Evidence of 1.5 THz Single-Photon Detection in Quantum Capacitance Detectors via Telegraph Rate Distribution Asymmetry

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***Abstract*—Quantum Capacitance Detectors (QCDs) are shot noise limited terahertz detectors. Radiation breaks Cooper pairs, causing quasiparticle poisoning of a charge qubit, read out by a microwave resonator. We find asymmetry in the distribution of telegraph transition rates, interpreted as resulting from discrete single-photon events.**

I. Introduction and Background

The Quantum Capacitance Detector (QCD) [1], [2] is a terahertz detector based on a Single Cooper-pair Box (SCB) charge qubit. Radiation breaks Cooper pairs in a superconducting absorber, leading to quasiparticle poisoning of the SCB, which can be read out via a superconducting microwave coplanar waveguide. QCDs have demonstrated shot noise limited scaling of noise equivalent power (NEP) from 1×10^{-18} W to below 1×10^{-20} W of absorbed power [3]. Though initially they suffered from poor optical efficiency ($\sim 3.5\%$) [3], [4], more recent devices have with capacitive coupling to the antenna have demonstrated efficiencies of order 35% while maintaining photon shot noise-limited scaling [5]. However, despite shot noise-limited scaling of NEP, QCDs have not previously shown more direct evidence of single-photon events.

In this work we explore the quasiparticle fluctuations of a QCD under photon flux at 1.5 THz. As absorptions of such photons represent ~ 20-quasiparticle events, these fluctuations will gradually outweigh generation-recombination noise. We show this will lead to an asymmetry in the distribution of quasiparticle occupations N_{qp}, with a long tail on the higher side. We then measure telegraph transition rates in real QCDs, showing qualitatively similar asymmetry in the distribution of telegraph transition rates. As these rates should be instantaneously proportional to the quasiparticle occupation number, this asymmetry is evidence of single photon events.

II. Quasiparticle Fluctuations

The mean quasiparticle population in the absorber in QCDs, can be described by detailed balance equations [1]:

$$\frac{dN_{\text{qp}}}{dt} = \Gamma_{\text{phot}} + \Gamma_{\text{gen}} - RN_{\text{qp}}(N_{\text{qp}} - 1) - KN_{\text{qp}}p_{\text{even}} + \Gamma_{\text{out}}p_{\text{odd}} \tag{1}$$

$$\frac{dp_{\text{odd}}}{dt} = KN_{\text{qp}}p_{\text{even}} - \Gamma_{\text{out}}p_{\text{odd}}, \tag{2}$$

where N_{qp} is the quasiparticle population, $\Gamma_{\text{phot}} = \epsilon\eta P_{\text{in}}/\Delta$ is the rate of quasiparticle generation from pair-breaking by photons, ϵ is the optical efficiency, η is the quasiparticle conversion efficiency, P_{in} is the input power, Δ is the superconducting gap energy, Γ_{gen} is the quasiparticle generation rate, R is the recombination rate, K is the rate of tunneling to the island, Γ_{out} is the rate of tunneling out of the island, and p_{even} and p_{odd} are the probability of the island being occupied by an even and odd number of quasiparticles respectively.

One can consider fluctuations about this mean by constructing a master equation [6]. At first, we will neglect the island to find the stationary mixture. Generation and recombination with rates of $\Gamma_{\text{gen}}/\delta n_{\text{g-r}}$ and $RN_{\text{qp}}(N_{\text{qp}}-1)/\delta n_{\text{g-r}}$ will alter the population by a shot size of $\delta n_{\text{g-r}} = 2$ quasiparticles. Photon arrival with a rate of $\Gamma_{\text{phot}}/\delta n_{\text{phot}}$ will alter the population by a shot size of $\delta n_{\text{phot}} = \eta h\nu/\Delta \approx 20$ quasiparticles, where h is Planck's constant and ν is the optical frequency. Letting p_n represent the probability of n quasiparticles in the reservoir we arrive at:

$$\frac{dp_n}{dt} \approx \frac{\Gamma_{\text{phot}}}{20}\left[p_{(n-20)} - p_n\right] + \frac{\Gamma_{\text{gen}}}{2}\left[p_{(n-2)} - p_n\right] + \frac{R}{2}\left[(n+2)(n+1)p_{(n+2)} - n(n-1)p_n\right], \tag{3}$$

where we have assumed $p_n = 0$ for $n < 0$.

