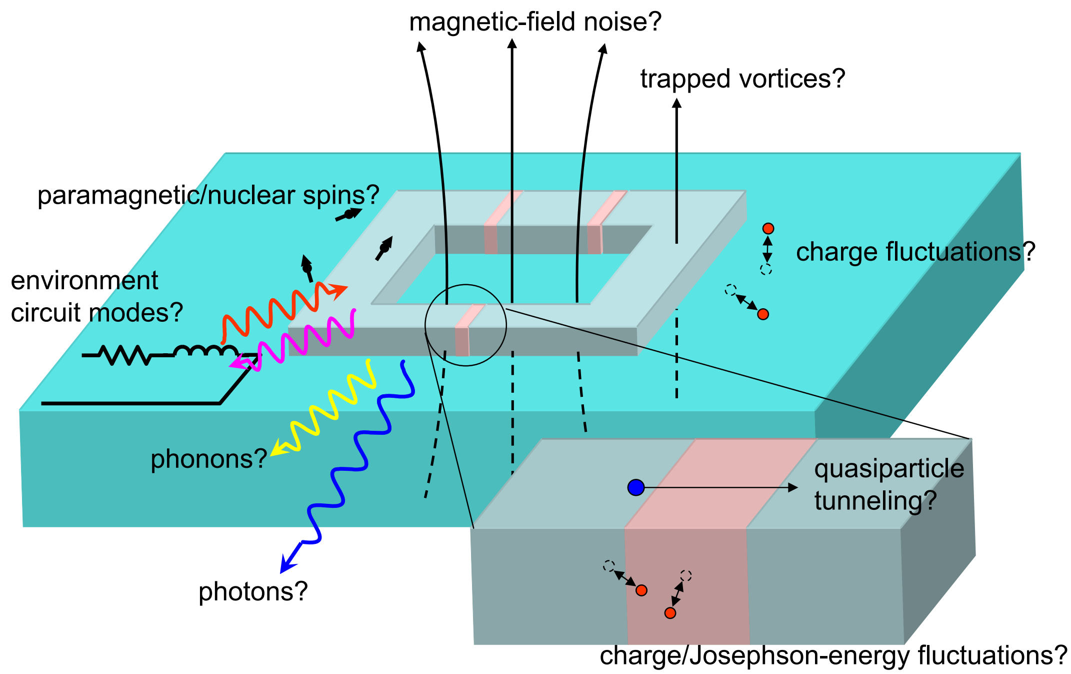
Sources of Decoherence



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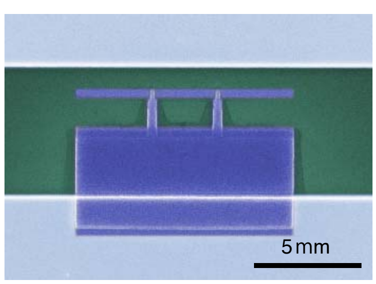
G. Ithier *et al.*, *Phys. Rev. B* **72**, 134519 (2005)

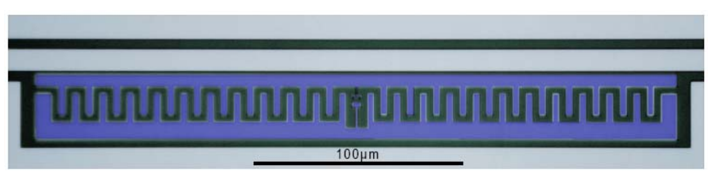
Reduce Decoherence using Symmetries

a Cooper pair box with a small charging energy

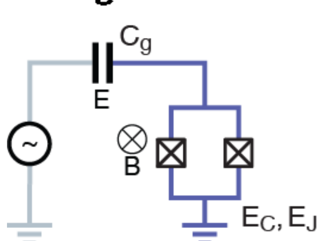
standard CPB:

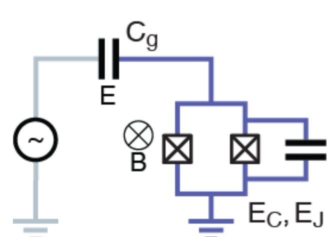


transmon:



circuit diagram:





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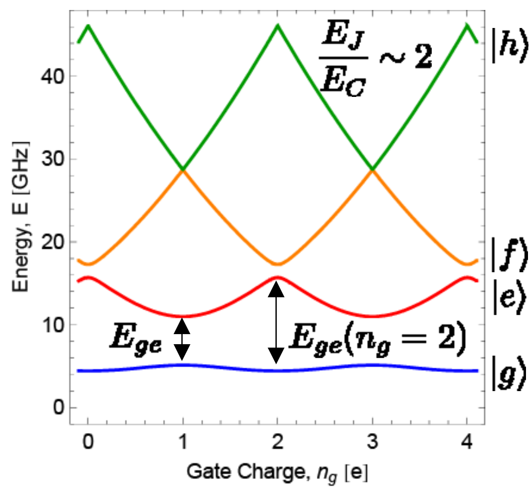
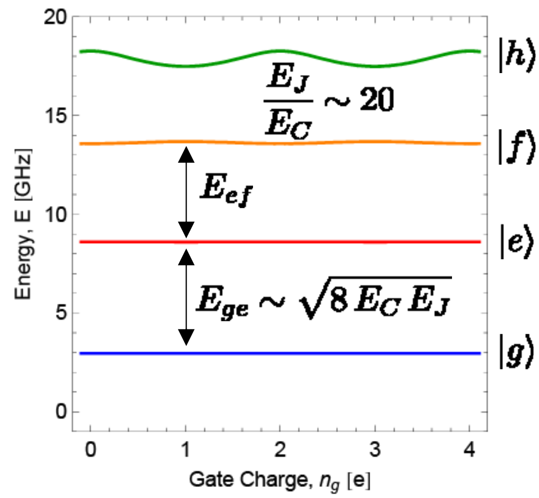
J. Koch *et al.*, Phys. Rev. A **76**, 042319 (2007)
J. Schreier *et al.*, Phys. Rev. B **77**, 180502 (2008)

