

Revisiting Dissipation-Driven Phase Transition in a Josephson Junction

Diego Subero^{✉,*}, Yu-Cheng Chang[✉], Miguel Monteiro, Ze-Yan Chen, and Jukka P. Pekola[✉]
*Department of Applied Physics, PICO Group, QTF Centre of Excellence, Aalto University School of Science,
 P.O. Box 13500, 0076 Aalto, Finland*



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Despite extensive experimental and theoretical work over several decades, Schmid-Bulgadaev quantum phase transition remains a subject of debate. Here we revisit this problem by performing systematic experiments on low-frequency current-voltage characteristics of Josephson junctions over a wide range of parameters. The experiments are conducted in a true resistive environment formed by a metallic on-chip resistor located near the junction. Over the parameter range of the experiment, we find that the transition occurs when the resistance crosses the quantum value $h/(4e^2) \simeq 6.5 \text{ k}\Omega$ for Cooper pairs, as originally predicted. The temperature T of the experiment is naturally nonzero, but our basic theoretical modeling corroborates that the observations under these conditions can serve as the basis for the conclusions made, in particular, the crossover resistance from superconducting to insulating regime is the same as that at $T = 0$.

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Dissipative effects in quantum systems have captivated researchers for many years due to their profound impact on the properties and behavior of these systems. One of the intriguing phenomena is the phase transition induced by the interaction between the quantum system and its surrounding environment. A notable example is the resistively shunted Josephson junction, which undergoes a superconductor-insulator transition that is influenced by the strength of dissipation. Pioneering works by Schmid [1] and Bulgadaev [2] revealed that, in the zero-temperature limit, the Josephson junction (JJ) would become insulating if the zero-frequency environmental impedance $\{R_e = \text{Re}[Z(\omega \rightarrow 0)]\}$ exceeds the superconducting resistance quantum $R_Q = h/4e^2 \approx 6.5 \text{ k}\Omega$, regardless of the strength of the Josephson coupling E_J .

Forty years later, this transition continues generating significant attention both experimentally [3–5] and theoretically [6–23]. Although dc charge transport experiments have mostly supported this transition [3,24–27], recent microwave experiments have not verified the insulating phase, questioning the validity of the Schmid-Bulgadaev (SB) transition [4,28]. Our recent bolometric heat transport experiment [3] and the theoretical model based on the nonequilibrium Green's functions [17] revealed that the Josephson coupling survives well beyond the predicted SB phase transition. Conversely, a reflectometry experiment on

a Josephson junction coupled to a long section of a transmission line has provided evidence of the transition by monitoring the line's internal dynamics [5], which is influenced by Josephson dynamics. The previous experimental finding has been supported by theoretical calculations involving finite-frequency response [9,13] and the utilization of exact diagonalization techniques [19]. Although finite-frequency measurements seemingly provide evidence of the SB phase transition by mimicking the resistor with an array of Josephson junctions or superconducting cavities, it is important to note that these resonators are far from replicating an actual resistor [29,30]: a one-dimensional JJ array acts as a high-impedance environment with well-defined resonances in its absorption spectrum up to the plasma frequency and becomes purely capacitive above it. We note that the on-chip resistive environment employed here is, in principle, compatible with high-frequency measurements, enabling the combination of dc transport and rf or microwave probes within the same dissipative framework, as demonstrated in related experiments [3,4].

In this Letter, we revisit the dissipative phase transition of a JJ in an Ohmic environment by performing systematic low-frequency lock-in transport measurements. The devices connected to an environment resistance $R_e < R_Q$ all exhibit a conductance peak at zero voltage bias, signaling the superconducting behavior of the JJ, whereas those with $R_e > R_Q$ show a pronounced conductance dip, characteristic of the insulating side of a JJ. Additionally, we conducted measurements on a superconducting quantum interference device (SQUID), acted upon by a tunable magnetic field JJ, which allowed us to explore the influence of Josephson coupling on the phase transition. In light of these findings, we construct a finite-temperature phase

*Contact author: suberoda123@gmail.com

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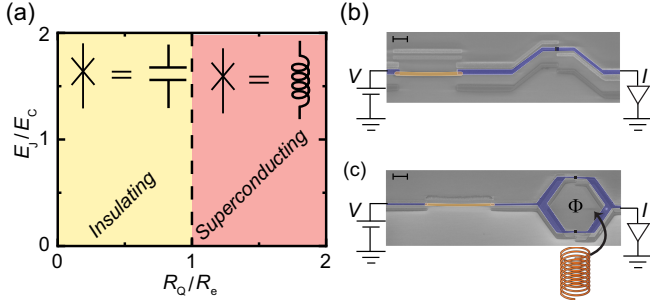