Previous works have solved similar master equations by linearizing the recombination term and finding a Fokker-Planck equation [6]. However, because of the large photon shot size and the small volume of our reservoirs (~ 0.005 μm^3), our fluctuations will not necessarily be smaller than the mean population. Thus linearizing is not possible and we will solve the full master equation numerically.

In Fig. 1 we plot example solutions $\{p_n\}$ for the stationary mixture for several different photon arrival rates Γ_{phot}. As the photon rate increases, an asymmetry in population distribution is clearly visible, with a long tail on the higher population side.

We must now consider the term $-KN_{\text{qp}}p_{\text{even}}$ describing tunneling to the island. Most generally, we can treat this master equation as a continuous-time Markov chain giving a phase-type distribution. However, if we assume that tunneling is fast compared to the generation-recombination dynamics, then measured over long times this will reduce to a hyperexponential distribution, $\sum_{n=0}^{\infty} p_n Kn \exp(-Knt)$, a mixture of

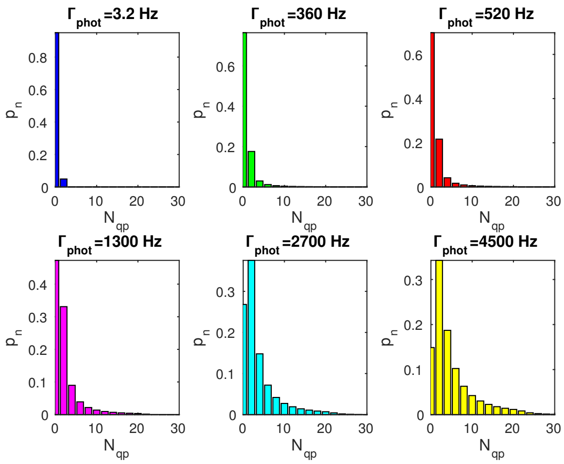

Fig. 1. Stationary mixtures $\{p_n\}$ of the master equation, Eqn. 3, at selected photon arrival rates. Note that initially significant asymmetry appears before the peak begins to shift, with a long tail on the right side. Values of $R = 2000$ Hz and $\Gamma_{\text{gen}} = 100$ Hz have been selected.

exponential distributions weighted by the stationary mixture $\{p_n\}$.

What if we measure the tunneling rate over shorter times? If we measure the tunneling rate in time windows that are short compared to the timescale of the generation-recombination dynamics, then in any given window we will tend to see a single state of the reservoir n rather than the stationary mixture, with dwell times distributed exponentially: $Kn\exp(-Knt)$. Then the fraction of windows in each state will be given by the values $\{p_n\}$. Plotting the tunneling rate Kn measured in each window on a histogram, the result will be proportional to the stationary mixture $\{p_n\}$.

III. Experiment

Fig. 2 shows an optical microscope image of a single QCD pixel. The outer spiral structure is the coplanar waveguide resonator with a frequency of order 3 GHz. At its center is an antenna capacitively coupled to the SCB. Incoming radiation breaks Cooper pairs in the reservoir, leading to quasiparticles which can tunnel to the island, causing quasiparticle poisoning of the SCB.

A 5x5 array of QCDs was operated in a ^{3}He/^{4}He dilution refrigerator, and illuminated with a filtered blackbody source (see [3] for details). The applied gate voltage was tuned to the degeneracy point of a single SCB qubit, at which the telegraph signal due to qubit transitions was measured in the response of a microwave tone applied to the coplanar waveguide resonator [4], [7]. The even and odd quasiparticle states were distinguished by a Schmitt trigger, providing a measurement of what state the SCB was in at a given time.

