Detecting parity effect in a superconducting device in the presence of parity switches

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We present a superconducting device showing a clear parity effect in the number of electrons, even when there is, on average, a single nonequilibrium quasiparticle present and the parity of the island switches due to quasiparticles tunneling in and out of the device at rates on the order of 100 Hz. We detect the switching by monitoring in real time the charge state of a superconducting island connected to normal leads by tunnel junctions. The quasiparticles are created by Cooper pairs breaking on the island at a rate of a few kilohertz. We demonstrate that the pair breaking is caused by the backaction of the single-electron transistor used as a charge detector. With sufficiently low probing currents, our superconducting island is free of quasiparticles 97% of the time.

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In a superconductor, electrons participating in conduction form Cooper pairs. The minimum energy for an unpaired quasiparticle excitation is $\Delta$, the superconducting gap, which leads to a free energy difference between states with an even and odd number of electrons in the absence of subgap states.

The resulting parity effect is commonly observed in features periodic in $2e$, with $e$ the electron charge, in the transport through an island or by measuring the average charge in an isolated box [1–4]. In thermal equilibrium, the parity effect disappears at temperatures where quasiparticles are excited, around 200 mK for typical micron-scale aluminum structures, as the free energy difference disappears. A clean $2e$ periodicity of Coulomb blockade is often taken to suggest a device free of quasiparticles [5–7].

In addition to suppressing the parity effect [8,9], quasiparticle excitations are generally detrimental for superconducting devices. In Josephson junction based qubits, quasiparticles tunneling across the junction cause decoherence [10,11]. For quantum computing using Majorana modes in superconductor-semiconductor hybrids, topological protection is only present when the total fermion parity of the system stays constant. The parity lifetime is a fundamental bound to the coherence time of such a qubit [12–14]. At low temperatures the quasiparticle density $n_{qp}$ should be exponentially suppressed, and the parity lifetime consequently exponentially long. In practice, often a saturation of $n_{qp}$ to values several orders of magnitude higher than in thermal equilibrium is observed in experiments on qubits [10,15,16], resonators [17–19], and quantum capacitance [20] and kinetic inductance detectors [21]. Another quantity related to $n_{qp}$ is the poisoning time between successive quasiparticle tunneling events. Quasiparticle densities or poisoning times can be inferred from transport measurements [13,14,22–24] or qubit coherence times [25]. Even-to-odd transitions from quasiparticle tunneling can also be measured in real time with radio-frequency reflectometry [15,26–28] or in the parity-dependent frequency shift of transmon qubits [16,29]. In this work, we measure in real time quasiparticle tunneling and parity switching on a superconducting island, and observe a parity effect in the parity-dependent occupation probabilities and tunneling rates of charge states. The quasiparticles are created from the backaction of the charge detector [9]. This is a critical issue for Majorana qubit proposals incorporating charge readout [30,31].

We characterize the state of the superconducting island with the excess charge $N$ and number of excitations $N_\text{S}$ on the island, where $N$ and $N_\text{S}$ are integers of the same parity, following Ref. [23], which provides the quantitative details of the model. The relevant processes in our system are shown in Fig. 1(a). If there are two or more excitations on the island, they can recombine to a Cooper pair with rates $\Gamma_{\text{rec}}(N_\text{S})$. We include recombination via the electron-phonon coupling. Cooper pairs on the island can break, creating two excitations, with a rate $\Gamma_{\text{pb}}$, assumed independent of the state of the island. The thermal electron-phonon pairbreaking rate is vanishingly small at the temperatures of the experiment, so this rate arises from nonequilibrium conditions. We directly detect the quasiparticle tunneling events between the superconducting island and normal metal leads at temperature $T_N$, which change both $N$ and $N_\text{S}$ by one. If excess quasiparticles are present (the superconductor temperature $T_S > T_N$) but $k_BT_S \ll \Delta$, the rate for quasiparticles tunneling out of the island $\Gamma_{\text{qp}}(N_\text{S}) = \Gamma(N \to N \pm 1, N_\text{S} \rightarrow N_\text{S} - 1)$ depends, for a range of energy gains, only on the quasiparticle density $n_{qp} = \sqrt{2\pi D(E_F)}\sqrt{\Delta k_BT_S}e^{-\Delta/k_BT_S}$ or $N_\text{S} = n_{qp} V$ before the tunneling event as [32]

