the case of Fig. 2b). It is seen that ΔU scales with T . The solid line in Fig. 4d) corresponds to $\Delta U(I_{Smax})/k_B T = 24.3 \simeq Y$ obtained from simulations presented in Figs. 4 a,b) and demonstrates excellent agreement with experiment. The large value of $\Delta U/k_B T$ implies that the junction can escape from S to R state only few times during the time of experiment. Therefore, the collapse is not due to transition into the phase-diffusion state, which may also lead to reduction of ΔI , previously observed in SIS junctions [9, 21] (even though we assume that the decrease of ΔI reported recently in Ref.[21] may also be described by our model). Indeed, phase diffusion requires repeated escape and retrapping, which is only possible for $\Delta U/k_B T \simeq 1$ [4, 20]. Careful measurements of S-branches in the IVC's at $T \gtrsim T^*$ did not reveal any signature of dc-voltage down to $\sim 10nV$ for S-2DEG-S and $\sim 1\mu V$ for IJJ's. Furthermore, as seen from comparison of Figs. 1b, 2b) and Figs. 1d, 3c), the IVC's remain hysteretic at T well above T^* , which is incompatible with the phase diffusion according to the RCSJ model [4]. As can be seen from Fig.1 c) the first indication for the phase diffusion in our IJJ's appears only at $T > 90K$, meaning that all the collapse of TA shown in Fig. 3 c) at $75K < T < 85K$ occurs before entering into the phase diffusion state.

For a quantitative comparison with experiment we performed full numerical simulations of Eqs. (1-3) taking into account the T -dependence of I_{c0} , shown in Fig. 1 b) and the exact value of hysteresis I_{c0}/I_{R0} within the

RCSJ model. Results of the simulations for the S-2DEG-S #3 at four magnetic fields, corresponding to Figs. 1b) and 2b) are shown in Fig. 2c). Dashed and solid lines represent the simulated width of histograms disregarding and taking into account retrapping, respectively. It is seen that simulations quantitatively reproduce T^* for all four magnetic fields. The capacitance $C = 0.15pF$, which was the only fitting parameter, is the same for all four curves and corresponds to the expected value of stray capacitance. Taking into account that T^* is very sensitive to I_{c0} and C , see Eq.(6), we may say that the agreement between theory and experiment is excellent.

In conclusion, we observed a paradoxical collapse of thermal activation with increasing T in two very different types of Josephson junctions with moderate damping. The phenomenon was explained by the interplay of two conflicting consequences of thermal fluctuations, which can both assist in premature switching and help in retrapping back into the S-state. The retrapping process is significant at small currents, causing cutting-off the thermal activation at small bias. We have analyzed the influence of dissipation on the thermal activation by tuning the damping parameter with the gate voltage, magnetic field, temperature and in-situ capacitive shunting. Numerical simulations are in good agreement with experimental data and explain both the paradoxical collapse and the unusual shape of switching histograms.

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