FIG. 1. (a) Schematic illustration of the Schmid-Bulgadaev phase transition in a Josephson junction. False-colored SEM images (scale bar = 2 μm) of (b) a single Josephson junction (Al in blue) and (c) a SQUID connected in series to an Ohmic environment of resistance R_e (Cr in orange).

diagram of a JJ revealing a transition near the critical point $R_Q/R_e \simeq 1$, on the resolution level of our experiment, that is insensitive to the ratio E_J/E_C , in agreement with the theoretical predictions of Schmid and Bulgadaev [1,2].

Two types of Josephson devices were studied: a single junction with an overlap area of $100 \times 100 \text{ nm}^2$ and a SQUID. In both cases, the devices were electrically connected via clean contacts to an on-chip chromium (Cr) resistor that defines the electromagnetic environment [Figs. 1(b) and 1(c)]. The properties of the Cr/Al contact are described in Supplemental Material [31], Sec. S1. For sample fabrication, we refer to Refs. [3,32] and Supplemental Material [31], Sec. S2. The distance between the Josephson element and the resistor was kept to a few micrometers to minimize suppression of environment-induced effects by stray capacitance and series inductance. One can estimate the relevant impedances connecting the junction to the resistor (see Supplemental Material [31], Sec. S3 and Ref. [33] for details of the impedance calculations). The requirement is that the impedance associated with the stray capacitance to ground at thermal frequencies f_{th} be much larger than the environmental resistance R_e , while the impedance associated with the series induc-

TABLE I. Main parameters of the measured single junction samples. The junction resistance R_J and environmental resistance R_e were determined as detailed in the text. Josephson energy E_J is calculated using the Ambegaokar-Baratoff formula, and the charging energy E_C was measured from the voltage offset $eV_b = E_C \approx 2.74 \text{ K}$.

Batch	Device	R_J (k Ω)	E_J (K)	R_e (k Ω)	L (μm)
I	1	22.6	0.330	2.43	1
	2			4.00	2
	3			8.80	4
II	4	73.3	0.102	22.2	10
	5			40.8	20

TABLE II. Experimental and fitting parameters of the three SQUID devices connected to an $R_e = 19.2 \text{ k}\Omega$ resistor. The SQUID loop area is nominally the same ($6 \times 6 \mu\text{m}^2$) for the three devices. The difference lies in the size of the Josephson junction. The fitting parameters were obtained using the $P(E)$ theory for normal junctions [34].

Device	JJ area (nm^2)	R_J (k Ω)	C^{Fit} (fF)	E_J (K)	E_C (K)
(a)	180×50	20.49	0.80	0.375	1.20
(b)	150×50	51.80	0.42	0.145	2.21
(c)	100×50	62.87	0.40	0.119	2.30

tance of the connection be much smaller than R_e . These conditions are satisfied at the relevant frequencies, see Supplemental Material [31], Sec. S3. The Cr resistance was tuned by varying the resistor length L up to 20 μm .

For the single junction devices, two fabrication batches were prepared (Table I). Batch I consisted of three devices on a chip with a tunnel resistance of 22.6 k Ω , each connected to a Cr resistor of different length, yielding resistances between 2 and 9 k Ω . Batch II comprised a junction with a tunnel resistance of $\sim 73 \text{ k}\Omega$, connected to Cr resistors of 22.2 and 40.8 k Ω , respectively. Also, for the SQUIDs, two batches were fabricated. Batch I included three devices with varying Josephson junction sizes (Table II), each coupled to an Ohmic resistor of approximately 19 k Ω . Batch II contained two devices connected to resistors of approximately 3.3 and 4.5 k Ω (Table III), respectively, enabling exploration of both sides of the Schmid-Bulgadaev transition.

The quasiparticle tunnel resistance R_J was independently determined from the I - V characteristic of a bare Josephson junction on chip with a nominally the same size as that in the measured device, Fig. 1(b). Moreover, to ensure the accuracy of our measurements, we have also subtracted R_J from the total resistance obtained by fitting the I - V curve of the composed device at high voltage bias as the sum of the two resistances in series $R_T = R_J + R_e$, leading to consistent results. The resistance of the Cr strip R_e was obtained the same way as R_J , with values listed in Table I. The Josephson energy E_J was calculated using the Ambegaokar-Baratoff relation as $E_J = \pi \hbar \Delta / 4e^2 R_J$, with

TABLE III. Parameters of the two SQUID devices with identical Josephson junction area, each connected to Cr resistors of $R_e = 3.3$ and 4.5 k Ω , respectively. Here, the charging energy E_C is estimated from the geometric capacitance $C^\square = 50 \text{ fF}/\mu\text{m}^2 \times A$, where A is the junction area.

