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Supplementary information

Impact of ionizing radiation on superconducting qubit coherence

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Supplementary material

Quasiparticle injection experiment

Quasiparticles can be injected into the circuit to study their relaxation dynamics. Here we attempt to determine whether the quasiparticle dynamics are dominated by the recombination rate r or trapping rate s, see Eq. (4) in the main text. In the absence of the external generation rate, the time evolution of the quasiparticle density can be solved from the differential equation in Eq. (4), see also Reference 26 in the main text,

$$x_{\mathrm{qp}}(t) = \frac{x_{\mathrm{qp}}(0)s}{-rx_{\mathrm{qp}}(0) + \mathrm{e}^{st}(s + rx_{\mathrm{qp}}(0))}. \tag{12}$$

In the two limiting cases of no trapping or no recombination the time evolution can be simplified as

$$x_{\mathrm{qp}}(t) = \frac{x_{\mathrm{qp}}(0)}{1 + x_{\mathrm{qp}}(0)rt} \tag{13}$$

or

$$x_{\mathrm{qp}}(t) = x_{\mathrm{qp}}(0)\mathrm{e}^{-st}, \tag{14}$$

respectively.

Following the experimental protocol introduced in Reference 26 in the main text, quasiparticles can be generated by strongly driving the resonator coupled to Q1. The energy pumped into the resonator creates a voltage over the Josephson junction of the qubit and breaks Cooper pairs, resulting in an elevated quasiparticle density. The generated quasiparticles then gradually diffuse into the superconducting material around the Jospehson junction. We observed that a steady state in the quasiparticle density in the qubit was reached after $d_{\mathrm{qp}} = 10\,\mathrm{ms}$ of quasiparticle injection, see Fig. 2a for the pulse sequence. After the initial quasiparticle injection pulse, the quasiparticle density was estimated by measuring the qubit energy relaxation rate, see Eq. (3) in the main text. By changing the delay between the injection pulse and the energy relaxation rate measurement, we can determine the quasiparticle relaxation dynamics in our device, see Extended Data Fig. 2. We fitted the full model of Eq. (12), shown by the solid green line in Extended Data Fig. 2b. The fit includes the internal relaxation rate of the qubit, $\Gamma_{\mathrm{other}} \approx 1/35\,\mu\mathrm{s}^{-1}$. The dash dotted orange line shows the fit using a model that only includes recombination. This line almost exactly matches the fit using the full model, confirming our assumption that recombination is the dominant quasiparticle decay process in our devices. The dotted orange line assumes no internal energy relaxation $\Gamma_{\mathrm{other}} = 0$. The blue dash dotted line shows the model which assumes trapping as the only decay mechanism of quasiparticles. The dotted blue line shows the model without Γ_{other}. The model that assumes only trapping is strongly disfavored by the data. From the full model, we extract values for s and r and conclude that the action of the quasiparticle trapping rate s is negligible compared with the recombination rate r.

Resonator measurements

Each qubit on the device is addressed and operated via a separate resonator using a microwave probe pulse in the qubit-resonator dispersive regime. To experimentally determine the resonant frequency of the resonator, we scan both the probe frequency and probe power and record the response. In the absence of radiation, at relatively low powers, the resonator frequency depends on the qubit state and serves as the basis for dispersive qubit readout. In the high-power regime, the resonator effectively decouples from the qubit and its frequency is "locked" and (ideally) independent of the qubit state. We systematically repeat this frequency and power scan at different source radiation intensities to study the behavior of our resonators in the presence of ionizing radiation. In the presence of radiation, in principle, such a measurement could provide a means to distinguish the impact of radiation on the qubit-resonator system and on the resonator itself, although we have not yet investigated this aspect in sufficient detail to comment on it further here.

