A superconductor free of quasiparticles for seconds

E. T. Mannila, P. Samuelsson, S. Simbierowicz, J. T. Peltonen, V. Vesterinen, L. Grönberg, J. Hassel, V. F. Maisi and J. P. Pekola

Superconducting devices, based on the Cooper pairing of electrons, play an important role in existing and emergent technologies, ranging from radiation detectors to quantum computers. Their performance is limited by spurious quasiparticle excitations from broken Cooper pairs. Efforts to achieve ultra-low quasiparticle densities have reached time-averaged numbers of excitations on the order of one in state-of-the-art devices. However, the dynamics of the quasiparticle population as well as the timescales for adding and removing individual excitations remain largely unexplored. Here, we experimentally demonstrate a superconductor completely free of quasiparticles for periods lasting up to seconds. We monitor the quasiparticle number on a mesoscopic superconductor in real time by measuring the charge tunnelling to a normal metal contact. Quiet, excitation-free periods are interrupted by random-in-time Cooper pair breaking events, followed by a burst of charge tunnelling within a millisecond. Our results demonstrate the possibility of operating devices without quasiparticles with potentially improved performance. In addition, our experiment probes the origins of nonequilibrium quasiparticles in our device. The decay of the Cooper pair breaking rate over several weeks following the initial cooldown rules out processes arising from cosmic or long-lived radioactive sources.

The Bardeen–Cooper–Schrieffer theory of superconductivity predicts that the number of quasiparticle excitations should be exponentially small at temperatures low compared with the superconducting gap (divided by Boltzmann's constant $k_B$). Nevertheless, it is experimentally well established that a residual population persists down to the lowest temperatures, being attributed to Cooper pair breaking in the superconductor due to non-thermal processes. Residual quasiparticles are detrimental to the performance of many superconducting devices, ranging from setting the fundamental limit for the sensitivity of kinetic inductance detectors to arguably limiting the coherence times of superconducting qubits. In addition, the statistics of number of quasiparticles created per event. This goes well beyond previous experiments on time-resolved quasiparticle tunnelling in superconducting structures or experiments with intentional injection of a large number of quasiparticles. In our device, the rate of Cooper pair breaking events, followed by bursts of tunnelling within a millisecond. The pair breaking events occur randomly in time, with an average rate of 1.5 Hz and a probability $\propto \exp(-0.9N_{\text{pair}})$ to break $N_{\text{pair}}$ Cooper pairs. That is, in 40% of the events, more than one Cooper pair is broken.

Due to the real-time probing of the single-electron tunnelling, three orders of magnitude faster than the Cooper pair breaking, we are able not only to measure the decay dynamics of individual quasiparticles but also to identify the pair breaking events as well the number of quasiparticles created per event. This goes well beyond previous experiments on time-resolved quasiparticle tunnelling in superconducting structures, or experiments with intentional injection of a large number of quasiparticles. In addition, the statistics of number of quasiparticles created might provide additional information on the origin of the pair-breaking processes. Here, we observe that the rate of Cooper pair breaking events decreases by a factor of four over a period of weeks. This rules out commonly suggested sources of nonequilibrium quasiparticles, such as insufficient shielding against stray light or ionizing radiation.

We monitor the charge on an aluminium superconducting island, sketched in Fig. 1a and shown in Fig. 1b, with volume $V = 2 \mu m \times 0.5 \mu m \times 35 nm$, charging energy $E_C \approx 90 eV$, and superconducting gap $\Delta \approx 220 \mu eV$. The island is coupled to normal metal copper leads via an insulating aluminium oxide tunnelling barrier. Measurements were done in a dilution refrigerator with a base temperature of 20 mK at a normal metal electron temperature $T_F \approx 100 mK$, obtained by fitting the temperature dependence of two-electron Andreev tunnelling rates (Supplementary Note 6). Coulomb blockade limits the observed charge states to $N = 0, \pm 1$ excess electrons on the island. The charge detector is a capacitively coupled radio-frequency single-electron transistor operating at 580 MHz, whose output is amplified with a Josephson parametric amplifier with an ultra-low bandwidth.