The Transmon: A Charge Noise Insensitive Qubit

Cooper pair box energy levels



Transmon energy levels



dispersion

$$\epsilon = E_{ge}(n_g = 1) - E_{ge}(n_g = 2)$$

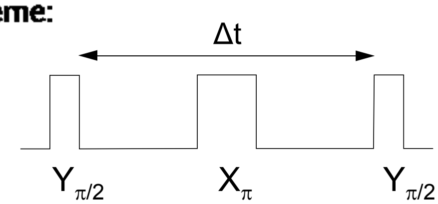
relative anharmonicity

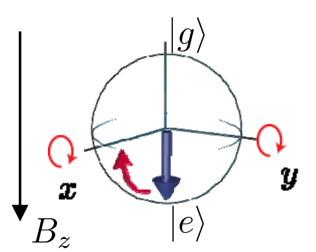
$$\alpha_r = \frac{E_{ef} - E_{ge}}{E_{ge}}$$

J. Koch *et al.*, Phys. Rev. A **76**, 042319 (2007)

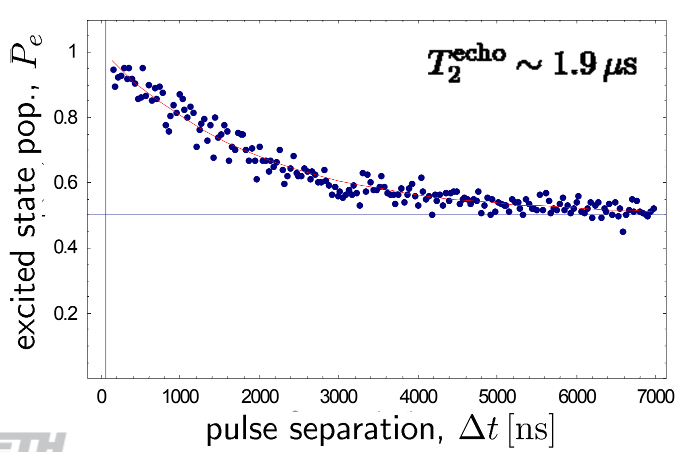
Reduce Decoherence Dynamically: Spin Echo

pulse scheme:





result:



- refocusing
- elimination of low frequency fluctuations
- increased effective coherence time

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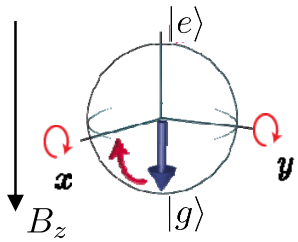
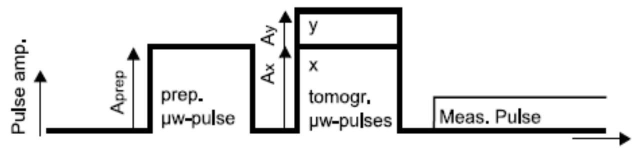
L. Steffen *et al.* (2007)

One-Qubit Tomography

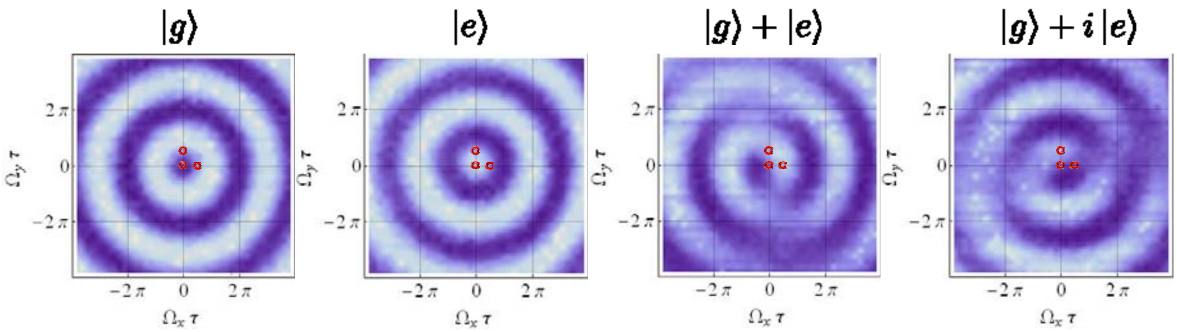
Bloch sphere:



pulse sequence:



initial states:

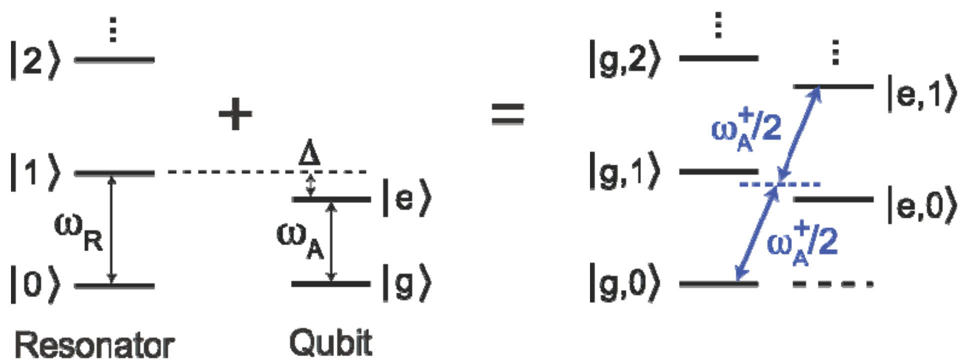


$\langle\sigma_z\rangle$ response vs. tomography pulse length along x and y simultaneously

Coupling Superconducting Qubits and Generating Entanglement using Sideband Transitions

Sideband Transitions in Circuit QED

- System in dispersive limit (~uncoupled)
- Weak dispersive coupling still allows joint excitations to be driven
- Use sidebands to generate entanglement between qubit and resonator
- Sideband transitions forbidden to first order: use two photon transition



