Excitation of superconducting qubits from hot non-equilibrium quasiparticles

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Superconducting qubits probe environmental defects such as non-equilibrium quasiparticles, an important source of decoherence. We show that “hot” non-equilibrium quasiparticles, with energies above the superconducting gap, affect qubits differently from quasiparticles at the gap, implying quasiparticles can probe the dynamic quasiparticle energy distribution. For hot quasiparticles, we predict a non-negligible increase in the qubit excited state probability $P_e$. By injecting hot quasiparticles into a qubit, we experimentally measure an increase of $P_e$ in semi-quantitative agreement with the model and rule out the typically assumed thermal distribution.

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Here, we invalidate this assumption using qubit excitation due to quasiparticles, akin to power-generating noise from quasiparticle scattering and recombination in other systems. We quantitatively model how high-energy quasiparticles directly excite qubits. We experimentally test this model by injecting a non-equilibrium quasiparticle population into a superconducting qubit and using the qubit to dynamically probe this population. We find semi-quantitative agreement between our model and the experimental data presented here, showing that non-equilibrium quasiparticles provide a mechanism for the spurious excitation of superconducting qubits, distinct from thermal effects. We further rule out a thermal distribution for these quasiparticles, even with a distinct quasiparticle temperature. In addition, our approach provides a new method to study the temporal dynamics of the non-equilibrium quasiparticle energy distribution and can be used to validate alternative methods.

A quasiparticle tunneling through the Josephson junction barrier in a qubit can cause both excitation and deexcitation in the qubit, as illustrated in Fig. 1. Consider a qubit initially in its excited state: A “cold” quasiparticle near the gap energy can absorb the qubit transition energy $E_{gs}$ between the qubit’s excited $|e\rangle$ and its ground $|g\rangle$ states, causing the qubit to switch to its ground state (blue arrows in Fig. 1(a,b)). Any quasiparticle in the junction area can absorb this energy, so the qubit $|e\rangle \rightarrow |g\rangle$ decay rate $\Gamma_\downarrow$ due to this channel is proportional to the quasiparticle density $n_{qp}$. For a qubit initially in its ground state, a “hot” quasiparticle sufficiently above the gap energy can excite the qubit, but only if the quasiparticle has energy greater than $\Delta + E_{gs}$ (red arrows in Fig. 1(a,c)). The qubit $|g\rangle \rightarrow |e\rangle$ excitation rate $\Gamma_\uparrow$ thus depends on the energy distribution of the quasiparticle population.

If the quasiparticle population were well-described by a temperature $T \approx 20 \text{ mK} \ll E_{gs}/k_B$, then a negligi-
Figure 1: (Color online) Qubit decay $\Gamma_{\downarrow}$ (blue) and excitation $\Gamma_{\uparrow}$ (red) mediated by tunneling quasiparticles. (a) Portion of the superconducting phase qubit potential energy diagram, showing the $\Gamma_{\downarrow}$ and $\Gamma_{\uparrow}$ transitions between the ground state $|g\rangle$ and the excited state $|e\rangle$, along with the qubit energy $E_{ge}$. (b) Cold non-equilibrium quasiparticles, which have energies near the superconducting gap $\Delta$, can only absorb $E_{ge}$, resulting in qubit $\Gamma_{\downarrow}$ decay. The density of states ($\rho(E)$, horizontal) on both sides of a Josephson junction (superconductor S - insulator I - superconductor S) is shown versus quasiparticle energy $E$ (vertical). The quasiparticle energy distribution $f(E)$ is shown by the shaded triangles. (c) Hot non-equilibrium quasiparticles with energy above $\Delta + E_{ge}$ (portion of $f(E)$ with $E > \Delta + E_{ge}$) not only can cause qubit $\Gamma_{\downarrow}$ transitions but can also relax by causing qubit $|g\rangle \rightarrow |e\rangle$ transitions.

In order to model the steady-state quasiparticle distribution, we assume quasiparticles are injected in the junction at a constant rate at an energy $E_{inj}$ well above $\Delta + E_{ge}$, with the resulting quasiparticle density $n_{qp}$ scaling as the square root of the injection rate; we verify below (discussion of Fig. 2d) that the qubit excited state probability $P_e$ is independent of the injection energy. Steady state is achieved by balancing phonon scattering and quasiparticle injection and recombination [41]. Although the resulting steady-state occupation probability $f(E)$ has a similar dependence on quasiparticle energy as a 70 mK thermal distribution for $\Delta < E < 1.4\Delta$ [42], no effective temperature can fully describe $f(E)$ for all energies, implying a non-thermal distribution.