1QTF Centre of Excellence, Department of Applied Physics, Aalto University, Helsinki, Finland. 2Physics Department and NanoLund, Lund University, Lund, Sweden. 3VTT Technical Research Centre of Finland Ltd, QTF Centre of Excellence, VTT, Espoo, Finland. 4Present address: Bluefors Oy, Helsinki, Finland. 5Present address: IQM, Espoo, Finland. 6E-mail: etsi.mannila@aalto.fi
We measure 5 s time traces of the detector output. A representative trace is shown in Fig. 1c. Quiet periods up to seconds long, with no tunnelling events and zero excess electrons, are interrupted by bursts of two or more one- or two-electron tunnelling events between the charge states $N = 0, \pm 1$ within a millisecond (Fig. 1d). We collect statistics from 4.6 h of time traces, containing over $2 \times 10^4$ bursts of tunnelling. In Fig. 2a we show that the waiting times between the bursts of tunnelling follow an exponential distribution, characterized by a rate $\Gamma_{\text{burst}} \approx 1.5$ Hz. This implies that the bursts occur independently, in a Poissonian process. Within the bursts of tunnelling, the average rates of single-electron tunnelling are $\Gamma_{0 \rightarrow +1} \approx 20$ kHz and $\Gamma_{+1 \rightarrow 0} \approx 11$ kHz. Here, rate subscripts denote the initial and final charge states. The tunnelling rates are thus several orders of magnitude higher than the rate at which the bursts occur.

To infer the instantaneous number of quasiparticles $N_{\text{QP}}$ from the time traces, we make a number of observations (see Supplementary Information for details): (i) The single-electron tunnelling rates $\Gamma_{0 \rightarrow +1}$ and $\Gamma_{+1 \rightarrow 0}$ are constant over a range of the gate offset $n_e$, as expected for quasiparticle excitations\(^6\). (ii) The number of single-electron tunnelling events within a burst is even. (iii) The two-electron events are due to Andreev tunnelling, which does not change $N_{\text{QP}}$. (iv) Based on the measured values of $\Gamma_{0 \rightarrow +1}$, $\Delta$ and $E_C$ and further analysis, we conclude that the rate for quasiparticles tunnelling back into the superconductor from the normal metal leads is much smaller than both the single- and two-electron tunnelling rates. (v) Moreover, based on earlier experiments\(^{0,23}\), the recombination of two quasiparticles into a Cooper pair is more than an order of magnitude slower than single-electron tunnelling. Taken together, these observations imply the following compelling, simple physical picture of the quasiparticle dynamics, illustrated in Fig. 1c:

A burst of tunnelling is initiated by the breaking of $N_{\text{QP}}$ Cooper pairs, creating $N_{\text{QP}} = 2N_{\text{QP}}$ quasiparticles on the island. They tunnel out to the normal leads as electrons or holes via single-electron tunnelling events, which decrease the number of quasiparticles one by one, $N_{\text{QP}} \rightarrow N_{\text{QP}} - 1$ as the charge state $N$ changes by $\pm 1$. After the last quasiparticle has tunnelled out, within a millisecond from the start of the burst, the superconducting island is completely free of quasiparticles until the next burst occurs, on average for 0.4 s. Therefore counting the number of events changing $N$ yields directly $N_{\text{QP}}$, which also allows us to infer $N_{\text{QP}}$ for each burst.

The statistical distribution of $N_{\text{QP}}$ (Fig. 2b) is well described by an exponential $\propto \exp(-\lambda N_{\text{QP}})$ with $\lambda \approx 0.9 \pm 0.1$. In 40% of the bursts, more than one Cooper pair was thus initially broken. Further insight into the dynamics of quasiparticle number relaxation is obtained from the probability $P(N_{\text{QP}}|t) = 0$ for having $N_{\text{QP}}$ quasiparticles at a time $t$ after the first tunnelling event in the burst. The probabilities for $N_{\text{QP}} = 0$ to 3 as well as $N_{\text{QP}} \geq 4$ are shown in Fig. 3a. Already at $t = 0.5$ ms, the probability for having any quasiparticles remaining is below 10%. At short times, $P(N_{\text{QP}}|t)$ increases (decreases) for $N_{\text{QP}}$ even (odd) as a function of $t$, a consequence of having an odd number of quasiparticles on the island directly after the first tunnelling event at $t = 0$.

