Cavity QED with superconducting qubits

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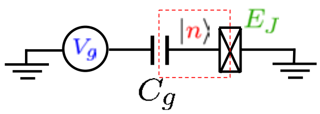
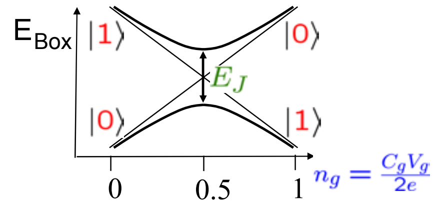
Outline

- Superconducting qubits
- Superconducting resonators
- sQubits + sResonator: Cavity QED?
  - Dressed states
  - Lifetime enhancement
  - Measurement
  - Entanglement

Cooper Box Hamiltonian





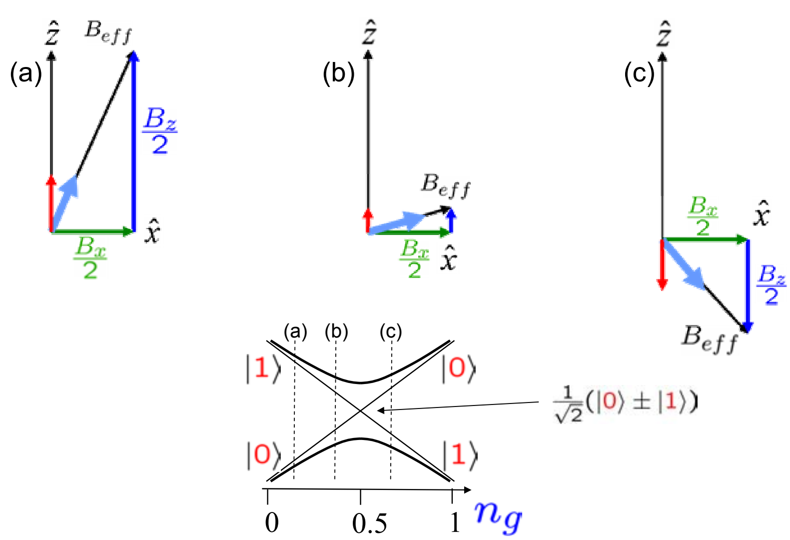
$$H = 4E_c \sum_{n=0,1} \left(n - \frac{C_g V_g}{2e} \right)^2 |n\rangle\langle n| - \frac{E_J}{2} \left(|0\rangle\langle 1| + hc \right)$$

Charge on the box acts as pseudo-spin ½:

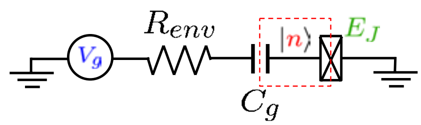
$$\rightarrow H = \vec{B}_{eff} \cdot \vec{\tilde{\sigma}} = 2E_c(1 - 2n_g)\tilde{\sigma}_z - \frac{E_J}{2}\tilde{\sigma}_x$$

Charge qubit

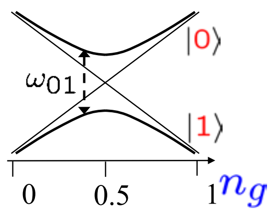
$$H = \vec{B}_{eff} \cdot \vec{\tilde{\sigma}} = 2E_c(1 - 2n_g)\tilde{\sigma}_z - \frac{E_J}{2}\tilde{\sigma}_x$$



Relaxation and dephasing



$$\frac{1}{T_1} = \Gamma = \frac{C_g}{C_\Sigma}\left(\frac{e}{\hbar}\right)^2 \frac{B_x^2}{B_x^2+B_z^2} S_V(\omega_{01}) \qquad \begin{cases} R_{env} = 50\Omega \\ T_1 \approx 1\mu\text{s} \end{cases}$$

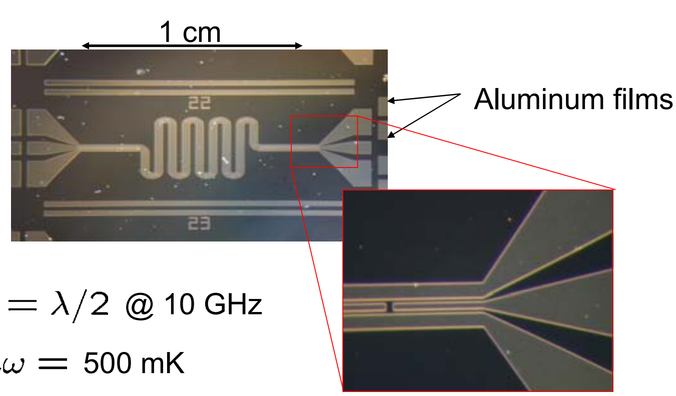


Insensitive to charge noise @ degeneracy

$$\Rightarrow |\uparrow,\downarrow\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$$