JJ area (nm^2)	R_e (k Ω)	R_J (k Ω)	$C^\square$ (fF)	E_J (K)	E_C (K)
60×60	3.3	12.4	0.18	0.60	5.16
60×60	4.5	9.6	0.18	0.78	5.16

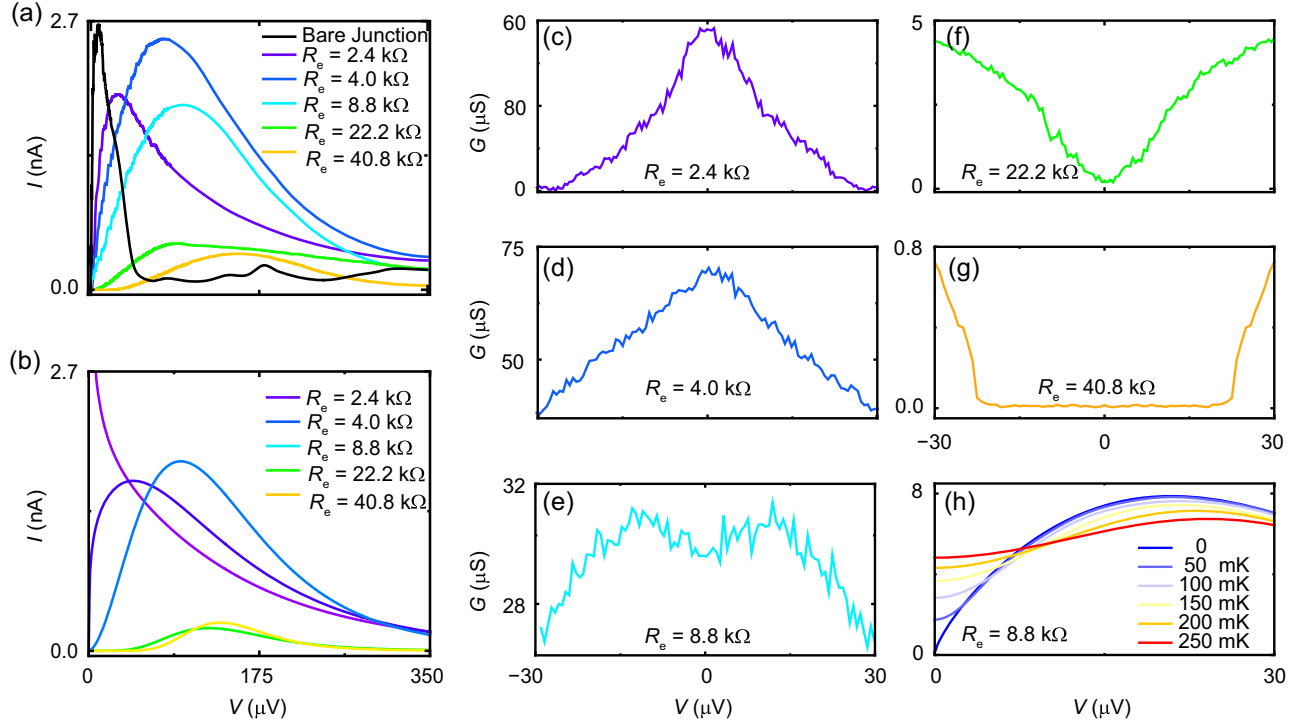


FIG. 2. (a) I - V characteristic of a JJ connected to various normal resistors with varying R_e at the base temperature of the cryostat (8 mK). The solid black line represents the I - V of the bare Josephson junction for batch I. (b) Theoretical results using $P(E)$ theory in an RC -environment. (c)–(g) Differential conductance $G \equiv dI/dV$ near zero voltage bias. (h) Effect of the temperature on the conductance $G \equiv dI/dV$ calculated within the $P(E)$ theory for a Josephson junction coupled to an environment with resistance $R_e = 8.8$ k Ω . As expected, the conductance drops to zero at absolute zero temperature, but remains nonvanishing at finite temperatures. Thus, the weak drop at $V = 0$ observed in (e) can be attributed to the influence of temperature.