Figure 3a also shows that $P(N_{\text{QP}}|t)$ decays faster for increasing $N_{\text{QP}}$. This is consistent with the prediction that the single-electron tunnelling rate for $N_{\text{QP}}$ quasiparticles on the island is proportional to $N_{\text{QP}}$ (ref. 27). It is further reflected in the time-dependent rates $\Gamma_{0 \rightarrow +1}(t)$ and $\Gamma_{+1 \rightarrow 0}(t)$ for single-electron tunnelling (Fig. 3b), evaluated in a short interval around time $t$ within the bursts. In particular, we see that the long-time ($t > 200$ ms) rate from the state $N = 0$, that is, $\Gamma_{0 \rightarrow +1}(t) \approx 15$ kHz, is twice the rate from $N = \pm 1$, that is $\Gamma_{+1 \rightarrow 0}(t) \approx 8$ kHz, since the even state has two quasiparticles before the end of the burst compared with one quasiparticle for odd states. Furthermore,
Fig. 2 | Statistics of Cooper pair breaking events. a. Lengths of quiet periods between bursts of tunnelling. The experimental data (circles), binned into intervals of equal length 0.2 s, are fitted with an exponential curve (solid line). The corresponding Poissonian waiting time distribution describes random-in-time bursts with an average burst rate $\Gamma_{\text{burst}} \approx 1.7$ Hz and average length of quiet period $\approx 0.4$ s. Note that $\Gamma_{\text{burst}}$ overestimates the true burst rate, 1.5 Hz, due to the finite length of the time traces (Supplementary Note 4). b, Counts of number of quasiparticle pairs $N_{\text{qp}}$ (2$N_{\text{par}}$) generated per event. Experimental data (circles) are obtained by counting the number of single-electron tunnelling events within each burst (Fig. 1c,d). The solid line is an exponential fit $\sim \exp(-\lambda N_{\text{par}})$, weighted by the counts, with $\lambda = 0.9 \pm 0.1$. Error bars in a,b represent statistical uncertainty due to the finite number of events per bin.

The initial decay is consistent with the picture that, initially, more than two quasiparticles may be created. The timescale for the decay arises from the quasiparticle tunnelling rate and is thus of the order of 100 $\mu$s. The measured single-quasiparticle rate $\Gamma_{\text{qp}} = \Gamma_{t=0}(t) = 8$ kHz is close to the estimate 17 kHz obtained based on other experiments (Supplementary Note 6). The dynamics of $N_{\text{qp}}$ within a burst, based on the simple physical picture, are modelled by a rate equation for $P(N_{\text{qp}}, t)$ (Methods). As the initial condition, we have the experimentally determined distribution $P(N_{\text{qp}}) \sim \exp(-0.9 N_{\text{par}}) = \exp(-0.45 N_{\text{qp}})$ at the start of the burst (Fig. 2). Only tunnelling out of quasiparticles is accounted for, making $\Gamma_{\text{qp}}$ the only free parameter of the model. From Fig. 3a, we see that the model reproduces the experimental results well for all times within the burst and over three orders of magnitude of $P(N_{\text{qp}}, t)$, for all $N_{\text{qp}}$ shown. The best fit is obtained for $\Gamma_{\text{qp}} = 8.0$ kHz, in agreement with the measurements in Fig. 3b. Moreover, in Fig. 3b, the results from the model for the time-dependent rates $\Gamma_{t=0}(t)$ and $\Gamma_{t=+1}(t)$ are plotted together with the experimental data. Both the observed initial decay and the long-time saturation are well captured by the model. The model also allows us (Methods) to obtain an accurate estimate of the time-averaged number of quasiparticles on the island $\langle N_{\text{qp}} \rangle = 2.5 \Gamma_{\text{burst}}/\Gamma_{\text{qp}} = 4.7 \times 10^{-4}$, measured 130 days after the start of the cooldown. The corresponding quasiparticle density is $n_{\text{qp}} = \langle N_{\text{qp}} \rangle/V = 0.013$ quasiparticles $\mu$m$^{-3}$ or $x_{\text{qp}} = \langle N_{\text{qp}} \rangle/(D(E_c) \Delta V) \approx 2 \times 10^{-4}$, if normalized by the Cooper pair density $\Delta D(E_c)$, with $D(E_c) = 2.15 \times 10^{-7}$ J$^{-1}$ m$^{-3}$ the density of states. This is comparable to the lowest measured values $x_{\text{qp}} \sim 10^{-4}$ reported in literature and below the bound $x_{\text{qp}} \approx 7 \times 10^{-9}$ estimated due to the ionizing radiation background in ref. 16.

