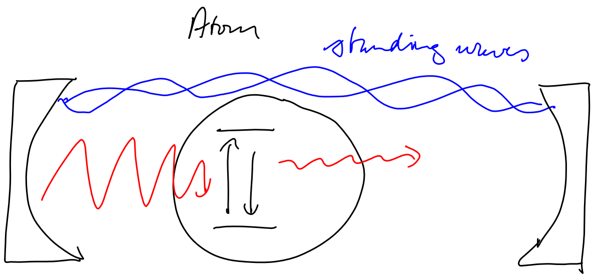
F. Marquardt 30.11.09 ①



Cavity-Quantenelectrodynamics

Optical frequencies: $\omega \sim 10^{15}$ Hz (cavity regime)

$\lambda \sim \mu m$

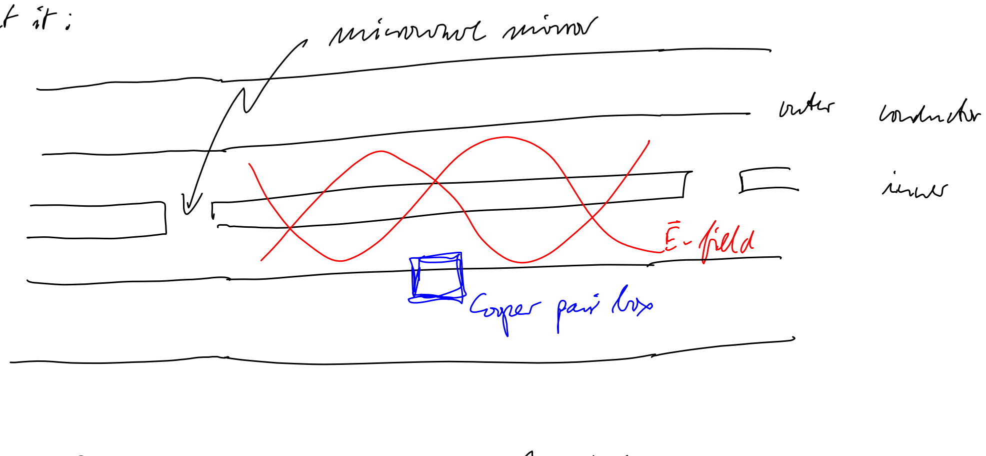
Superconducting cavity QED: $\omega \sim 10^{9}$ Hz (microwave regime)

$\lambda \sim cm$

②

Coaxial cables

If you cut it:



$$H = \frac{\varepsilon}{2}\hat{\sigma}_z + \hbar\omega a^\dagger a + g\,\hat{\sigma}_x (a^\dagger + a)$$

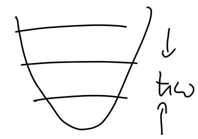
qubit 1-10 GHz 10-100 MHz

3

Quantisiertes Strahlungsfeld:

$$H = \hbar\omega\,(a^\dagger a + 1/2)$$

Nullpunktenergie



$E_n = \hbar\omega\,(n + 1/2)$

Interaction: Dipole moment of atom: $-\hat{p}\,\hat{E}$

Dipoloperator

Transition induced by $\hat{\sigma}_x$:

$$\hat{E} \sim (\hat{a} + \hat{a}^\dagger)$$ (Electric field strength.

$g > \kappa$ = Decay rate of Photon (strong-coupling regime)

4

Strong coupling! Why?

Large dipole moment (since Cooper pair box is large)

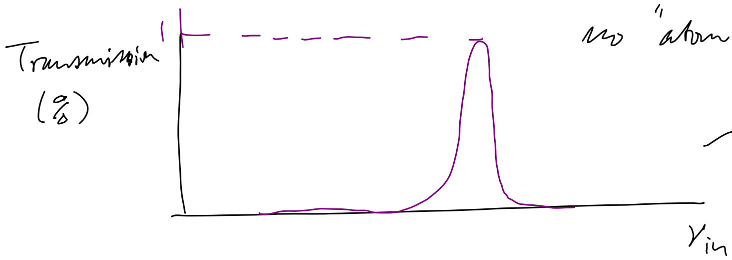
Large field per volume! Longitudinal length ~ only one wavelength!

Transverse length ~ much smaller!

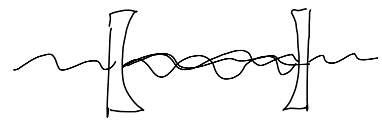
$\hbar\omega$ confined to $\frac{\lambda^3}{1000}$ means big energy density $\Rightarrow$ big field!