With $f(E)$ determined in this manner, we calculate the qubit excitation rate $\Gamma_{\uparrow}$ and decay rate $\Gamma_{\downarrow}$. For a tunnel junction with resistance $R_T$ and capacitance $C$, and for normalized quasiparticle density of states $\rho(E) = E/\sqrt{E^2 - \Delta^2}$, the qubit decay (excitation) rate induced by all quasiparticles is [11, 12]

$$\Gamma_{\downarrow(\uparrow)} = \frac{1 + \cos\phi}{R_TC} \int_{\Delta}^{\infty} \frac{dE}{E} \frac{E}{E_{ge}} f(E) \rho(E) \rho(E_f)$$  \hspace{1cm} (1)$$

where the final quasiparticle energy $E_f = E + E_{ge}$ ($E_f = E - E_{ge}$) is higher (lower) than $E$ due to the absorption (emission) of the qubit energy $E_{ge}$. Here, $\phi$ is the junction phase, which is typically $\phi \approx 0$ for the transmon and $\phi \approx \pi/2$ for the phase qubit. For cold non-equilibrium quasiparticles, corresponding to $f(E)$ having population only at the gap energy $\Delta$, this integral gives

$$\Gamma_{\downarrow\Gamma_{\uparrow}} = \frac{1 + \cos\phi}{\sqrt{2} R_TC \Delta^{3/2}} \frac{n_{qp}}{n_{cp}}.$$  \hspace{1cm} (2)$$

Here, $n_{cp} = D(E_F)\Delta$ is the Cooper pair density, $n_{qp} = 2D(E_F)\int_{0}^{\Delta} \rho(E) f(E) dE$ is the quasiparticle density, incorporating both hot and cold quasiparticles, and $D(E_F)/2$ is the single spin density of states. This is the standard result for quasiparticle dissipation [13], and is equivalent [12] to the Mattis-Bardeen theory [13] for $\phi = 0$.

In Fig. 2a,b we plot $\Gamma_{\downarrow}/\Gamma_{\uparrow}$, the ratio of the numerically-integrated qubit decay rate $\Gamma_{\downarrow}$ assuming both hot and cold non-equilibrium quasiparticles (Eq. 1)
FIG. 3: (Color online) Experimental apparatus and protocol. (a) Schematic of phase qubit, with voltage $V_{sq}$ applied to readout SQUID and flux bias $\Phi_{bias}$. Quasiparticles generated with the SQUID can only reach the qubit through the common ground. (b) Photo of qubit. Two paths for quasiparticles to diffuse to the qubit junction are indicated by dotted and solid arrows. (c) Pulse sequence. Quasiparticles are generated with a voltage pulse on the SQUID line of amplitude $V_{inj} > 2(\Delta + E_{ge})/e$ for a time $t_{inj}$, which are varied to adjust the quasiparticle density. After a delay time $t_{diff}$, 40$\mu$s of which is at the operating bias, allowing quasiparticles to diffuse to the qubit, the qubit state is projected with a flux bias pulse and read out using a voltage pulse on the SQUID.

FIG. 4: (Color online) Experimental impacts of injected quasiparticles. Increases in (a,b) qubit decay rate $\delta \Gamma_{\downarrow}$ and (c,d) qubit excited state probability $\delta P_{e}$ are measured with respect to values without quasiparticle injection. The quasiparticle density was varied by changing (b,d) the length $t_{inj}$ of the injection pulse or (a,c) the diffusion time $t_{diff}$. Data are for two slightly different designs: 1 (Ref. [4]) and 2 (Ref. [4]). Experimental parameters are in the supplementary material [45]. These increases directly demonstrate a non-equilibrium distribution.