When exposed to ionizing radiation, the resonators become unstable and exhibit random fluctuations in their resonance frequency. As the radiation intensity decreases with time, the fluctuation decreases until the resonator is stable once again (Fig. 4**a-d**). This behavior is consistent with previous measurements of superconducting resonators in the presence of quasiparticles[1,2]. We monitor the resonator frequency and full-width-half-max (FWHM) throughout the duration of the ^{64}Cu radiation experiment. We observe that as the radiation power decreases, both properties of the resonator fluctuations decrease until they converge to the value measured during our control experiment. Furthermore, the median of the resonator frequency shift ($\Delta\omega_{\mathrm{r}}$) and the FWHM for our measurements follows an exponential decay as a function of time with a half-life of $t_{1/2} = (21.74 \pm 2.8)$h and $t_{1/2} = (24.16 \pm 0.78)$h respectively. The observed decay half-life values are very close to being twice the half-life of the ^{64}Cu source. This effect can be explained by quasiparticle induced change in the kinetic inductance of the resonator. The kinetic inductance of superconducting resonators is directly correlated with the number of quasiparticles[3]: $\delta L_k/L_k = \frac{1}{2}\delta n_{\mathrm{qp}}/n_{\mathrm{qp}}$. Furthermore, the change in the resonator frequency is directly proportional to the change in the kinetic inductance: $\delta\omega/\omega_0 = \frac{\alpha}{2}\delta L_k/L_k$. Therefore, $\delta\omega/\omega_0 \propto \delta n_{\mathrm{qp}}/n_{\mathrm{qp}}$. According to Eq. (5) in the main text, the quasiparticle density depends on the square root of radiation power, and therefore we expect the resonator frequency decay constant to be twice that of the radiation source.

Absorption of radiation power in the sample

According to Eq. (3), the energy relaxation rate due to ionizing radiation power density absorbed in the aluminum comprising the qubit can be written as

$$\Gamma_1(t) = a\sqrt{\omega_{01}P_{\mathrm{src}}^{\mathrm{Al}}(t)}, \tag{15}$$

where P_{src} is the power density of the ^{64}Cu source in aluminum. Here we calculate how much bigger the impact of ionizing radiation is on the energy-relaxation rate of the qubit if we consider total absorbed power in the entire sample – aluminum plus silicon – instead of the absorbed power in aluminum only and, ultimately, the absorbed power density in aluminum, as considered in the main text. As we will show, the use of power density in aluminum differs from the total absorbed power by a factor of order unity for our experimental conditions (absorbed power densities in aluminum and silicon are similar in our experiment).

The total power absorbed in aluminum is $V_{\rm Al}P_{\rm src}^{\rm Al}(t)$, and we can write

$$\Gamma_1(t) = \alpha\sqrt{\omega_{01}V_{\rm Al}P_{\rm src}^{\rm Al}(t)}, \tag{16}$$

where $V_{\rm Al}$ is the aluminum volume, and α is an unknown coefficient. Alternatively, one can consider the total power absorbed in the whole sample,

$$\Gamma_1(t) = \beta\sqrt{\omega_{01}\left(V_{\rm Al}P_{\rm src}^{\rm Al}(t) + V_{\rm Si}P_{\rm src}^{\rm Si}(t)\right)}, \tag{17}$$

where V are the volumes of the materials and β is a different constant. The energy-relaxation rate of the qubit due to external radiation can be similarly written as

$$\Gamma_{\rm ext}^{\alpha} = \alpha\sqrt{\omega_{01}V_{\rm Al}P_{\rm ext}^{\rm Al}}, \tag{18}$$

for the absorption in aluminum, or as

$$\Gamma_{\rm ext}^{\beta} = \beta\sqrt{\omega_{01}\left(V_{\rm Al}P_{\rm ext}^{\rm Al} + V_{\rm Si}P_{\rm ext}^{\rm Si}\right)}. \tag{19}$$

We can compare the difference of these two ways of estimating $\Gamma_{\rm ext}$ by solving for their relation

$$f_{\rm c} = \frac{\Gamma_{\rm ext}^{\beta}}{\Gamma_{\rm ext}^{\alpha}} = \frac{\beta}{\alpha}\sqrt{\frac{V_{\rm Al}P_{\rm ext}^{\rm Al} + V_{\rm Si}P_{\rm ext}^{\rm Si}}{V_{\rm Al}P_{\rm ext}^{\rm Al}}}. \tag{20}$$

We can solve for α and β in Eqs. (16) and (17) and substitute those to Eq. (20) to yield

$$f_{\rm c} = \sqrt{\frac{V_{\rm Al}P_{\rm src}^{\rm Al}(t)}{V_{\rm Al}P_{\rm src}^{\rm Al}(t) + V_{\rm Si}P_{\rm src}^{\rm Si}(t)}}\sqrt{\frac{V_{\rm Al}P_{\rm ext}^{\rm Al} + V_{\rm Si}P_{\rm ext}^{\rm Si}}{V_{\rm Al}P_{\rm ext}^{\rm Al}}}. \tag{21}$$