Spectroscopy:

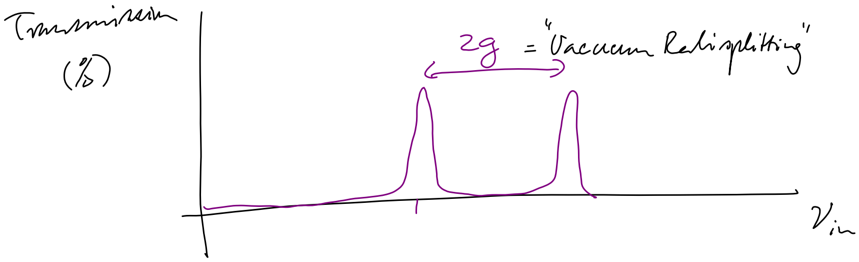
Send in microwave, see what is reflected?



no "atom": $g=0$



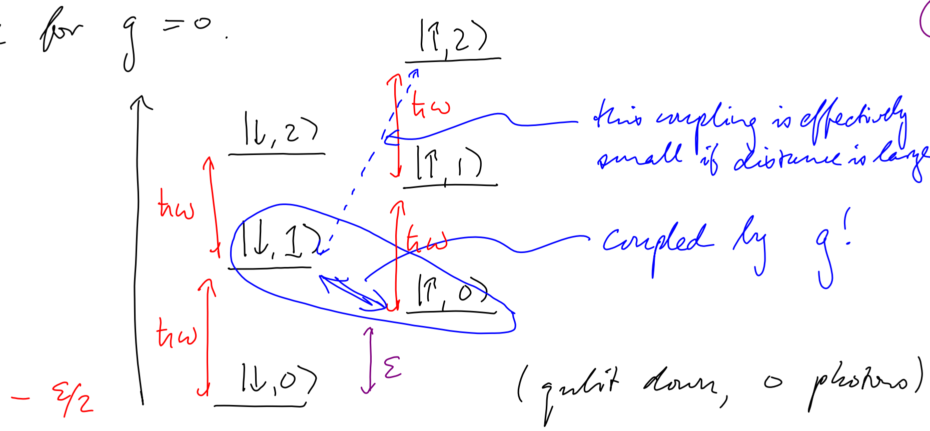
destructive interference unless $\nu = n\omega$



with "atom"

$g \neq 0$

Level scheme for $g=0$.



(qubit down, 0 photons)

Notation $\quad |\sigma, n\rangle \quad \sigma = \uparrow, \downarrow, \quad n = 0, 1, 2, \ldots$

Resonant case: $\quad \varepsilon = \hbar\omega$; now turn on $g \neq 0$:

$$\sigma_x (\hat{a} + \hat{a}^\dagger) |\uparrow, 0\rangle \sim |\downarrow, 1\rangle$$

photon excited
qubit de-excited!!

(7)

Effective Hamiltonian near resonance:

$$\hat{H}_{eff} = \begin{array}{cc} |\uparrow,0\rangle & |\downarrow,1\rangle \\ \end{array} \atop \begin{pmatrix} \varepsilon & g \\ g & \varepsilon \end{pmatrix} \Rightarrow \text{eigenenergies} \quad E_\pm = \varepsilon \pm g$$

eigenstates: $\frac{1}{\sqrt{2}}\left(|\uparrow,0\rangle \pm |\downarrow,1\rangle\right)$

"Vacuum Rabi splitting" $= 2g$!!

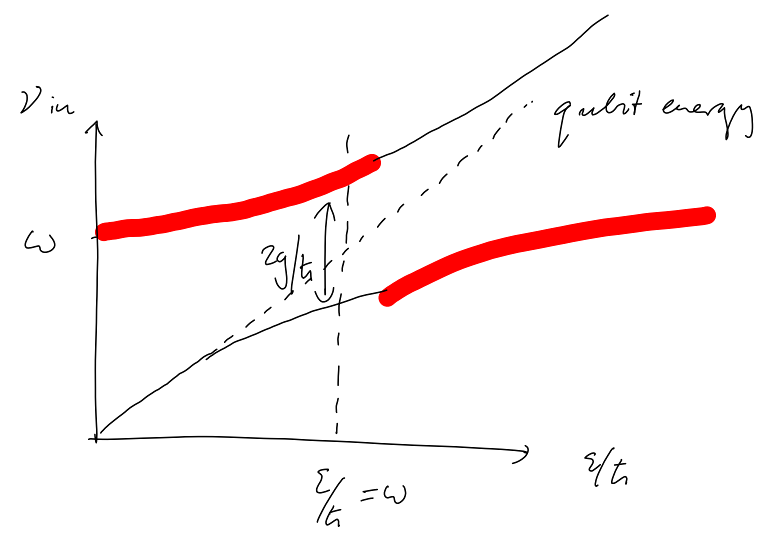
Incident microwave tries to make transition $|\downarrow,0\rangle \to |\downarrow,1\rangle$