$\omega_A/2 = (\omega_R + \omega_A)/2$

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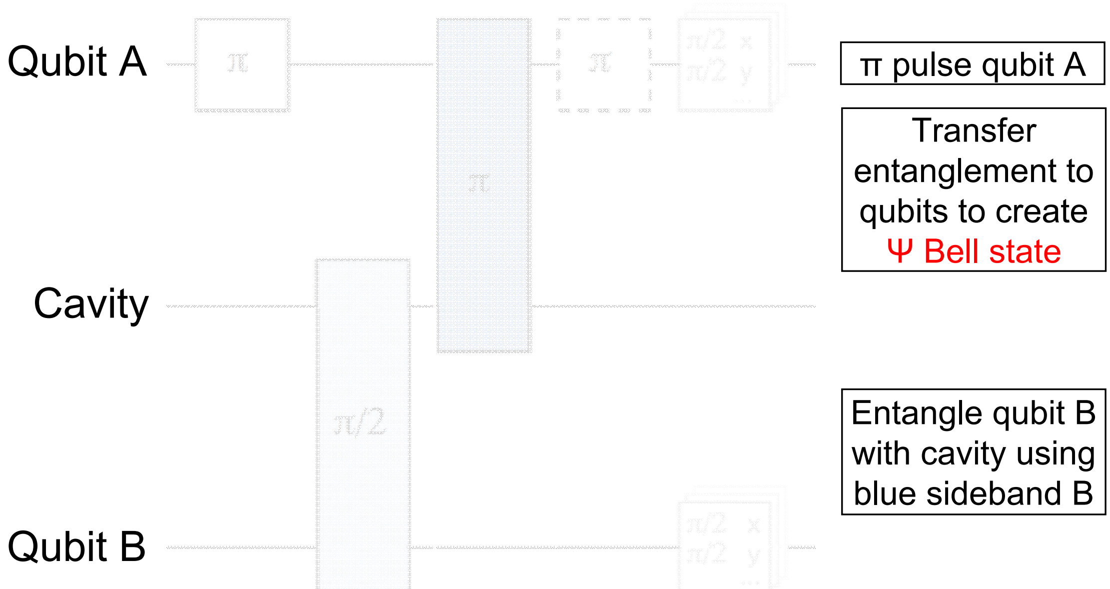
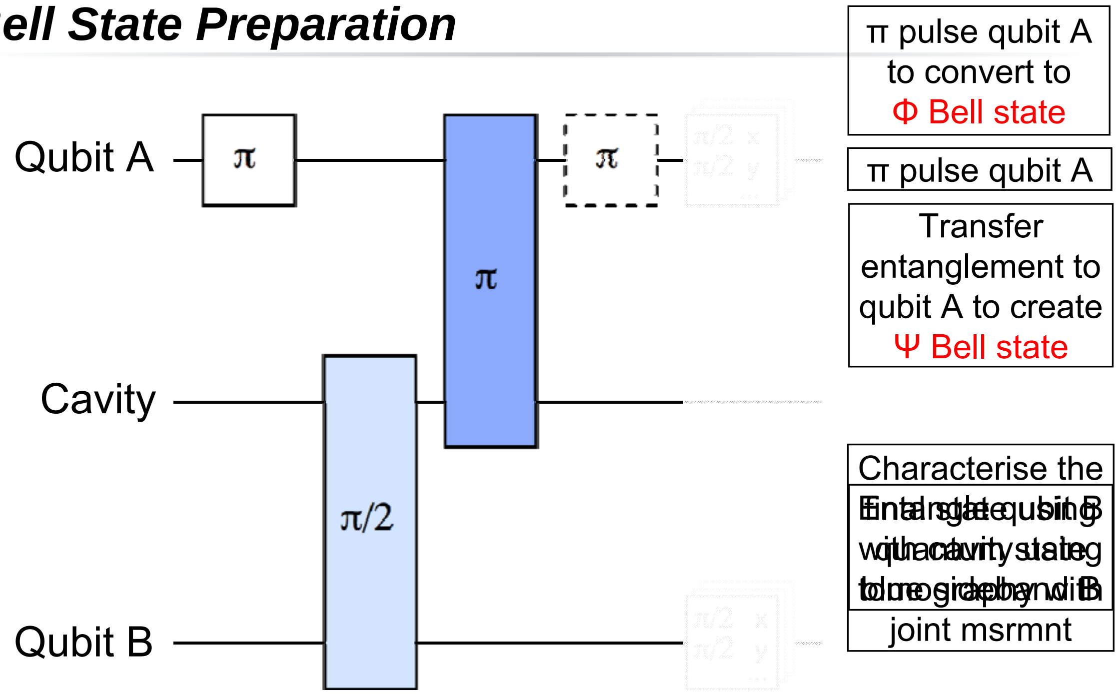
Bell State Preparation



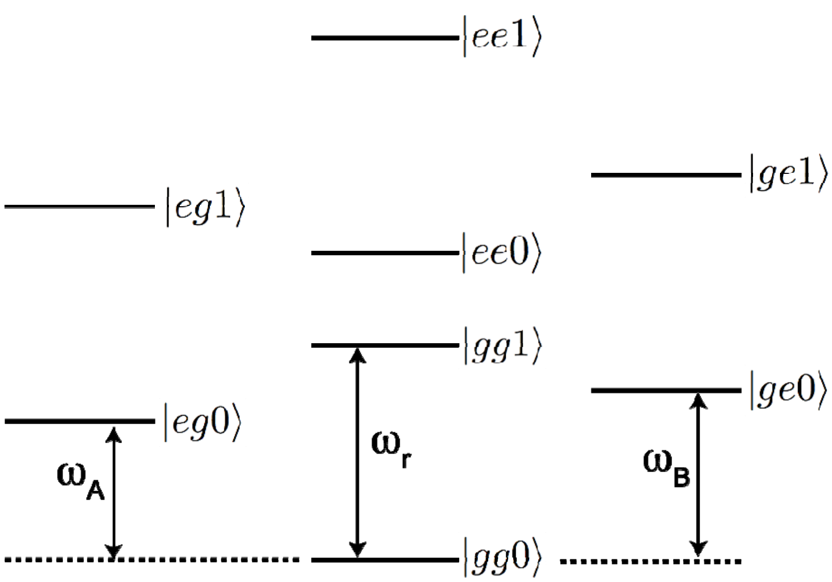
$$|gg0\rangle \longrightarrow |eg0\rangle \longrightarrow \frac{1}{\sqrt{2}}(|eg0\rangle + |ee1\rangle) \longrightarrow \boxed{\frac{1}{\sqrt{2}}(|eg\rangle + |ge\rangle)} \otimes |0\rangle$$