Assuming $V_{\rm Al} \ll V_{\rm Si}$ and that the absorbed power densities in all the materials are similar, we can simplify the above equation to give

$$f_{\rm c} \approx \sqrt{\frac{V_{\rm Al}P_{\rm src}^{\rm Al}(t)}{V_{\rm Si}P_{\rm src}^{\rm Si}(t)}}\sqrt{\frac{V_{\rm Si}P_{\rm ext}^{\rm Si}}{V_{\rm Al}P_{\rm ext}^{\rm Al}}}, \tag{22}$$

and thus

$$f_{\rm c} \approx \sqrt{\frac{P_{\rm src}^{\rm Al}(t)}{P_{\rm src}^{\rm Si}(t)}}\sqrt{\frac{P_{\rm ext}^{\rm Si}}{P_{\rm ext}^{\rm Al}}}, \tag{23}$$

which is the same as Eq. (8) in the methods section. The absorbed power density from the ^{64}Cu source is given by $P_{\rm src}(t) = A(t)\rho_{\rm src}$, where $A(t)$ is the activity of the source as a function of time. The power densities are provided in the Extended Data Table 6d. Finally, the correction coefficient is

$$f_{\rm c} \approx \sqrt{\frac{\rho_{\rm src}^{\rm Al}}{\rho_{\rm src}^{\rm Si}}}\sqrt{\frac{P_{\rm ext}^{\rm Si}}{P_{\rm ext}^{\rm Al}}} \approx 1.6, \tag{24}$$

which is of order unity. Note that the result does not depend on the volumes of either aluminum or silicon, and therefore the above error estimate can be calculated either using the total absorbed power in the materials, the power densities in the materials, or any combination of the two, as long as the power densities are similar and the assumption $V_{\rm Al} \ll V_{\rm Si}$ holds. Even though the impact in our estimate for $\Gamma_{\rm ext}$ does not significantly depend whether we consider power density in the aluminum or the total absorbed power in the sample, the numeric value of the coefficient a would be scaled by the sample volume if we considered the total absorbed power. Therefore, if the total absorbed power dominates the quasiparticle generation, changing the volume of the sample would have an impact on the quasiparticle density as opposed to the approximation where we only consider the absorbed power density near the qubit. Verifying which of these models better describe our superconducting samples is a topic for future research.

T_2 and qubit frequency shift due to ionizing radiation

During the radiation exposure measurement, the T_2 coherence times of the qubits were measured in addition to the energy-relaxation rate. The quasiparticles are expected to shift the qubit transition frequency $\delta\omega_{\rm q}$ as

$$\delta\omega_{\rm q} = -\sqrt{\frac{\Delta\omega_{\rm q}}{2\hbar\pi^2}}x_{\rm qp}, \tag{25}$$

where $x_{\rm qp}$ is the fraction of broken Cooper pairs and Δ is the superconductor gap[4].

In addition to an average shift in the qubit frequency, the coherence time T_2 of the qubit is reduced due to frequency fluctuations caused by the fluctuating quasiparticle density. Extended Data Fig. 5a shows the qubit frequency as a function of time during the exposure to radiation from ^{64}Cu source measured using a Ramsey measurement, see Extended Data Fig. 5b. Panel a shows the Fourier transform of the measured Ramsey oscillations during the ^{64}Cu exposure experiment. The frequency of the oscillations corresponds to the difference between the qubit transition frequency and the frequency of the control pulses, $\omega_{\rm R} = \omega_{\rm control} - \omega_{\rm q}$. Panels c - e show the Ramsey oscillations and fit T_2 coherence times at 152 h, 212 h, and 340 h from the installation of the ^{64}Cu source. During that time, the coherence time of the qubit Q1 improved from 700 ns to 5.8 µs. The average frequency of the qubit shifted by $-230\,\mathrm{kHz}$, though this estimate is not very accurate due to the fluctuations in the qubit frequency originating from sources other than the quasiparticles, such as charge fluctuations. The observed shift can be compared to Eq. (25) with x_{qp} inferred from the energy-relaxation rate measurement in Fig. 2, which yields $\delta\omega_{\mathrm{q}}/(2\pi) = -15\,\mathrm{kHz}$. The shift in the qubit frequencies is small, yet we observe a clear reduction in the coherence times of the qubit due to the ionizing radiation.

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