But $\langle\downarrow,0|\, a^\dagger\, |E_\pm\rangle \neq 0 \Rightarrow$ two transitions!

microwave absorption in cavity:

(8)

If we tune ε:



If one is **not** in resonance: ⑨

dispersive qubit readout: **shift** in ω depends on qubit:

$\delta\omega \gtrless 0$ for $\begin{matrix}|\uparrow\rangle \\ |\downarrow\rangle\end{matrix}$!!

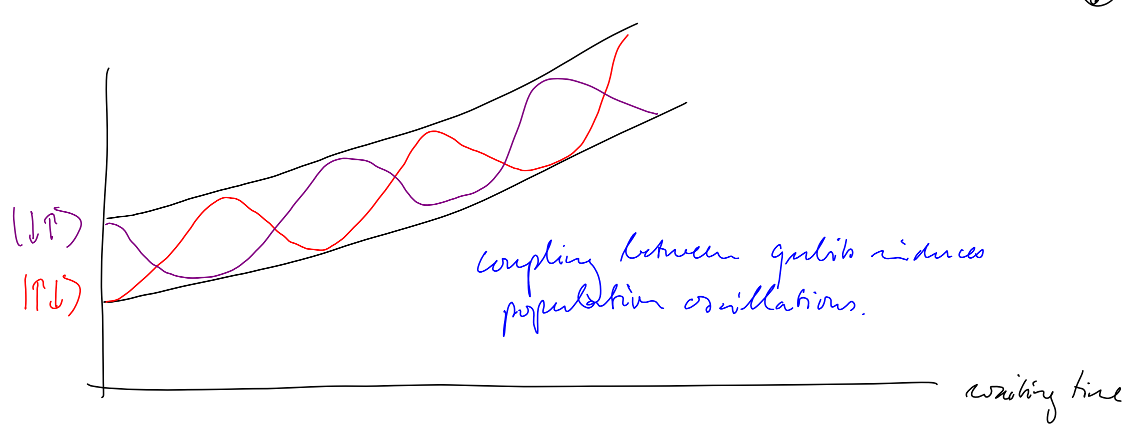
- Single qubit degeneration: excite qubit, it decays, sends out photon. $\alpha|\uparrow\rangle + \beta|\downarrow\rangle \longrightarrow \alpha|1\rangle + \beta|0\rangle$

- Photon number splitting

Dispersive 2-qubit gate; Yale setup

⑩

Two-qubit gates via cavity

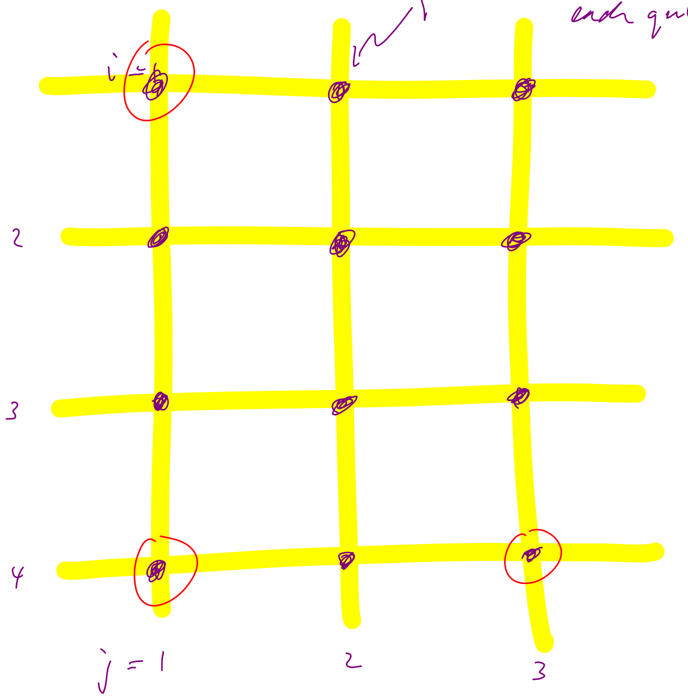


Cavity grid

(11)

qubit at each crossing, each qubit has different ε_{ij}

grid of cavities



induce interaction between (1,1) and (4,3), via (4,1)

Theoretical challenges:

(12)

- Simulation of dynamics: via master equations for density matrices
- How to generate nontrivial