This time stream measurement was taken and divided into windows. In each window, a histogram of the dwell times in each state can be plotted. Assuming that the distribution of events is Poissonian (memoryless), this will yield an exponential distribution of dwell times [4]. After correcting for the finite bandwidth of the measurement [7], we obtain a measure of the even-to-odd transition rate, or rather the rate at which quasiparticles tunneled from the reservoir to the island in that window. For a sufficiently short window length, shorter than the rate of recombination dynamics, this would be proportional to the $KN_{\text{qp}}p_{\text{even}}$ term in Eqn. 2. For longer window lengths, though, there will be contributions from multiple occupation states N_{qp} as the quasiparticles in the reservoir recombine.

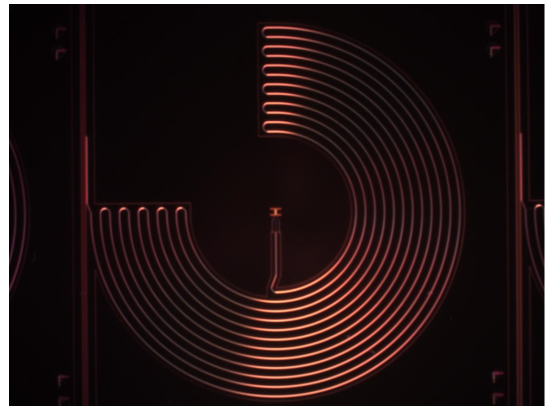

Fig. 2. Optical micrograph of a single QCD pixel.

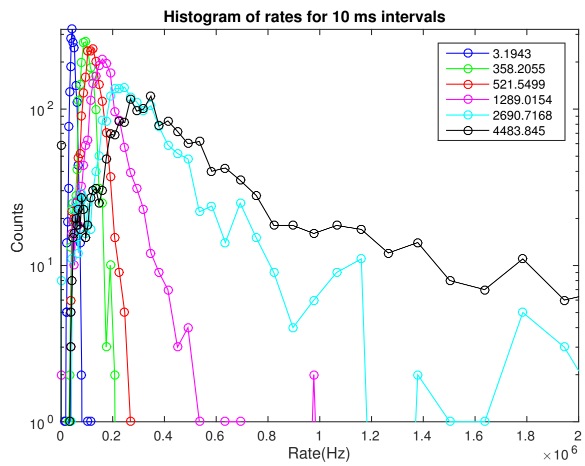

Fig. 3. Histogram of measured transition rates in 10 ms windows for selected photon arrival rates Γ_{phot}, as measured by the temperature of the black body source [3]. Rates are corrected for finite measurement bandwidth [7].

IV. Telegraph Rate Distribution Asymmetry

Fig. 3 shows a histogram of observed transition rates during 10 ms intervals. Increasing asymmetry is visible towards the highest power (black). This asymmetry is evidence of temporary excursions to states with a higher number of quasiparticles, and thus with a higher average transition rate (Eqn. 2.)

Unfortunately, the simple model discussed in Sec. II is not adequate for fits of the data presented here. First, the 10 ms windows are too long compared to the recombination dynamics, so any given window samples from multiple occupation states N_{qp}. In addition, this model does not account for the interaction of quasiparticles with phonons [6]; this can effectively trap quasiparticles and provide access to the odd states of the master equation. However, the data shows qualitative agreement, with the predicted tail extending to very high rates, as well as the shift of the most likely rate.

V. Conclusion

In this work, we observe qualitative agreement between the predicted asymmetry in the distribution of quasiparticles and our measured distribution of telegraph rates (predicted in Eqn. 2 to be proportional).

Coupled with our earlier demonstration of photon shot noise limited scaling of noise equivalent power in QCDs [3], this telegraph rate asymmetry provides compelling statistical evidence of single photon events. However, we can not cleanly isolate individual photon events because we are not able at this time to observe the transition rate on a timescale faster than the recombination dynamics.

This will require some combination of devices with slower recombination dynamics (larger reservoirs) and higher measurement bandwidth. Another path forward might be full simulation of the system as a continuous time Markov chain. In the future we aim to develop algorithms using sequential analysis changepoint detection [8] to identify single photon events.

While QCDs are not a natural candidate for operation as an array of photon-counters (due to difficulty in tuning all qubits to the degeneracy point simultaneously), this observed asymmetry provides useful confirmation of the earlier photon shot noise result [3].

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