$\Delta \approx 200$ μ eV being the aluminum superconducting energy gap. The charging energy $E_C = e^2/2C$ was obtained experimentally from the offset voltage bias $eV_b = E_C$ observed at large voltage bias in the I - V curve of a bare JJ on chip in the normal state [34].

Figure 2(a) shows a close-up view of the I - V curves of a JJ coupled to an Ohmic resistor with different resistance values, measured at 7 mK. As can be seen, the current peak at $V = 0$ characteristic of the Josephson current is shifted to a finite voltage as R_e increases, as compared with that in a bare single junction (solid black line). R_e tends to gradually suppress the electrical current of the system at low voltages, which is most notable when $R_e > R_Q$. This behavior is well understood within the so-called $P(E)$ theory [34] in RC environment, as shown in Fig. 2(b): the presence of the environment impedes charge relaxation in Cooper-pair tunneling through the junction, resulting in suppressed conductance. Possible reasons for the quantitative discrepancy between the experimental data in Fig. 2(a) and the $P(E)$ -theory predictions in Fig. 2(b) include nonequilibrium effects, most notably, a bias-dependent effective electronic temperature in the experiment. In addition, the standard $P(E)$ approach employed here is based on a perturbative expansion in the Josephson energy E_J and therefore has a limited range of validity [35,36]. This

behavior becomes more evident in the differential conductance measurements displayed in Figs. 2(c)–2(f). For the devices with $R_e < R_Q$, Figs. 2(c) and 2(d), a conductance peak developed at zero voltage bias is observed, indicative of the persistence of the critical current (Josephson effect). In contrast, for the devices with $R_e > R_Q$ as seen in Figs. 2(e)–2(g), the conductance peak tends to be suppressed, signaling the breakdown of the Josephson coupling and the emergence of the insulating behavior. This behavior arises because the superconducting phase becomes delocalized due to increased voltage noise in the electromagnetic environment. We relate this behavior to the framework predicted by Schmid [1] and Bulgadaev [2]. Particularly in our measurements, the transition starts to be visible for the device with $R_e = 8.8$ k Ω , shown in Fig. 2(e), consistent with the theory. Nevertheless, for $R_e \gtrsim R_Q$ one might expect an abrupt drop to zero of the conductance at $V = 0$, but such behavior is only anticipated at $T = 0$; hence, the deviation of conductance from zero observed in Fig. 2(e) can be attributed to the effect of temperature. This assumption is supported by theoretical results obtained by using the $P(E)$ theory as demonstrated in Fig. 2(g) and agrees with previous theoretical works in Refs. [37,38]. In the present Letter, the theory is therefore used as a qualitative framework to identify the robust features of the

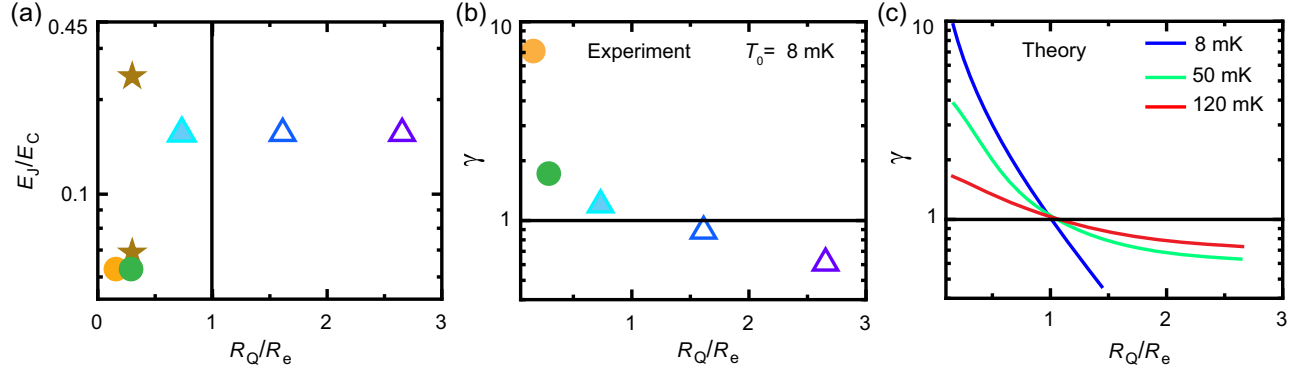


FIG. 3. (a) SB phase transition of a Josephson junction. Triangles and circles correspond to data from this Letter for sample batches I and II, respectively, while stars indicate our prior results from Ref. [3]. Open (solid) symbols denote superconducting (insulating) behavior, respectively. (b) Power-law scaling (exponent γ) extracted from the I - V characteristic shown in Fig. 2(a) in the very low-bias voltage regime $eV \ll R_Q E_C / R_e$ as a function of R_Q / R_e . (c) Theoretical predictions for γ based on the $P(E)$ theory at various temperatures.

superconducting-insulating crossover, rather than as a quantitative fitting model.

