Counting quasiparticles: generation-recombination noise in microwave resonators

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Space / ground based astronomy

Circuit QED
Detection by pair breaking

1. Most electrons are paired in equilibrium
2. A photon breaks a pair
3. Resistance increases
4. Detection with microwave resonator
Quasiparticle number fluctuations

In equilibrium: generation and recombination balanced

Number of excitations fluctuates: fundamental noise!
Quasiparticle number fluctuations in equilibrium

Power spectrum:

\[ S_N = \frac{4 < N^2 >}{1 + \omega^2 \tau^2} = \frac{4N\tau}{1 + \omega^2 \tau^2} \]

\[ N_{qp} = 2N_0 \sqrt{2\pi kT\Delta} \exp(-\Delta / kT) \]

\[ \tau = \frac{\tau_0}{\sqrt{\pi}} \left( \frac{kT_c}{2\Delta} \right)^{5/2} \sqrt{\frac{T_c}{T}} \exp(\Delta / kT) \]

\[ N_{qp} \tau = 2\tau_0 N_0 V \frac{(kT_c)^3}{(2\Delta)^2} \]

Probe the complex conductivity ($\sigma_1 + i\sigma_2$) of the resonator

Dip depth / amplitude: dissipation response $\sigma_1$
Quasiparticle fluctuations in a resonator

\[ S_A = S_N \left( \frac{dA}{dN_{qp}} \right)^2 = \frac{4N_{qp} \tau}{1 + \omega^2 \tau^2} \left( \frac{dA}{dN_{qp}} \right)^2 \]

Amplitude noise = number fluctuations * response

Responsivity is the phase/radius change per quasiparticle

Observing this noise => fundamental sensitivity reached!
Measurement: aluminium resonator

- 50 nm Al film, sputtered on sapphire
- $T_c = 1.1$ K
- Half wave CPW resonators
- Resonant at 6.6 GHz, $Q \approx 40k$, $Q_i \approx 160k$
Calibration: subtract system noise

- System noise measured off-resonance
- System noise subtraction

![Graph showing amplitude noise vs frequency with on resonance, off resonance, and corrected lines.](image-url)
Measurement: Noise at different temperatures

\[ S_N = \frac{4N\tau}{1 + \omega^2\tau^2} \]

\[ N_{qp} \propto \exp\left(-\Delta / kT\right) \]

\[ \tau \propto \exp\left(\Delta / kT\right) \]

Clear sign of quasiparticle number fluctuations!!

Fundamental noise reached!
Quasiparticle lifetime

$S_N = \frac{4N\tau}{1 + \omega^2\tau^2}$

2 methods: consistent lifetime
But it saturates at low Temperature
Noise is a signal!

Counting quasiparticles with microwave resonators

Noise spectrum -> number of quasiparticles

Lifetime limited by excess quasiparticles
Fundamental sensitivity for KIDs

$\text{NEP}_A(\omega) = \sqrt{S_A \left( \frac{\eta \tau}{\Delta} \frac{dA}{dN_{qp}} \right)^{-1} \sqrt{1 - \omega^2 \tau^2}}$
**Fundamental sensitivity for KIDs**

\[ \text{NEP}_{g-r} \propto \sqrt{\frac{N_{qp}}{\tau_{qp}}} \approx N_{qp} \]

\( \text{NEP}_{g-r} \) behaves as theoretically expected.

Low temperature NEP limited by excess quasiparticles.
Sources of quasiparticles

- Stray light creates quasiparticles -> Light-tight setup
  No photon noise observed

- (Cosmic ray) hits -> filter peaks out of noise analysis
Sources of quasiparticles

- The number of quasiparticles and lifetime are \textit{microwave readout power dependent / limited}.
- Means that we are sure other effects do not limit $N_{qp}$!
- Small range: one side bifurcation, other side amplifier noise.
Resonator noise limited by intrinsic generation-recombination noise

Noise is a signal: powerful tool to count quasiparticles and determine their lifetime

Both saturate consistently at low temperature - due to the readout power
This opens the door to fundamentally limited KID - detectors
Microwave absorption changes the distribution function

- Quasiparticle distribution function can change drastically
- Resulting distribution depends on ratios of scattering/recombination rates
- Number of quasiparticles and their lifetime energy dependent
- Microwave absorption can also result in effective cooling

Full treatment will require solving kinetic equations

Electron-phonon coupling in metals

- $P_{e-ph} = \Sigma (T_e^5 - T_{ph}^5)$
- $\Sigma = 0.2 \text{ nW/K}^5 / \mu \text{m}^3$
- We take $\Sigma = 480 \text{ nW/K}^5$

See also: J. Appl. Phys. 108, 114504, 2010
Determine the amplitude responsivity

\[ \frac{d\theta}{dN_{qp}} = -4Q_i \frac{d\left( \frac{\delta f}{f_0} \right)}{dN_{qp}} \]

\[ \frac{dR}{dN_{qp}} \rightarrow \frac{dR}{d\theta} \frac{d\theta}{dN_{qp}} \]

\[ S21 [\text{dB}] \]

\[ F [\text{Ghz}] \]
Amplitude vs phase noise

- Phase noise is dominated by two level system noise in the dielectric (Rami’s thesis)
- Amplitude noise dominated only by amplifier