$$\Gamma_{\text{qp}}(N_\text{S}) = \frac{N_\text{S}}{2e^2R_TD(E_F)V}. \quad (1)$$
FIG. 1. (a) States \((N,N)\) with \(N\) excess charges and \(N\) quasi-particle excitations on the superconducting island. Quasiparticles tunneling from the island to normal metal leads at rates \(\Gamma_{ph}(N)\) given by Eq. (1) are directly detected, while quasiparticle tunneling into the island (light blue) is suppressed by the superconducting gap. Cooper pairs break at a rate \(\Gamma_{ph}\) and recombine with \(\Gamma_{nc}\). Andreev tunneling events \((\Gamma_{pr})\) transfer two electrons on or off the island while keeping the number of quasiparticles constant. (b) The parity-dependent free energy \(E = E_C(N - n_g)^2 + F(T_3) \times N\) mod 2 of even (solid lines) and odd (dashed) charge states \(N\), calculated at \(k_B T_3/\Delta = 0.02\) and \(E_C/\Delta = 0.33\). Arrows show values of the gate offset \(n_g\) for the charge detector traces shown in Fig. 2.

Here, \(R_T\) is the resistance of the tunnel junction, \(k_B\) the Boltzmann constant, and \(D(E_F) = 2.15 \times 10^{17} \text{ J}^{-1} \text{ m}^{-2}\) [17] the normal density of states (including spin) at the Fermi level. In particular, a single quasiparticle in the island with volume \(V = 550 \text{ nm} \times 2 \mu \text{m} \times 50 \text{ nm}\) and \(R_T = 15.6 \text{ M} \Omega\) corresponds to \(\Gamma_{ph} = 110 \text{ Hz}\). Tunneling events which increase \(N\) are suppressed by the superconducting gap when \(N\) is close to the gate offset \(n_g\).

If \(\Gamma_{ph}\) is zero in the model above, we recover the thermal equilibrium case. The free energies of the charge states \(\gamma\) of a superconducting island are \(E = E_C(N - n_g)^2 + F(T_3) \times N\) mod 2, which includes, in addition to the contribution of the charging energy \(E_C = c^2/2C_S\) with \(C_S\) the total capacitance of the island, the free energy cost \(\gamma F(T_3) \approx \Delta - k_B T_3 \ln [D(E_F) \times V \Delta]\) of an unpaired excitation [13]. The approximation is valid when \(k_B T_3 < \Delta\). These free energies are sketched in Fig. 1(b) against \(n_g = C_V/e\), where \(C_V\) is the voltage applied to a gate electrode coupled via capacitance \(C_g\). When \(F(T_3) > E_C\), as in our devices below 120 mK, the ground state has even parity, and we expect to see only two-electron Andreev tunneling events. The states with odd \(\gamma\) should become significantly occupied only above the temperature \(T_0 \approx \Delta/[k_B \ln |V D(E_F)\Delta|] \approx 190 \text{ mK}\), where a single quasiparticle is thermally excited on the island.

Our device, shown in Fig. 2(a), is a single-electron transistor (SET) with a superconducting aluminum island connected to normal metal copper leads with aluminum oxide tunnel barriers a few nanometers thick. The capacitively coupled charge detector is another SET, but with a copper island and aluminum leads. The devices were fabricated with standard electron-beam lithography and three-angle evaporation on thermally oxidized silicon substrates. We have measured two similar devices, samples A and B. The energy gap \(\Delta = 206 \mu \text{eV} (210 \mu \text{eV})\), total tunnel resistance of the two junctions \(70 \text{ M} \Omega (40 \text{ M} \Omega)\), and the charging energy \(E_C = 0.33\Delta = 68 \mu \text{eV} (0.45\Delta = 95 \mu \text{eV})\) of sample A (B) were determined by fitting the current-voltage characteristics as shown in Fig. 2(b). For the electron counting experiments, the superconducting island was kept at zero bias. The island acts as a single-electron box connected to normal leads through the parallel resistance of the two junctions \(R_T = 15.6 \text{ M} \Omega (8.9 \text{ M} \Omega)\), with both devices having unequal tunnel junctions whose areas and resistances differ by a factor of 2. Sample A was measured at 60 mK in a DC measurement setup sketched in Fig. 2(a), where we directly record the amplified detector current \(I_{det}\). Sample B was measured at 25 mK in a setup where the detector was used as an RF-SET [33,34].