Bell State Preparation

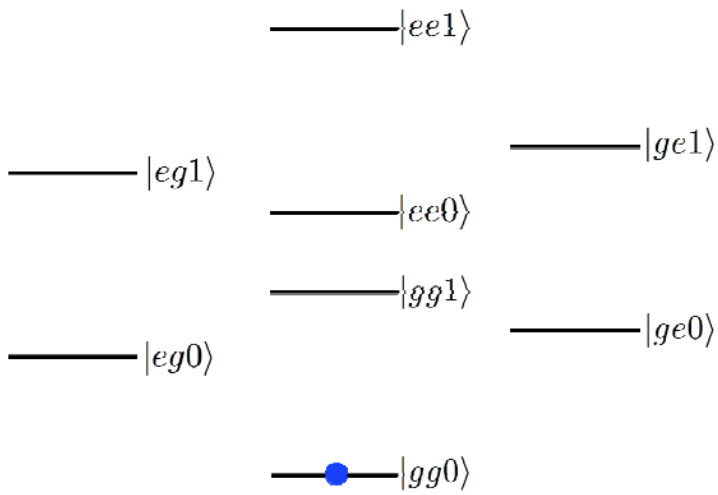


$$\dots \longrightarrow \frac{1}{\sqrt{2}}(|eg\rangle + |ge\rangle) \otimes |0\rangle \longrightarrow \frac{1}{\sqrt{2}}(|gg\rangle + |ee\rangle) \otimes |0\rangle$$

Sidebands with 2 qubits and 0,1 photons

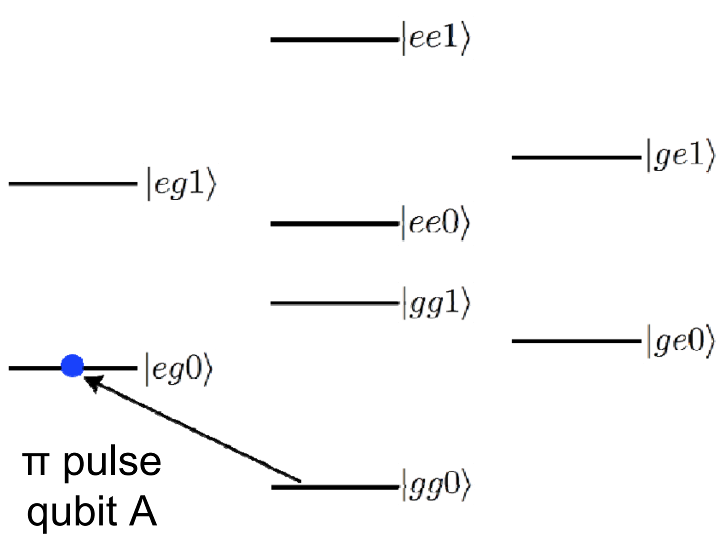


Bell state preparation sequence



$$\boxed{|gg0\rangle}$$

Bell state preparation sequence



$$|gg0\rangle \longrightarrow \boxed{|eg0\rangle}$$

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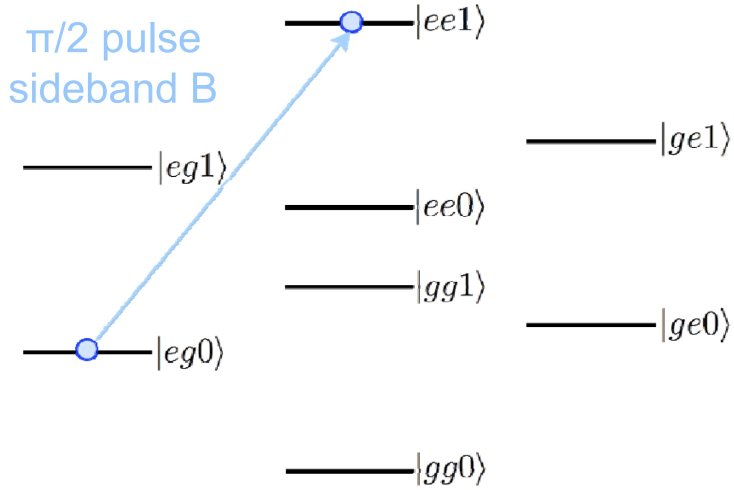
Bell state preparation sequence



Entangle qubit B with photon

$$|gg0\rangle \longrightarrow |eg0\rangle \longrightarrow \boxed{\frac{1}{\sqrt{2}}(|eg0\rangle + |ee1\rangle)}$$