In our experiment, the rate of the bursts $\Gamma_{\text{burst}}$ decreased over time from the start of a cooldown on timescales of weeks following a power law $\Gamma_{\text{burst}} \propto t^{-\alpha}$, where $t$ is the time after the sample reached temperatures below 77 K. This was observed reproducibly in two subsequent cooldowns of the same sample, as shown in Fig. 4. The observed long-time decay of $\Gamma_{\text{burst}}$ rules out a number of observed or suggested sources of quasiparticles being dominant in our system. In particular, external infrared or microwave photons and environmental radioactivity and cosmic rays are all expected to be stationary sources of quasiparticles. Moreover, the distribution of Cooper pairs broken per burst did not change during the cooldown (Supplementary Figs. S10–S12), suggesting that the same source of quasiparticles was dominant throughout the experiment. Although heat leaks decreasing over timescales of weeks are well known in experiments at low temperatures, we cannot certify what in our experiment is the mechanism of Cooper pair breaking.

The real-time monitoring of the single-electron tunnelling (Fig. 1) reveals the dynamics of the charge state of the island charge $N$, and hence the parity, during a burst. On a typical timescale $1/\Gamma_{\text{qp}}$, the charge changes from $N = 0$ to $N = \pm 1$ and back, a number of times. However, for less than 1% of the bursts, a distinctly different
We attribute the switching between different types of charge tunneling events (Supplementary Note 8 and Supplementary Fig. S13). A power-law fit $t_{\text{burst}} \propto r^{t-1}$ is shown by a solid line. The right $y$ axis shows the corresponding time-averaged quasiparticle density $n_{\text{QP}}$, proportional to $\Gamma_{\text{burst}}$ (see text) since the distribution of quasiparticles generated per burst as well as the single-electron tunneling rate were found to be constant over the entire cooldown period (Supplementary Note 7). Circle indicates data used in Figs. 1–3, and error bars indicate statistical uncertainty as well as uncertainty in the timing from the start of the cooldown.

In conclusion, we have investigated the dynamics of the number of quasiparticles on a superconducting island via real-time monitoring of single-electron tunneling. We demonstrate that a mesoscopic superconducting island can remain completely free from quasiparticles for time periods up to seconds. These findings open a new route to identifying periods of quasiparticle free operation of superconducting devices, of key interest for, for example, superconducting quantum computation. Our approach, giving access to the number of Cooper pairs broken in a given event, also provides new information on the properties of the source of quasiparticles, which is presently an actively investigated and debated topic.16–19 Furthermore, our device could potentially be adapted to operate as an energy-resolving single-photon detector in the terahertz range similar to the quantum capacitance detector.2

Online content
Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41567-021-01433-7.