Figures 2(c)–2(j) show real-time traces of the charge detector output at \(n_g = 0\) [(c),(d),(g),(h)] and \(n_g = 1\) [(e),(f),(i),(j)]. In sample A [Figs. 2(c)–2(f)], three charge states are always occupied for a significant fraction of time, even though the charging energy \((E_c/k_B \approx 800 \text{ mK})\) is much larger than the bath temperature. Most of the transitions are single-electron...
always has even parity. The transition rates have plateaus at probability, a nonequilibrium situation, but the most probable state are always at least three charge states occupied with more than 10% A. Filled (open) circles are measured data for even (odd) 80 Hz and \( \Gamma_{1} \). The time-averaged number of excitations from the simulations is \( (N_{S}) = 0.86 \) in even charge states and 1.6 in odd states. The equilibrium temperature where the parity effect is expected to disappear corresponds to a single quasiparticle being excited. It is somewhat against the common view that the parity effect is clearly visible even with a single nonequilibrium excitation present and quasiparticles continuously tunneling in and out of the device, as we demonstrate here. The ratio of the pair breaking and recombination rates \( \Gamma_{pb}/\Gamma_{rec} \) determines the quasiparticle density. However, we cannot determine these two rates independently: the agreement between simulations and experiment in Fig. 3 remains equally good if \( \Gamma_{pb} \) and the electron-phonon coupling constant \( \Sigma \) setting \( \Gamma_{rec} \) are scaled up or down but by the same factor.

FIG. 3. (a) Occupation probabilities \( P(N) \) and (b), (c) tunneling rates \( \Gamma_{N,N\pm1} \) between charge states \( N \) over a range of \( n_{g} \) in sample A. Filled (open) circles are measured data for even (odd) \( N \). There are always at least three charge states occupied with more than 10% probability, a nonequilibrium situation, but the most probable state always has even parity. The transition rates have plateaus at \( \Gamma_{even} = 80 \text{ Hz} \) and \( \Gamma_{odd} = 160 \text{ Hz} \) with the rate depending only on the parity of the initial state. This corresponds to a parity-dependent quasiparticle density on the island. Solid lines are simulations with the Cooper pair breaking rate \( \Gamma_{pb} = 4.6 \text{ kHz} \) as the only free parameter.

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We now turn to the origin of the Cooper pair breaking rate observed. We repeat the measurement of time traces versus $n_\text{q}$ in sample A at different $V_{b,\text{det}}$ between 385 and 560 $\mu$V and extract $\Gamma_{qp}(N_{\text{S,even}})$ and $\Gamma_{qp}(N_{\text{S,odd}})$ at the quasiparticle-induced plateaus, shown as a function of $I_{\text{det}}$ in Fig. 4. The tunneling rates increase linearly with detector current, but $\Gamma_{qp}(N_{\text{S,even}})$ extrapolates to 10 ± 7 Hz at $I_{\text{det}} = 0$ and $\Gamma_{qp}(N_{\text{S,odd}})$ to somewhat below 100 Hz, close to the calculated tunneling rate 110 Hz of one quasiparticle. To model pair breaking by backaction, we assume $\Gamma_{pb} = A I_{\text{det}}/e$ without any detector-independent rate. The fit parameter $A = 1/300 000$ is the probability for an electron tunneling in the detector to break a Cooper pair. We calculate the mean quasiparticle number in even and odd states at $n_\text{q} = 0.5$ as a function of $\Gamma_{pb}$ (Fig. 4) and convert it to a tunneling rate using Eq. (1). Fitting the occupation probabilities and tunneling rates as in Fig. 3 to measurements at different $V_{b,\text{det}}$ confirms that the effect of the detector is only to break Cooper pairs, as no other parameters need to be changed for a good fit (data not shown). A similar linear dependence on the current of the occupation probabilities of the charge states of a superconducting SET was observed as quasi-particle poisoning rate of a fully superconducting SET in Ref. [9].

In conclusion, we have observed a clear parity effect in the occupation probabilities and tunneling rates of the charge states of a superconducting island, even in the presence of a single nonequilibrium excitation and frequent parity switches. The excitations are generated by Cooper pairs breaking on the superconducting island, and the quasiparticles almost always recombine before tunneling out. The poisoning time or parity lifetime of the island—defined as the time between quasiparticle tunneling events—can be long, even though the island is still poisoned in the sense of quasiparticles being present. The Cooper pair breaking is caused by the backaction of the charge detector, which can be minimized by reducing the detector current. We expect that in future experiments, the statistics of electron counting yields access to the recombination and pair breaking rates independently of each other as in the spin-blockade studies [45–47], where the electron occupation preserving spin-flip rate was determined from the tunneling statistics.

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