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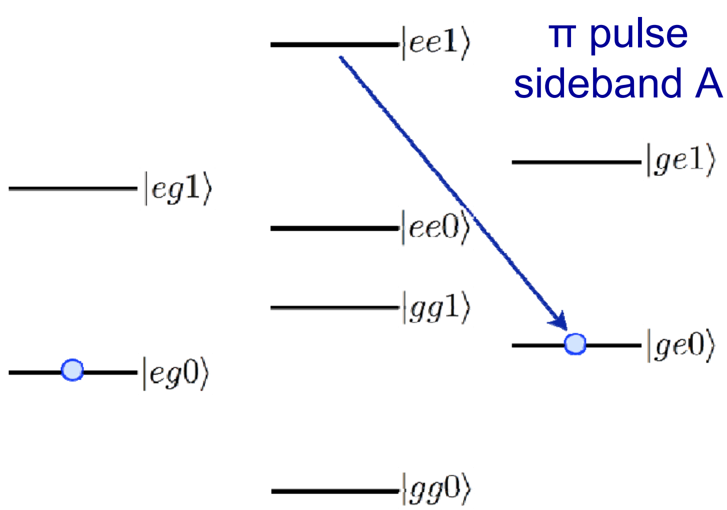
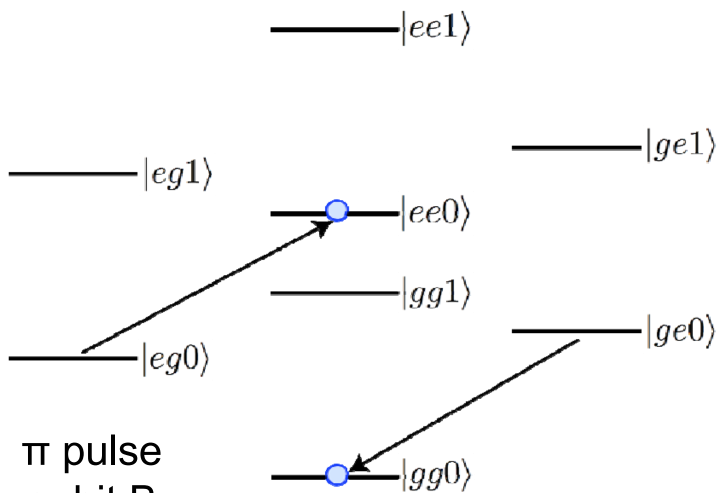
Bell state preparation sequence



Transfer entanglement to qubits to create
Ψ Bell state

$$|gg0\rangle \longrightarrow |eg0\rangle \longrightarrow \frac{1}{\sqrt{2}}(|eg0\rangle + |ee1\rangle) \longrightarrow \boxed{\frac{1}{\sqrt{2}}(|eg\rangle + |ge\rangle)} \otimes |0\rangle$$

Bell state preparation sequence

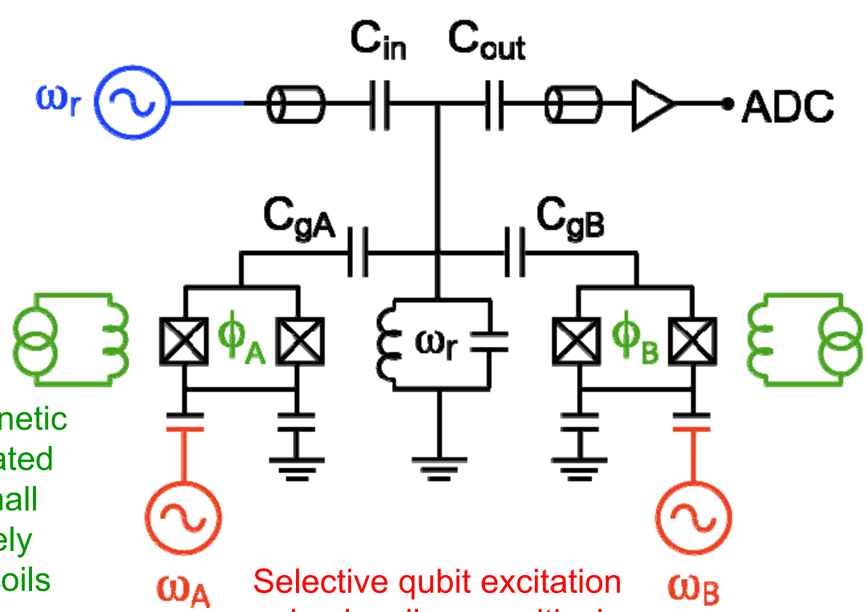


π pulse
qubit B

Transfer to
Φ Bell state

$$\ldots \longrightarrow \frac{1}{\sqrt{2}}(|eg\rangle + |ge\rangle) \otimes |0\rangle \longrightarrow \boxed{\frac{1}{\sqrt{2}}(|gg\rangle + |ee\rangle)} \otimes |0\rangle$$

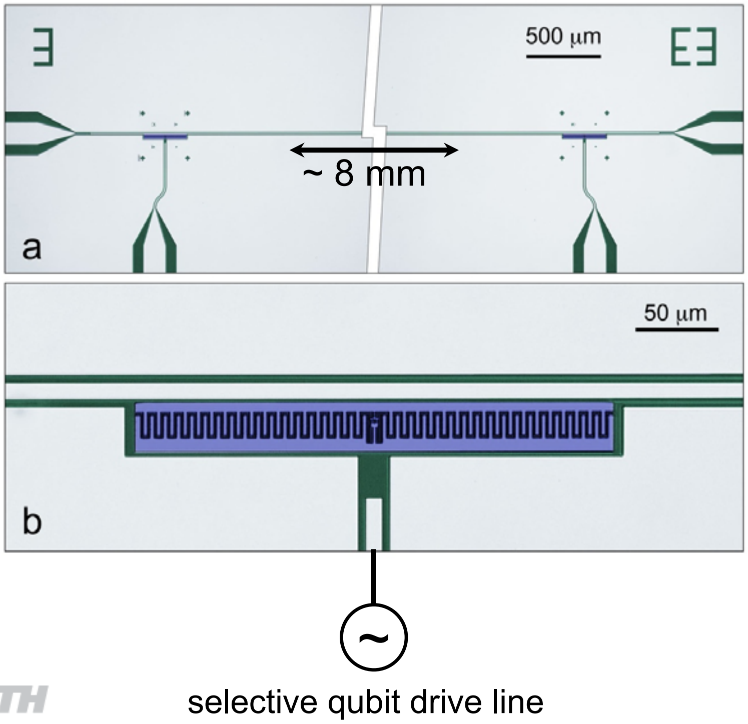
2-Qubit Circuit QED with Selective Control