Published online: 20 December 2021

Published on 20 December 2021

References
1. Day, P. K., LeDuc, H. G., Mazin, B. A., Vayonakis, A. & Zmuidzinas, J. A broadband superconducting detector suitable for use in large arrays. Nature 425, 817 (2003).
2. Echtternach, P. M., Pepper, B. J., Reck, T. & Bradford, C. M. Single photon detection of 1.5 THz radiation with the quantum capacitance detector. Nat. Astron. 2, 90 (2018).
3. Kjaergaard, M. et al. Superconducting qubits: current state of play. Annu. Rev. Condens. Matter Phys. 11, 369 (2020).
4. Aumentado, J., Keller, M. W., Martinis, J. M. & Devoret, M. H. Nonequilibrium quasiparticles and 2e periodicity in single-cooper-pair transistors. Phys. Rev. Lett. 92, 066802 (2004).
5. Shaw, M. D., Lutchyn, R. M., Delsing, P. & Echtternach, P. M. Kinetics of nonequilibrium quasiparticle tunneling in superconducting charge qubits. Phys. Rev. B 78, 024503 (2008).
6. de Visser, P. J. et al. Number fluctuations of sparse quasiparticles in a superconductor. Phys. Rev. Lett. 106, 167004 (2011).
7. Martinis, J. M., Ansmann, M. & Aumentado, J. Energy decay in superconducting Josephson-junction qubits from nonequilibrium quasiparticle excitations. Phys. Rev. Lett. 103, 077002 (2009).
8. Catelani, G. et al. Quasiparticle relaxation of superconducting qubits in the presence of flux. Phys. Rev. Lett. 106, 077002 (2011).
9. Pop, I. M. et al. Coherent suppression of electromagnetic dissipation due to superconducting quasiparticles. Nature 508, 369 (2014).
10. Wang, C. et al. Measurement and control of quasiparticle dynamics in a superconducting qubit. Nat. Commun. 5, 5836 (2014).
11. Patel, U., Pechenezhsky, I. V., Plourde, B. L. T., Vavilov, M. G. & McDermott, R. Phonon-mediated quasiparticle poisoning of superconducting microwave resonators. Phys. Rev. B 96, 205201(R) (2017).
12. Gustavsson, S. et al. Suppressing relaxation in superconducting qubits by quasiparticle pumping. Science 354, 1573 (2016).
13. Ferguson, A. J. Quasiparticle cooling of a single Cooper pair transistor. Appl. Phys. Lett. 93, 052501 (2008).
14. Higginbotham, A. P. et al. Parity lifetime of bound states in a proximitized semiconductor nanowire. Nat. Phys. 11, 1017 (2015).
15. Vool, U. et al. Non-Poissonian quantum jumps of a fluxonium qubit due to quasiparticle excitations. Phys. Rev. Lett. 113, 247001 (2014).
16. Vepsäläinen, A. et al. Impact of ionizing radiation on superconducting qubit coherence. Nature 584, 551 (2020).
17. Cardani, L. et al. Reducing the impact of radioactivity on quantum circuits in a deep-underground facility. Nat. Commun. 12, 2733 (2021).
18. Wilen, C. D. et al. Correlated charge noise and relaxation errors in superconducting qubits. Nature 594, 369 (2021).
19. Martinis, J. M. Saving superconducting quantum processors from qubit decay and correlated errors generated by gamma and cosmic rays. npj Quantum Inf. 7, 90 (2021).
20. Wilson, C. M., Frunzio, L. & Prober, D. E. Time-resolved measurements of thermodynamic fluctuations of the particle number in a nondegenerate Fermi gas. Phys. Rev. Lett. 87, 067004 (2001).
21. Lambert, N. J. et al. Experimental observation of the breaking and recombination of single Cooper pairs. Phys. Rev. B 90, 140503 (2014).
22. Serniak, K. et al. Direct dispersive monitoring of charge parity in offset-charge-sensitive transmons. Phys. Rev. Appl. 12, 044052 (2019).
23. Van Woerkom, D. J., Geresdi, A. & Kouwenhoven, L. P. One minute parity lifetime of a NbTiN Cooper-pair transistor. Nat. Phys. 11, 547 (2015).
24. Hays, M. et al. Direct microwave measurement of Andreev-bound-state dynamics in a semiconductor-nanowire Josephson junction. Phys. Rev. Lett. 121, 047001 (2018).
25. Karzig, T., Cole, W. S. & Pikulin, D. I. Quasiparticle poisoning of Majorana qubits. Phys. Rev. Lett. 126, 057702 (2021).
26. Barends, R. et al. Minimizing quasiparticle generation from stray infrared light in superconducting quantum circuits. Appl. Phys. Lett. 99, 113507 (2011).
27. Saira, O.-P., Kemppinen, A., Maisi, V. F. & Pekola, J. P. Vanishing quasiparticle density in a hybrid Al/Cu/Al single-electron transistor. Phys. Rev. B 85, 012504 (2012).
28. Maisi, V. F. et al. Excitation of single quasiparticles in a small superconducting Al island connected to normal-metal leads by tunnel junctions. Phys. Rev. Lett. 111, 147001 (2013).
29. Pohell, F. Matter and Methods at Low Temperatures 3rd edn (Springer-Verlag, 2007).
Methods
Sample fabrication. The sample is fabricated by standard electron-beam liftoffography and multiple-angle deposition on a silicon substrate. The normal metal leads of the superconducting island are capacitively shunted by a 2 nm/30 nm/2 nm-thick Ti/Au/Au ground plane, which helps suppress quasiparticle-assisted tunneling events\(^\text{[31]}\). The charge detector is a normal-metal single-electron transistor fabricated with the laterally proximitized tunnel junction technique\(^\text{[27]}\), expected to minimize quasiparticle poisoning due to nonequilibrium phonons\(^\text{[17]}\). A 10-μm-long chromium capacitor creates the capacitive coupling between the detector and superconductor island. The ground plane and coupler are insulated from the actual devices by a 40-nm-thick aluminium oxide layer grown by atomic layer deposition. Further details on the sample design and fabrication are given in Supplementary Note 1 and Supplementary Fig. S1.