Superconducting resonator

Coplanar waveguide transmission line



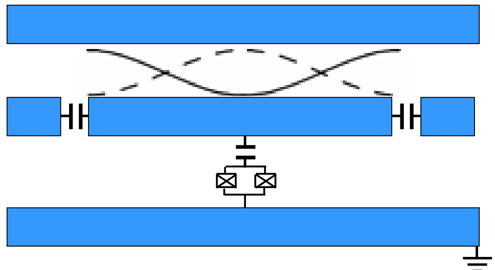
$l = \lambda/2$ @ 10 GHz

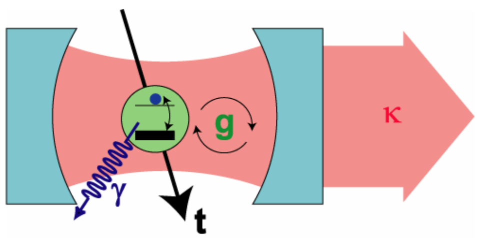
$\hbar\omega =$ 500 mK

$\langle n_\gamma \rangle \approx 0$ @ 50 mK

Q's of 10^4-10^6 are possible

Cavity QED with superconducting qubits



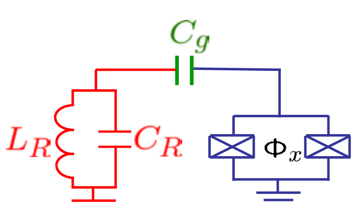


$2g$ = vacuum Rabi freq.

κ = cavity decay rate

γ = “transverse” decay rate

Jaynes-Cumming Hamiltonian



@ the degeneracy point:

$$H_Q = \hbar \frac{\omega_{01}}{2} \sigma_z$$

$$H_R = \hbar \omega_R a^\dagger a$$

$$H_{JC} = \hbar g (\sigma_+ a + a^\dagger \sigma_-)$$

$L_R \sim 0.5\text{nH}$

$C_R \sim 0.5\text{nF}$

$C_g / C_\Sigma \sim 0.1$

$$\Rightarrow \quad g = \frac{1}{2\hbar} \frac{e C_g}{C_\Sigma} \sqrt{\frac{\hbar \omega_R}{2 C_R}} \sim 2\pi \times 30\text{MHz/s}$$

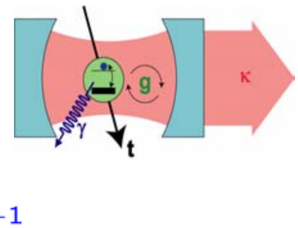
Strong Coupling Possible?

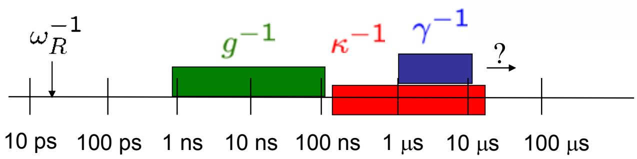
$g = 200\text{MHz} \Rightarrow g/\omega_R \sim 3\times10^{-3}$ $\quad\quad$ $\omega_R = 2\pi \times 10\text{GHz}$

$\gamma = (1\mu\text{s})^{-1}\text{MHz} \Rightarrow \gamma/\omega_R \sim 10^{-5}$ $\quad$ $Q = 10^4 \Rightarrow \kappa/\omega_R \sim \times 10^{-4}$

(Lehnert et al.)

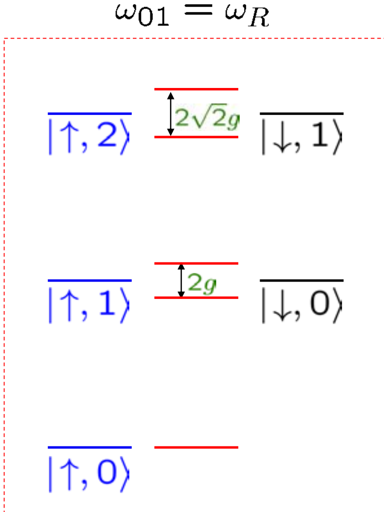
Timescales: $\quad g > [\kappa, \gamma]$