Local magnetic fields created using small inductively coupled coils

Selective qubit excitation using locally capacitively coupled drive lines

2-Qubit Circuit QED Chip with Selective Control



- Two near identical superconducting qubits
- Local control of magnetic flux allows independent selection of qubit transition frequencies
- Local drive lines allow selective excitation of individual qubits

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Spectroscopy on selective drive lines

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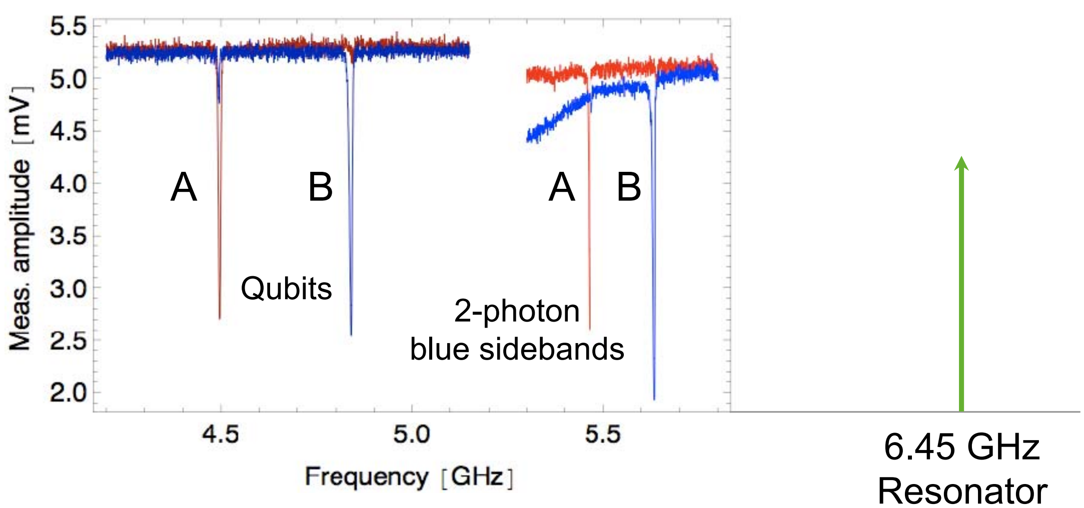
‣spectral lines observed halfway between qubits and resonator
=> 2-photon blue sidebands



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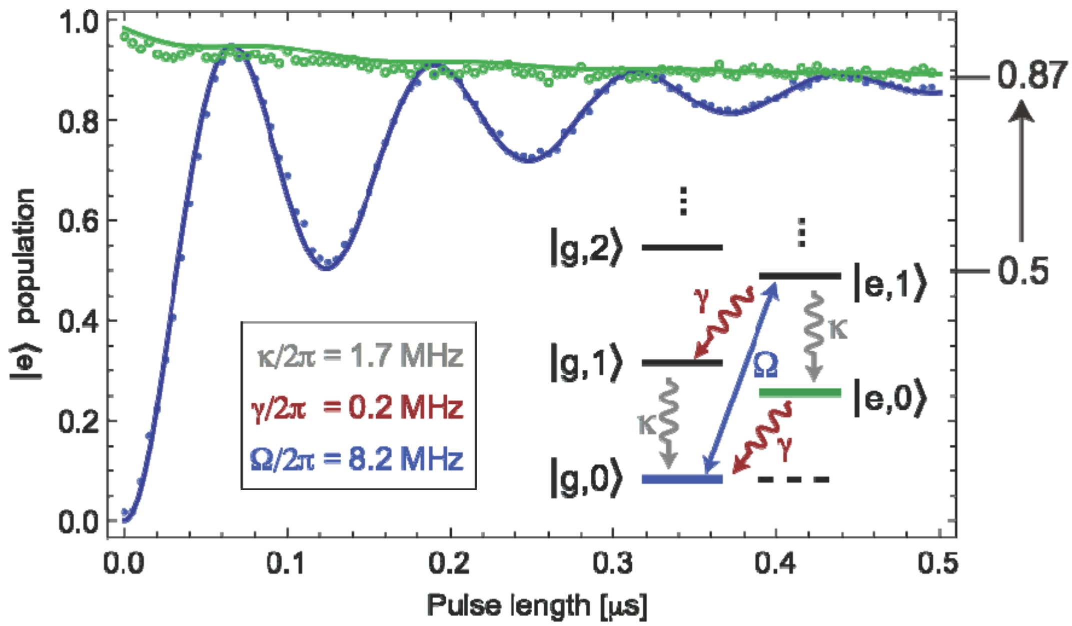
Blue Sideband Rabi Oscillations

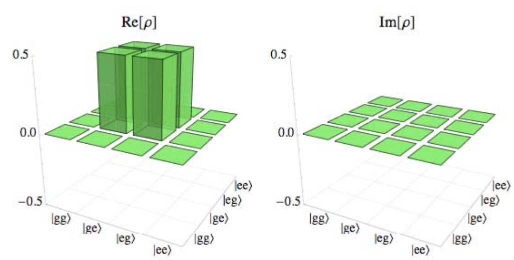


Full Two-Qubit Tomography

- Quantum state characterised with its density operator $\rho = |\Psi\rangle\langle\Psi|$
- Consider for example the Bell state $|\Psi_+\rangle = \frac{1}{\sqrt{2}}(|ge\rangle + |eg\rangle)$

$$\rho_{\Psi_+} = |\Psi_+\rangle\langle\Psi_+| = \frac{1}{2}(|ge\rangle\langle ge| + |ge\rangle\langle eg| + |eg\rangle\langle ge| + |eg\rangle\langle eg|)$$