Measurements. The sample is attached to a copper sample holder weighing approximately 0.5 kg by using vacuum grease. Aluminium wire bonds connect the sample chip and the resonator chip (see below) to the printed circuit board of the sample stage. The bond wires to one of the bias leads and the gate electrode of the superconducting island had disconnected during the cooldown, but we were able to tune \(g\) by applying a voltage to the surviving bias lead instead. In the measurements shown in the main text, the gate voltage was held constant at \(N_0 = 0\). The sample holder is closed with a single indium-sealed cap, which is coated by Ecosorb. The sample holder is thermally anchored to the mixing chamber stage of a cryogen-free dilution refrigerator with a base temperature of 20 mK, with the innermost radiation shield attached to the still flange of the refrigerator (temperature between 0.5 and 1 K).

The low-frequency measurement lines to the sample are filtered with approximately 2 m of Thermocoucas.\(^\text{[34]}\) The radio-frequency lines are filtered and attenuated with commercial attenuators and filters at different temperature stages of the refrigerator. We have measured the same sample in two subsequent cooldowns. For the second cooldown, we added home-made Ecosorb filters to the input and output RF lines at the mixing chamber stage, as well as disconnecting a RF gate line not used in this experiment. A detailed wiring schematic is provided in Supplementary Fig. S2 and Supplementary Note 2.

We operate the charge detector as a radio-frequency single-electron transistor\(^\text{[33]}\) at 580 MHz, with details on the detector given in Supplementary Note 3. We have verified by changing the probe power that the detector does not cause measurable back action on the superconducting island in this experiment (Supplementary Fig. S3). The output signal from the detector is amplified by a Josephson parametric amplifier (IPA) with added noise on the order of 100 mK (ref. \textsuperscript{[22]}) at the mixing chamber, followed by semiconductor amplifiers at the 2 K stage and at room temperature. The parametric amplifier is similar to the devices presented in ref. \textsuperscript{[22]}, but has a higher bandwidth. Operating the IPA in the phase-sensitive mode enables charge sensitivities of \(2 \times 10^{-4} \text{e}/\sqrt{\text{Hz}}\) and charge detection with a signal-to-noise ratio of 6 in 3 s (Supplementary Fig. S4). We note that the measured time trace appears noisier in Fig. 1c than in 1d although the same data are shown in both panels, but this is purely a visual effect. The JPA improves the measured time-averaged number of quasiparticles on the island at a time \(t\) of having \(N_0\) quasiparticles on the island at a time \(t\) a tunneling event in a burst. From the general model (Supplementary Notes 5 and 6 and Supplementary Fig. S7) and considering only single-electron tunneling out from the island, we have

\[
\frac{dP(N_Q, t)}{dt} = -\sigma \Gamma_Q N_Q P(N_Q, t) + \sigma \Gamma_Q (N_Q + 1) P(N_Q + 1, t)
\]

where \(\sigma = 1, 2\) and \(\sigma = 2, \sigma = 1\) for \(N_Q = 1, 3, 5, \ldots (N_Q = 0, 2, 4, \ldots)\). The factors \(\sigma\) arise from the fact that, starting from the state \(N = 0\), where \(N_Q\) is even, the quasiparticles can tunnel out as both electrons and holes with two possible final states \(N = \pm 1\). On the other hand, starting from \(N = \pm 1\), where \(N_Q\) is odd, strong Coulomb interactions restrict the possible final states to \(N = 0\). With the initial condition observed experimental distribution of number of broken Cooper pairs (Fig. 2b), the probability distribution plotted in Fig. 3a is evaluated numerically. The effective time-dependent single-electron tunneling rates \(\Gamma_{\text{QP}}(t)\) and \(\Gamma_{\text{QP}}(0)\) (Fig. 3b) are obtained from (see Supplementary Note 5 for details)

\[
\Gamma_{N, N_Q}(t) = \Gamma_{\text{QP}} \sum_{N_Q'} \frac{\sigma \Gamma_Q N_Q P(N_Q, t) P(N_Q', t)}{\sum_{N_Q} P(N_Q', t)}
\]

where the sum runs over \(N_Q = 2, 4, 6, \ldots\) for \(N = 0\) and \(N_Q = 1, 3, 5, \ldots\) for \(N = \pm 1\).