To map out the SB phase diagram, we have plotted the zero-bias conductance character (indicative of superconducting or insulating behavior) for our samples on the coordinate plane with axes R_Q / R_e , E_J / E_C , represented by triangles (batch I) and circles (batch II) in Fig. 3(a). As previously mentioned, the insulating nature of a JJ manifests as conductance suppression at zero-bias voltage. The solid line denotes the phase transition by definition. As can be seen, devices 1 and 2 are placed on the superconducting side of the phase diagram (open triangles), while devices 3–5 fall on the insulating side, denoted by solid triangles and circles, respectively. The response of the Josephson junction in the presence of a dissipative environment with different resistance values is thus consistent with that predicted by Schmid and Bulgadaev.

Comparing our phase diagram with the existing experimental phase diagram reported by Yagi *et al.* [24] and Subero *et al.* [3] (stars) shows that the results in [24] align with theoretical expectations. Yet the two devices with very low $E_J / E_C = 0.08$ exhibit insulating behavior (solid squares in Ref. [24]). This disagreement could be explained by the fact that the Josephson energy was of the order of the temperature at which the experiment was carried out. As a result, the Josephson phase can evolve due to thermal fluctuations, leading to suppression of tunneling by the environmental resistance. Conversely, in Subero *et al.* [3] charge transport results agree well with the theoretical predictions.

To complement the above discussion, one might see the phase transition as a change in the slope of the I - V curve, following a power law $I \propto V^\gamma$ that holds at $T = 0$ and very low voltage bias $eV \ll R_Q E_C / R_e$, with $\gamma = 2R_e / R_Q - 1$, representing the critical exponent associated with the transition. Figure 3(b) displays the dependence of γ as

a function of R_Q / R_e from our experiment. As anticipated, the phase transition occurs at $\gamma = 1$, i.e., at $R_e = R_Q$. The influence of temperature on the exponent γ based on $P(E)$ theory is shown in Fig. 3(c), with the top-to-bottom lines representing the behavior of γ from the lowest to highest temperature. It is worth noting that the crossover point of the transition is unaffected by temperature below 120 mK.

To investigate the dependence of the crossover on the ratio E_J / E_C , we have conducted measurements on a set of SQUID devices with parameters listed in Table III. Figures 4(a)–4(c) show the differential conductance G as a function of bias voltage for three SQUID devices connected to a Cr resistance of $R_e \simeq 19.2$ k Ω . Remarkably, all devices exhibit a pronounced dip in conductance at $V = 0$, regardless of the applied magnetic flux, highlighting the insulating character of the Josephson junction. Here, the junction capacitance was extracted by fitting the normal-state I - V characteristic with $P(E)$ theory [34], as shown in the inset of Figs. 4(a)–4(c), where superconductivity was suppressed using a permanent magnet placed beneath the sample holder. On the other hand, Figs. 4(d) and 4(e) display the differential conductance of SQUID devices coupled to a lower resistance, $R_e = 3.3$ and $R_e = 4.5$ k Ω , respectively. Here, a pronounced peak emerges at zero-bias voltage, consistent with a nonvanishing critical current and indicative of coherent Josephson tunneling in the superconducting regime. These observations exemplify the phase-charge duality: in low-impedance environments (superconducting regime), the phase across the junction is well defined and the charge fluctuates, while in high-impedance environments (insulating regime), the charge becomes localized and the phase undergoes large fluctuations. The zero-bias anomaly is represented on a plane R_Q / R_e , E_J / E_C , as depicted in Fig. 4(f), illustrating the robustness of the insulating (superconducting) behavior across the entire range of E_J / E_C explored.