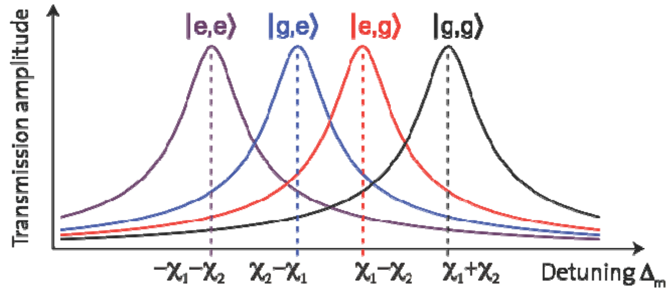
$$\rho_{\Psi_+} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1/2 & 1/2 & 0 \\ 0 & 1/2 & 1/2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$



- Matrix is Hermitian, trace 1 => for 2 qubits, 15 independent parameters
- Full measurement of density matrix possible with repeated experiments and state tomography with 15 combinations of single qubit rotations

Joint Two-Qubit State Measurement

- Resonator Hamiltonian: $\hat{H} = \hbar(\Delta_m + \overbrace{\chi_1 \hat{\sigma}_z^1 + \chi_2 \hat{\sigma}_z^2}^{\hat{\chi}})\hat{a}^\dagger \hat{a}$
- Two-qubit state dependent resonator frequency shift:

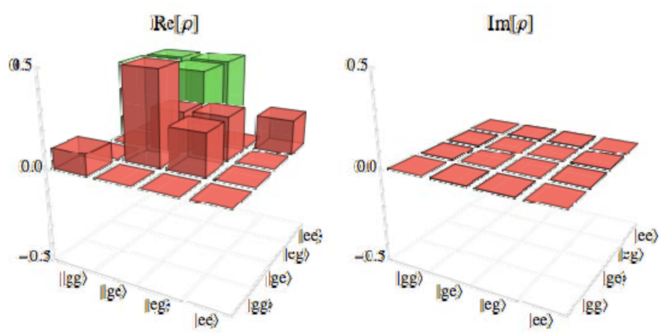


- Measured quantities are non-linear in the frequency shift

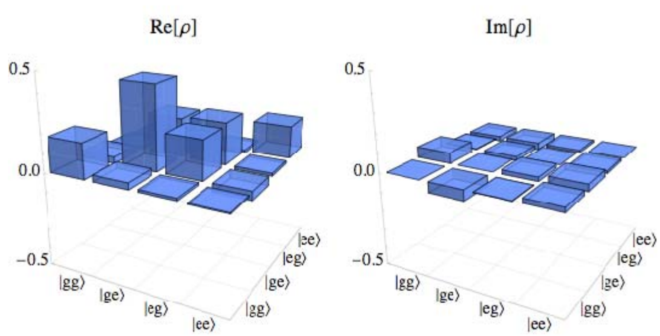
$$\hat{M}_I = \frac{2(\Delta_m + \hat{\chi})}{(\Delta_m + \hat{\chi}) + (\kappa/2)^2} \qquad \hat{M}_Q = \frac{i\kappa}{(\Delta_m + \hat{\chi}) + (\kappa/2)^2}$$

- => $\hat{\sigma}_z^1 \otimes \hat{\sigma}_z^2$ terms are present in the measurement operator, and two qubit correlations are intrinsically measurable

Bell State $|\Psi_+\rangle = \frac{1}{\sqrt{2}}(|ge\rangle + |eg\rangle)$



Simulation
F = 76%



Experimental
state fidelity
F = 73%

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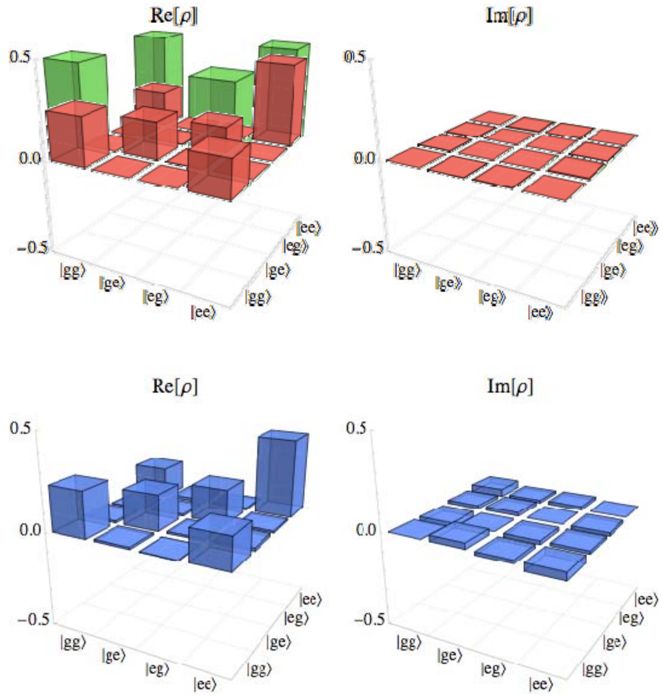
Bell State $|\Phi_+\rangle = \frac{1}{\sqrt{2}}(|gg\rangle + |ee\rangle)$



Simulation
F = 72%

Experiment
F = 72%

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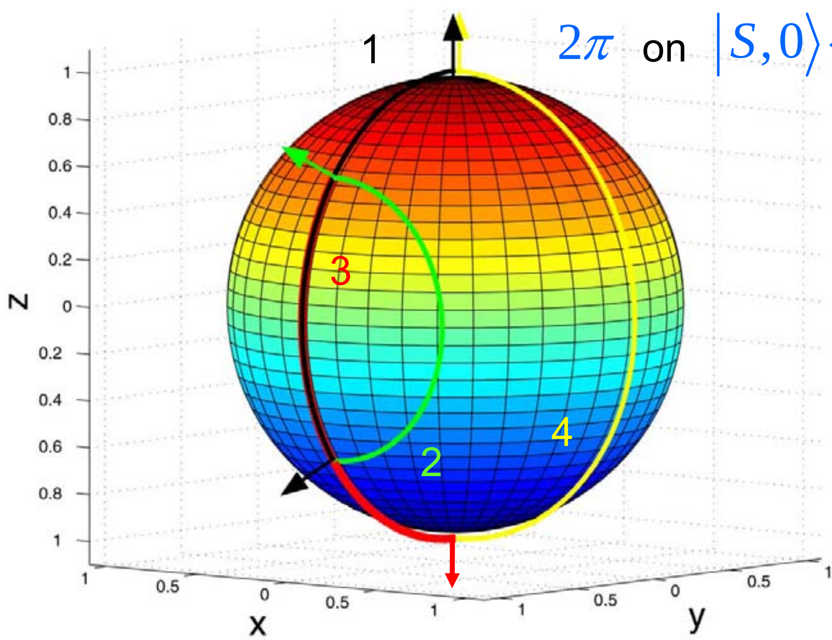
A phase gate with 4 pulses