In the text, the time-averaged number of quasiparticles \(\langle N_Q \rangle\) on the island is discussed. From the probability distribution in equation (1) we can evaluate \(\langle N_Q \rangle\) along the following lines: From the observed distribution of waiting times between quasiparticle breaking events in Fig. 2a, we have that the average burst duration is \(\langle \Delta t \rangle\). During a burst, the time-dependent number of quasiparticles \(N_Q(t)\) on the island is given by

\[
\langle N_Q(t) \rangle = \sum_{N_Q} P(N_Q, t) N_Q = 0, 1, 2, \ldots
\]

The average number \(\langle N_Q \rangle\) is then directly given by

\[
\langle N_Q \rangle = \Gamma_{\text{QP}} \sum_{N_Q} P(N_Q, t) N_Q = 0, 1, 2, \ldots
\]

where a numerical evaluation gives the coefficient \((\mathcal{L} = 0.45) = 2.5\), which depends on the initial condition. We note that the \(1/\Gamma_Q \) dependence arises since \(P(N_Q, t)\), from equation (1), depends only on the renormalized time \(\tau_{\text{QP}}\). Moreover, the upper limit \(\mathcal{L}\) of the integral can be taken due to the orders of magnitude difference between the burst duration \(-1/\Gamma_Q\) and the average time between bursts \(-1/\Gamma_{\text{QP}}\). We can also estimate the probability of having undetected quasiparticles on the island at any given moment of time within the quiet periods, which is less than \(10^{-6}\) based on the probabilities of missing tunneling events due to the finite detector bandwidth and quasiparticles decaying by recombination instead of tunneling (see Supplementary Notes 4 and 6 for details).

Data availability
Data for figures that support the manuscript are available at https://doi.org/10.5281/zenodo.5574415. All other data that support the findings of this study are available from the corresponding author upon reasonable request.

References
30. Pekola, J. P. et al. Environment-assisted tunneling as an origin of the Dynes density of states. Phys. Rev. Lett. 105, 026803 (2010).
31. Koski, J. V., Peltonen, J. T., Meschke, M. & Pekola, J. P. Laterally proximized aluminum tunnel junctions. Appl. Phys. Lett. 98, 203501 (2011).
32. Zorin, A. B. The thermocoax cable as the microwave frequency filter for single-electron circuits. Rev. Sci. Instrum. 66, 4296 (1995).
33. Schoelkopf, R. J., Wahlgren, P., Kozhevnikov, A. A., Delsing, P. & Prober, D. E. The radio-frequency single-electron transistor (RF-SET): a fast and ultrasensitive electrometer. Science 280, 1238 (1998).
34. Simbierowicz, S. et al. A flux-driven Josephson parametric amplifier for sub-GHz frequencies fabricated with side-wall passivated spacer junction technology. Superconductor Sci. Technol. 31, 105001 (2018).

Acknowledgements
The authors thank O. Maillet for useful discussions, J. Ala-Heikkilä for support with shielding solutions and J. Lehtinen and M. Prunnila from VTT Technical Research Center of Finland Ltd., who were also involved in the JPA development. This work was performed as part of the Academy of Finland Centre of Excellence program (projects 312077, 312059 and 312294). We acknowledge the provision of facilities and technical support by Aalto University at OtaNano - Micronova Nanofabrication Centre and OtaNano - Low Temperature Laboratory. E.T.M. and J.P.P. acknowledge financial support from Microsoft. V.V. acknowledges financial support from the Swedish National Science Foundation, and VEM acknowledges financial support from the Quant ERA project ‘2D hybrid materials as a platform for topological quantum computing’ and NanoLund.

Author contributions
E.T.M., P.S., V.F.M. and J.P.P. conceived the experiment and model and interpreted the results. E.T.M. and J.P.P. conducted the experiment and model and interpreted the results. E.T.M., P.S. and V.F.M. performed the experimental part of the work. E.T.M. and J.P.P. acknowledged financial support from the Swedish National Science Foundation, and VEM. E.T.M. and P.S. with input from all authors with input from all authors.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41567-021-01433-7.