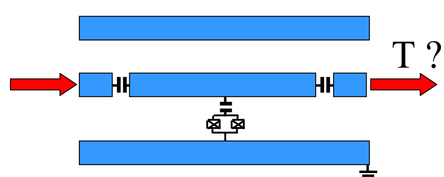


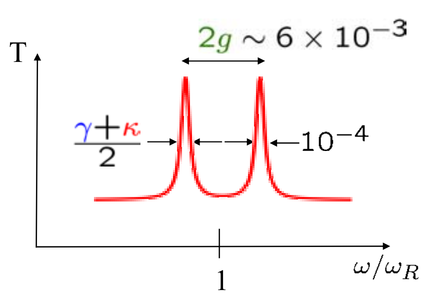


Dressed Atoms: Resonant Case

$\omega_{01} = \omega_R$

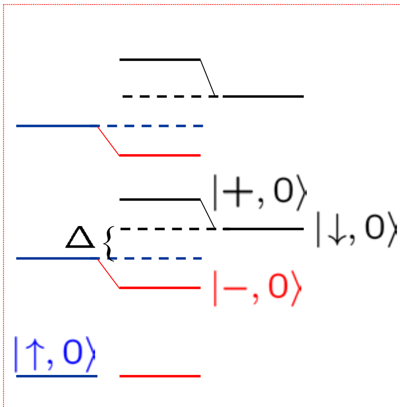






Off-Resonant Case: Lifetime Enhancement

$$\Delta = \omega_{01} - \omega_R$$



$$|+,0\rangle \sim |\downarrow,0\rangle + \frac{g}{\Delta}|\uparrow,1\rangle$$

$$|-,0\rangle \sim -\frac{g}{\Delta}|\downarrow,0\rangle + |\uparrow,1\rangle$$

$$\Gamma_{+,0} \sim \gamma + \left(\frac{g}{\Delta}\right)^2 \kappa$$

$$\Gamma_{-,0} \sim \left(\frac{g}{\Delta}\right)^2 \gamma + \kappa$$

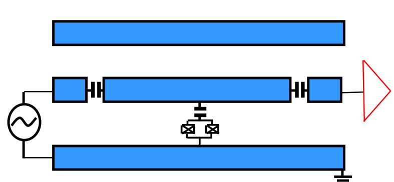
If $\gamma = 0$: $\Gamma_{\downarrow,0} \approx \left(\frac{g}{\Delta}\right)^2 \kappa \sim 10^{-7}$

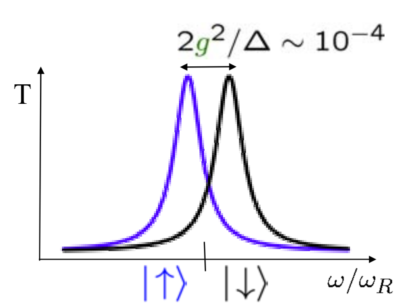
➡ Can learn more about non-EM part of γ

Dispersive Measurement of a Qubit?

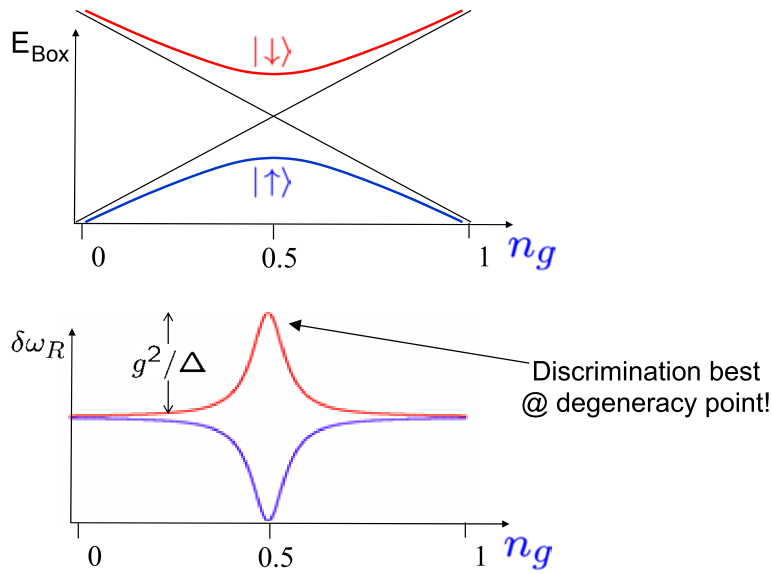
Frequency pulling:

$$H_{JC} \approx \hbar \frac{g^2}{\Delta}(\hat{N} + \tfrac{1}{2})\sigma_z \quad \Rightarrow \quad \omega_R \to \omega_R \pm \frac{g^2}{\Delta} N$$

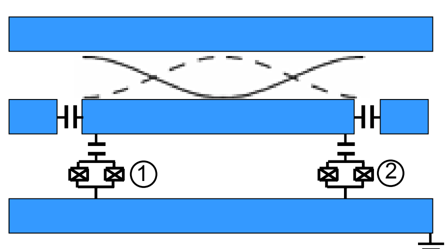




Dispersive Measurement of a Qubit?



Entanglement via resonator



In the large detuning case:

$$H_{eff} = \frac{g^2}{\Delta}\left(\sigma_1^- \sigma_2^+ + \sigma_1^+ \sigma_2^-\right)$$

Operation time: $T_{op} = \Delta / g^2 \sim$ 10-100ns

$\Rightarrow$ $Q_{op} \sim T_{op}^{-1} / \mathrm{Max}\left[\gamma, \kappa (g/\Delta)^2\right]$

Summary

- Strong coupling regime of cavity QED appears to be achievable
- Cavity-enhanced qubit lifetime
- Dispersive read-out of qubit state (@ degeneracy point)
- Entangle qubit through resonator bus