$$R(\theta,\phi) = R_1^+(\pi,\pi/2)\,R_1^+\left(\pi/\sqrt{2},0\right)R_1^+(\pi,\pi/2)\,R_1^+\left(\pi/\sqrt{2},0\right)$$

2π on $|S,0\rangle \leftrightarrow |D,1\rangle$



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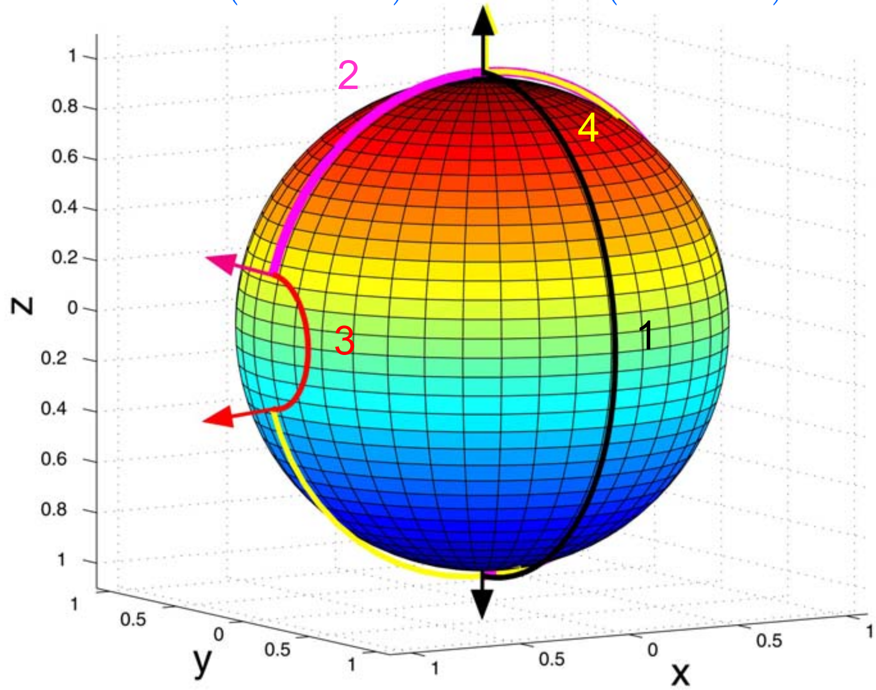
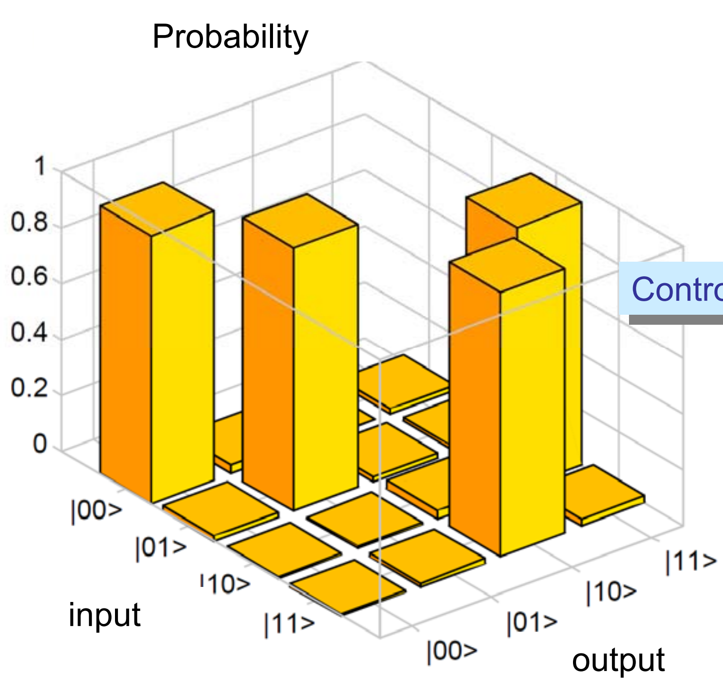
Population of |S,1> - |D,2> remains unaffected

$$R(\theta,\phi) = R_1^+\left(\pi\sqrt{2},\pi/2\right)R_1^+\left(\pi,0\right)R_1^+\left(\pi\sqrt{2},\pi/2\right)R_1^+\left(\pi,0\right)$$



Truth table of the CNOT



$|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle$

$|0\rangle|1\rangle \rightarrow |0\rangle|1\rangle$

$|1\rangle|0\rangle \rightarrow |1\rangle|1\rangle$

$|1\rangle|1\rangle \rightarrow |1\rangle|0\rangle$

Control bit

Target bit

The 5 (+2) DiVincenzo Criteria for Implementation of a Quantum Computer:

in the standard (circuit approach) to **quantum information processing** (QIP)

#1. A scalable physical system with well-characterized qubits. ✓

#2. The ability to initialize the state of the qubits to a simple fiducial state. ✓

#3. Long (relative) decoherence times, much longer than the gate-operation time. ✓

#4. A universal set of quantum gates. ✓

#5. A qubit-specific measurement capability. ✓

#6. The ability to interconvert stationary and mobile (or flying) qubits. ✓

#7. The ability to faithfully transmit flying qubits between specified locations. ✓