To experimentally test these concepts, we performed an experiment in which we deliberately injected quasiparticles into a phase qubit (Fig. 3(a,b)) and measured the excited state probability $P_{e}$ and the increase in the qubit decay rate $\delta \Gamma_{\downarrow}$, which is proportional to $n_{qp}/n_{cp}$ (Eq. 3). As shown in Fig. 4(c), we generated quasiparticles by applying a voltage pulse above the gap voltage $\Delta/e$ to the qubit’s readout superconducting quantum interference device (SQUID). The duration $t_{inj}$ of this pulse was varied to adjust the quasiparticle density and $f(E)$. We reset the qubit into the $|\uparrow\rangle$ state using $\Phi_{bias}$ and then waited a variable time $t_{diff}$ following the pulse, giving the quasiparticles time to diffuse to the qubit and allowing study of the temporal dynamics. After the qubit control pulses, we measured the qubit $P_{e}$, reading out the qubit by increasing $V_{eq}$ to approximately $0.7\Delta/e$ to switch the SQUID into the normal state while minimizing quasiparticle generation. Note this is similar to previous work [12], except here the qubit measurements include the enhancement $\delta P_{e}$ versus the energy relaxation rate increase $\delta \Gamma_{\downarrow}$. The increases $\delta P_{e}$ and $\delta \Gamma_{\downarrow}$, as shown in Fig. 4, are measured by comparing $P_{e}$ and $\Gamma_{\downarrow}$ both with and without the quasiparticle injection pulse.

In Fig. 4 we plot the observed changes $\delta P_{e}$ versus $\delta \Gamma_{\downarrow}$ for two different phase qubits (details in [4]), parameters in the supplementary material [45] as we varied $t_{diff}$ and $t_{inj}$ (Fig. 4). We find that $\delta P_{e}$ monotonically increases with $\delta \Gamma_{\downarrow}$, thus scaling with quasiparticle density, as predicted by the theory. As $\delta \Gamma_{\downarrow} \neq 0$, the quasiparticles are in a non-equilibrium distribution. In addition, we were able to increase $P_{e}$ by more than 10%, demon-
Varying the diffusion time showing that hot quasiparticles can significantly excite the presence of hot quasiparticles and directly strating the presence of hot quasiparticles and directly showing that hot quasiparticles can significantly excite the qubit.

The quasiparticle density was changed in three ways: Varying the diffusion time $t_{\text{dif}}$ (triangles), the injection time $t_{\text{inj}}$, and the injection voltage $V_{\text{inj}}$ (open vs. closed). There is essentially no difference between changing the injection voltage and the injection time; this makes sense, as $P_e$ is relatively insensitive to the injection energy (Fig. 2(a)). In addition, for times less than $t_{\text{inj}} + t_{\text{dif}} \lesssim 350 \mu s$ (equality denoted by arrows), the data where $t_{\text{dif}}$ was varied is similar to the data where $t_{\text{inj}}$ is varied. However, we observed a significant difference with varying the diffusion time for $t_{\text{inj}} + t_{\text{dif}} > 350 \mu s$. This is not surprising, as $P_e$ is sensitive to the quasiparticle energy distribution, which changes with the diffusion time. As shown in Fig. 2(b), quasiparticles generated at the measurement SQUID must diffuse through approximately 700 µm of ground plane metal in order to reach the qubit junction. This gives time for quasiparticle scattering and relaxation with respect to the injected distribution. In fact, this transition time is consistent with typical quasiparticle recombination times [38, 46], where $f(E)$ is expected to become dominated by thermal equilibrium excitation independent of quasiparticle density.

We also considered a thermal quasiparticle distribution, where the quasiparticle temperature was set to give the appropriate $\delta T_\uparrow$ (dashed line). The only experimental data fit by the thermal model is when $t_{\text{dif}}$ is varied for qubit (1), consistent with much of these data having $t_{\text{inj}} + t_{\text{dif}}$ longer than typical quasiparticle recombination times. For qubit (2) or when $t_{\text{inj}}$ is varied, this thermal model does not fit the experimental data in magnitude or slope, indicating a non-thermal distribution.

Predictions from the model are plotted in Fig. 5 as solid lines. Although the power-law dependence (slopes) between model and measurement are in reasonable agreement, the model $\delta P_e$ is low by about a factor of three for qubit (1) and high by about a factor of four for qubit (2). This can not be attributed to the small differences in the qubit geometries, because a third device (not shown), with the same design as (1), gave data about a factor of two lower than the model. These differences could be due to subtleties in the model not considered here. For instance, there can be sample-to-sample variation such as a difference in film thickness or film quality, yielding variations in the gap energy, in the quasiparticle diffusion path, and in junction parameters. In addition, we note that the calculation of $P_e$ assumes non-equilibrium quasiparticle relaxation through electron-phonon scattering and recombination. Other effects such as quasiparticle diffusion and trapping of quasiparticles from non-uniform gaps may significantly affect the distribution $f(E)$, altering the prediction for the excitation rate; however, such effects are difficult to model due to the qubit geometry [12]. We further assume a constant quasiparticle injection rate; while this describes infrared-generated quasiparticles, here it may mask effects of the repetition rate and quasiparticle-induced heating. In addition, even though quasiparticles are expected to be generated with energies of $eV_{\text{inj}}/2$, in reality there will be a distribution of quasiparticle energies centered around this value for a given $V_{\text{inj}}$, so even for $eV_{\text{inj}} > 2(\Delta + E_{\text{ge}})$, some of the generated quasiparticles may instead be cold. We conclude that the simple theoretical model used here for the quasiparticle energy distribution $f(E)$ is only semi-quantitative, predicting $\Gamma_\uparrow$ in the non-thermal regime to about a factor of 4.

