Resolving photon number states in a superconducting circuit

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Introduction

Resolving Photon Number States in a Superconducting Circuit

What was done:
Demonstrated the ability to resolve individual photon number states using superconducting circuits.

Why it matters:
Photon number resolution is of great importance in quantum computation, QND measurements, and cavity QED experiments.

Parameter space

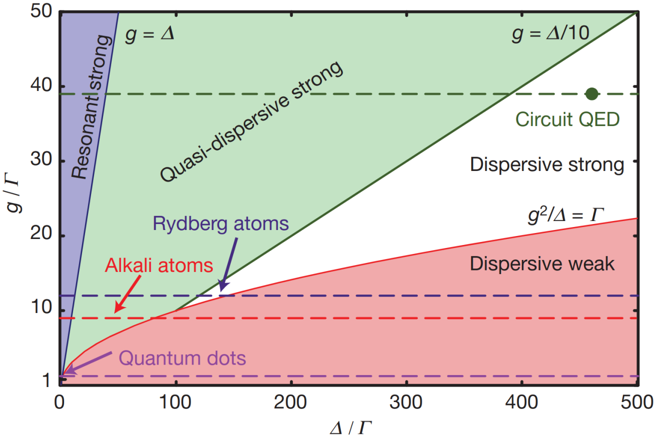


Figure: Parameter space diagram for cavity QED

Jaynes-Cummings Hamiltonian

Let's consider the Jaynes-Cummings Hamiltonian:

$$H_{JC} = \underbrace{\hbar\omega_r a^\dagger a + \frac{\hbar\omega_a}{2}\sigma_z}_{H_0} + \underbrace{\hbar g\left(a^\dagger\sigma^- + a\sigma^+\right)}_{V} + H_\Gamma + H_\kappa \tag{1}$$

Strong coupling $g \gg \Gamma, \kappa$, so we ignore the decay terms. Further we are in the dispersive limit $g \ll \Delta = \omega_a - \omega_r$ so we can use perturbation theory, diagonalizing the Hamiltonian we using the Schrieffer-Wolff transformation

$$S = \frac{g}{\Delta}\left(a\sigma^+ - a^\dagger\sigma^-\right) \tag{2}$$

$$H' = e^{-S} H e^{S} \tag{3}$$

$$= H_0 + \frac{1}{2}[S, V] + \mathcal{O}(V^2) \tag{4}$$

$$= \hbar\omega_r a^\dagger a + \frac{\hbar\omega_a}{2}\sigma_z + \frac{\hbar g^2}{\Delta}\left(a^\dagger a + \frac{1}{2}\right)\sigma_z + \mathcal{O}\left(\frac{g^2}{\Delta^2}\right) \tag{5}$$

Strong dispersive regime

Jaynes-Cummings Hamiltonian

$$H_{JC} = \hbar\omega_r a^\dagger a + \frac{\hbar\omega_a}{2}\sigma_z + \hbar g\left(a^\dagger\sigma^- + a\sigma^+\right) + H_\Gamma + H_\kappa \tag{6}$$

Strong coupling: $g \gg \Gamma, \kappa$
Dispersive approximation: $|\Delta| \gg g$
$\chi = \frac{g}{\Delta}$

Dispersive Hamiltonian

$$H_{disp} = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma_z + \hbar\chi\left(a^\dagger a + \frac{1}{2}\right)\sigma_z \tag{7}$$

Dispersive Hamiltonian

$$H_{disp} = \hbar\omega_r \left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma_z + \hbar\chi \left(a^\dagger a + \frac{1}{2}\right)\sigma_z \quad (8)$$

Atom effect on resonator

$$\omega_r' = \omega_r + \hbar\chi\sigma_z \quad (9)$$

Resonator effect on atom

$$\omega_n = \omega_a + (2n+1)\,\chi \quad (10)$$

The χ-shift commutes with the individual terms!

We can use this to perform QND measurements on either the atom or the cavity

Photon absorption probability $\left(\frac{g}{\Delta}\right)^2$

χ-shift

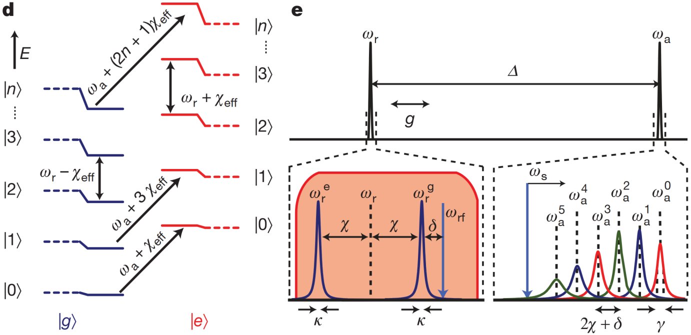
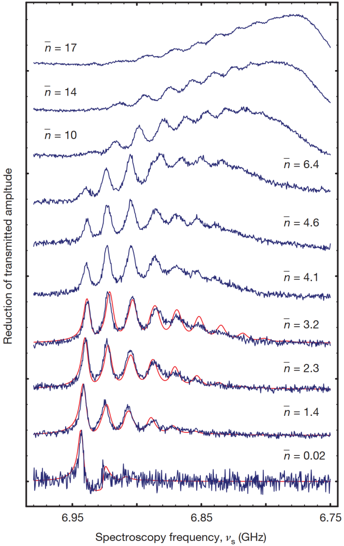


Figure: Effect of χ-shift on CPB and resonator

Spectroscopy



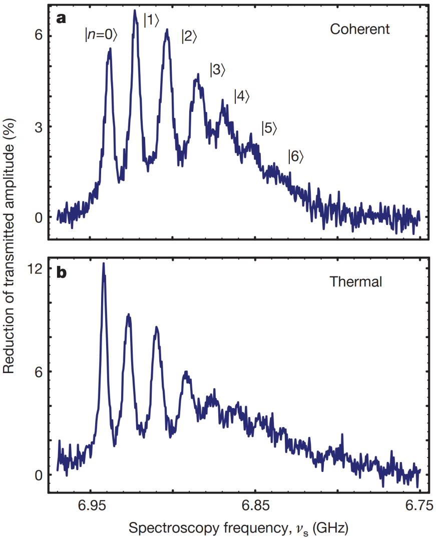
Coherent states with average cavity occupation $\bar{n}$
And background thermal photon $n_{th} = 0.1$

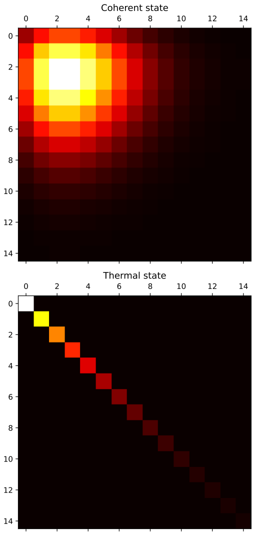
Linewidth

$$\gamma_n = \frac{\gamma}{2} + \gamma_\phi + \frac{(\bar{n} + n)\,\kappa}{2} \tag{11}$$

Resolution limit of $\bar{n} = \frac{2\chi}{\kappa}$?

Qubit spectrum distinguishes between coherent and thermal distributions





Photon-qubit conditional logic

"Outlook"

- CNOT gate between qubit and photon, allowing photon to be reused 'elsewhere'.
- Qubit readout using dispersive measurement

Questions / Discussion

(Alternatively, lunch?)