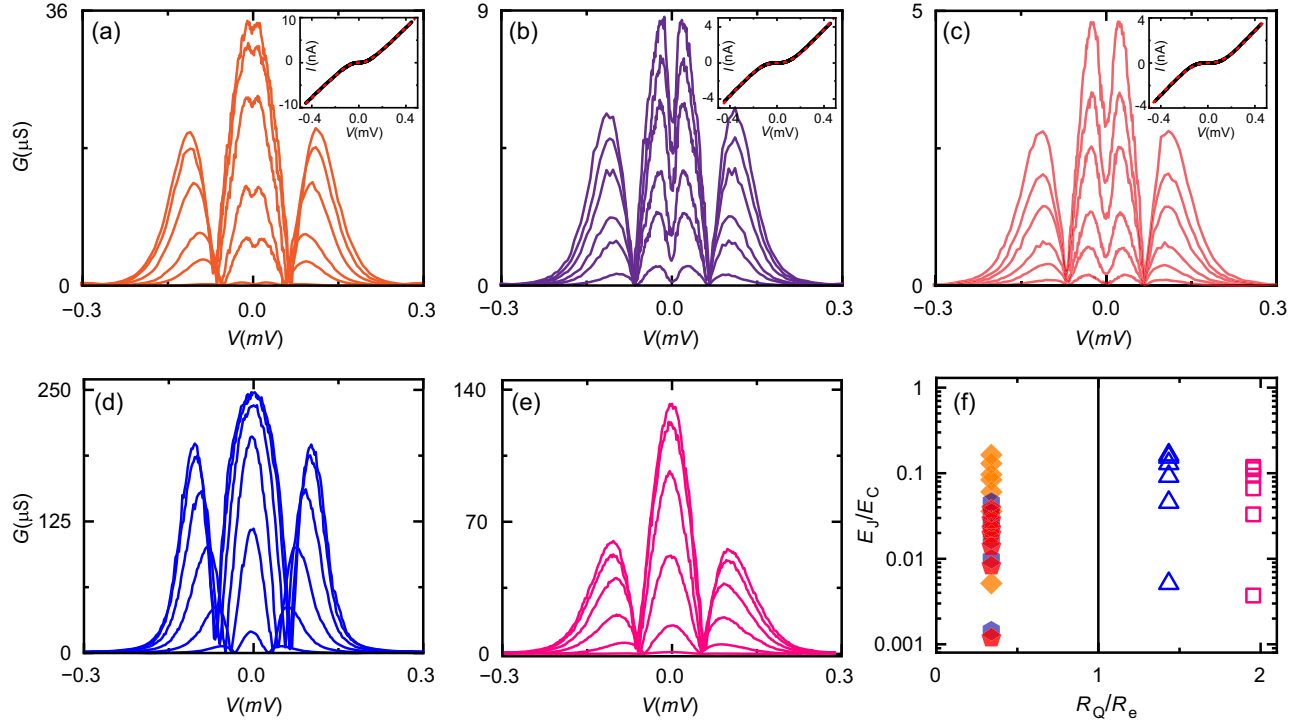


FIG. 4. (a)–(c) Differential conductance of three SQUID devices connected to a Cr resistor with $R_e \simeq 19$ k Ω as a function of bias voltage at various normalized magnetic flux values $\Phi/\Phi_0 = 0, 0.1, 0.2, 0.3, 0.4, 0.5$, from top to bottom. Inset: the normal-state I - V characteristics at 8 mK, where the solid red line represents the $P(E)$ -theory fit, allowing us to determine the junction capacitance within an RC environment. (d), (e) Differential conductance of another two SQUIDs coupled to Cr resistors with $R_e \simeq 3.3$ and $\simeq 4.5$ k Ω , respectively, as a function of bias voltage for different Φ/Φ_0 . (f) Zero-bias conductance of all devices mapped onto the Schmid-Bulgadaev phase diagram where E_J/E_C is controlled by varying magnetic flux.

In summary, our Letter investigates the superconducting-insulating phase transition of a Josephson junction, with a focus on the dc response when coupled to a well-defined dissipative environment. Our findings systematically provide strong evidence that the transition occurs at $R_e \approx R_Q$, regardless of the strength of the Josephson coupling. Moreover, the current-voltage characteristic exhibits a power-law scaling near zero-bias voltage, consistent with a quantum phase transition. These findings contribute to the ongoing debate over the existence of a dissipative phase transition in Josephson junctions. The apparent discrepancies in the literature likely stem from differences in the frequency regimes in which the experiments are conducted, as highlighted by earlier experimental [4,5,28,39] and theoretical [9,13] studies.

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Data availability—The data are not publicly available. The data are available from the authors upon reasonable request.

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