In conclusion, we have shown that “hot” quasiparticles with energies greater than $\Delta + E_{\text{ge}}$ can cause significant ground-to-excited state transitions in superconducting qubits. This is in contrast to “cold” quasiparticles solely at the gap, which only cause superconducting qubits to relax. This means quasiparticles cannot be adequately described by a single parameter such as $n_{\text{gp}}/n_{\text{cp}}$ or temperature. As illustrated by varying both $t_{\text{inj}}$ and $t_{\text{dif}}$, the particular quasiparticle distribution affects the observed qubit excitation probability. This theory semiquantitatively matches the observed behavior of the qubit excitation probability versus quasiparticle density, indicating one must consider a non-thermal quasiparticle distribution.

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Supplementary Material for “Excitation of superconducting qubits from hot non-equilibrium quasiparticles”

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Here, we present experimental details along with a description of the phase qubits used.

### TABLE S1: Experimental parameters.

The injection voltage $V_{\text{inj}}$ is provided assuming a junction superconducting gap $\Delta/e = 2K$ as for aluminum. We also include parameters measured independently without quasiparticle injection: excited state probability $P_0^e$, qubit decay rate $\Gamma_0^{\downarrow}$, qubit frequency $E_{\text{ge}}/\hbar$, and qubit critical current $I_c$. Symbols are as used in Figs. 4-5.

| Data     | $V_{\text{inj}}$  | $P_0^e$   | $1/\Gamma_0^{\downarrow}$ | $E_{\text{ge}}/\hbar$ | $I_c$   |
|----------|-------------------|-----------|---------------------------|------------------------|--------|
| (1) Triangles | 0.57 mV, 3.5$\Delta/e$ | 3-4%     | 880 ns                    | 5.8 GHz               | 1.0 $\mu$A |
| (1) Circles  | 0.57 mV, 3.5$\Delta/e$ | 1-9%     | 880 ns                    | 5.5 GHz               | 1.0 $\mu$A |
| (2) Open     | 0.41 mV, 2.6$\Delta/e$ | 4.0%     | 380 ns                    | 6.1 GHz               | 1.7 $\mu$A |
| (2) Closed   | 0.59 mV, 3.7$\Delta/e$ | 4.7%     | 380 ns                    | 6.1 GHz               | 1.7 $\mu$A |

**FIG. S1:** (Color online) SQUID voltage $V_{sq}$ vs current $I_{sq}$. The SQUIDs are shunted by a 30Ω resistor, as shown in Fig. 3(a). The qubits are labeled as in Table S1 and Figs. 4-5.

Both qubits tested were fabricated using a multi-layer process with optical lithography. The qubit and SQUID junctions are Al/AlO$_x$/Al on a sapphire substrate, while the parallel-plate capacitor shunting the qubit had a hydrogenated amorphous silicon dielectric with a capacitance of 1 pF.

In Figs. S1 and Table S1, we present the qubit and SQUID parameters for qubits 1 (Ref. [1]) and 2 (Ref. [2]). The SQUID current vs. voltage for both devices is shown in Fig. S1, whereas the qubit junction critical current and qubit frequency are in Table S1. Further, we include in Table S1 the qubit decay rate and excited state probabilities without quasiparticle injection to which the data with quasiparticle injection is compared; the range in excited state probabilities for Qubit (1) indicates different no-injection values correspond to different data points.

In Figs. 4-5, we only present data where the second excited state is not appreciably populated. To do this, we use the measurement fidelities for the ground and first and second excited states as measured without quasiparticle injection to correct the probabilities of being in these states with quasiparticle injection [3]. We then compare the resulting quasiparticle-induced excited state probability with the raw increase in the excited state probability due to quasiparticle injection and exclude data where these are significantly different.

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