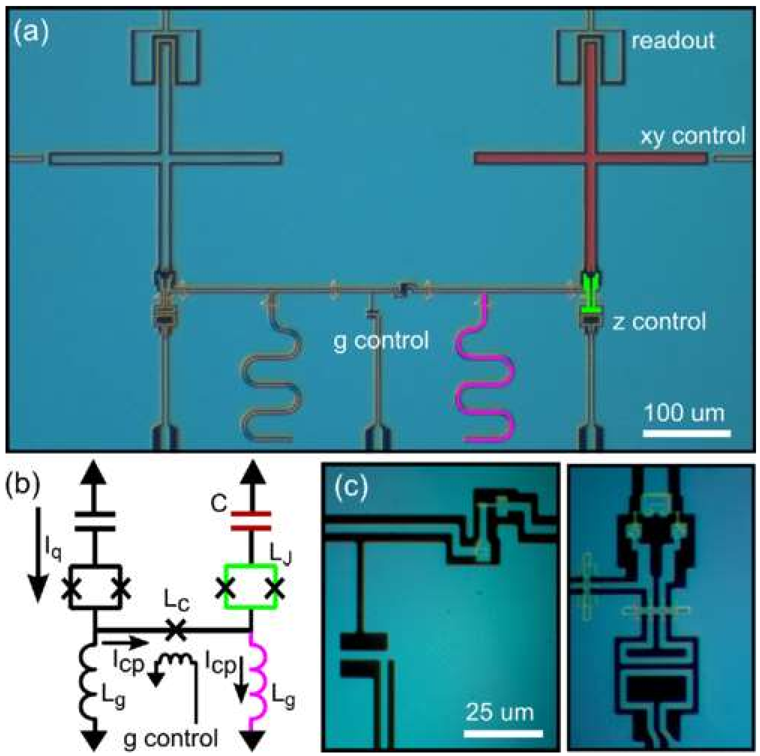
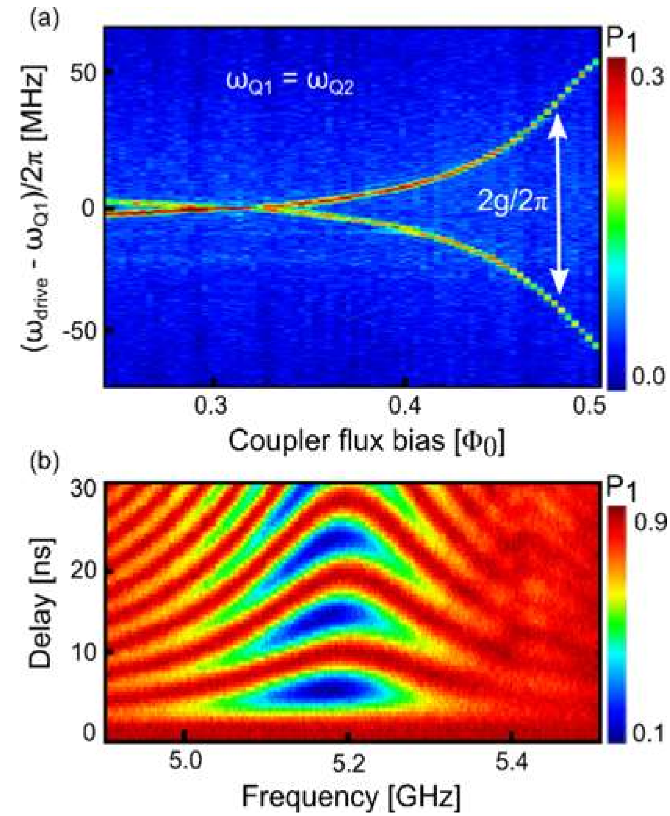
G-mon

martes, 23 de febrero de 2016 10:41



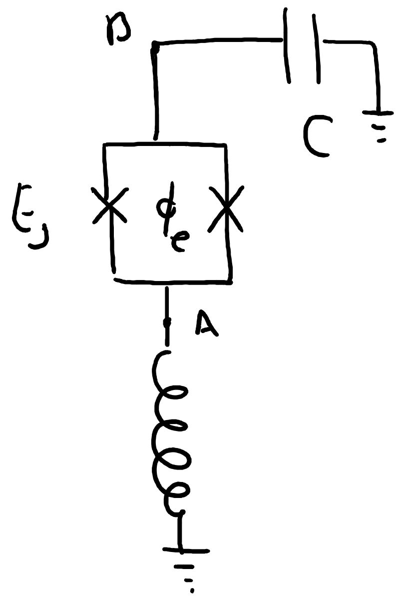
A device that allows tuning the coupling between X-mons using bias currents



Yu Chen et al
Phys. Rev. Lett. 113, 220502 (2014)

Model

martes, 23 de febrero de 2016 19:16



1) The qubit is modified in a simple way that does not affect the dynamics

$$\mathcal{L} = \frac{1}{2} C \left(\dot{\phi}_B\right)^2 - \frac{1}{2L_g} \phi_A^2 + E_J(\phi_e) \cos\left([\phi_B - \phi_A] \frac{2\pi}{\Phi_0} \right)$$

The dynamics of ϕ_A mimics that of the phase jump across the qubit

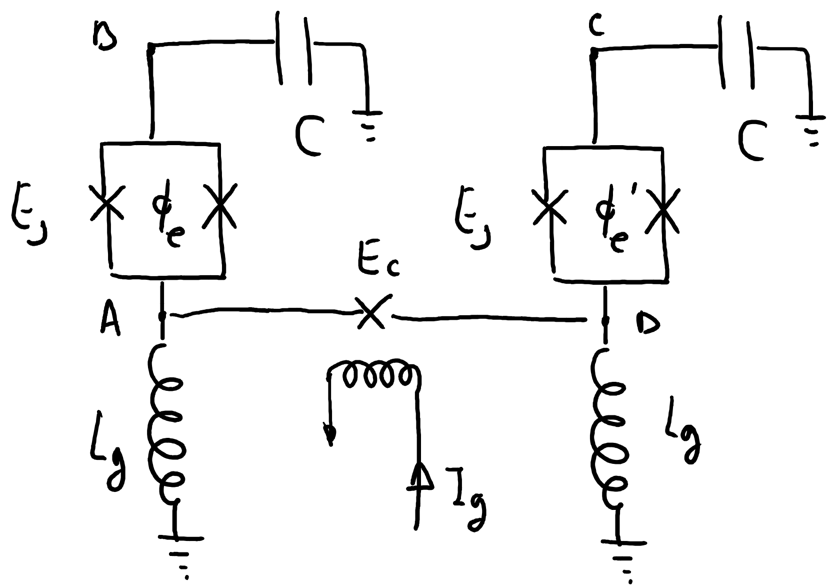
$$\frac{1}{L_g} \phi_A = I_c(\phi_e) \sin\left[\left(\underbrace{\phi_B - \phi_A}_{\phi} \right) \frac{2\pi}{\phi_0} \right] \approx \frac{1}{L_J} \phi$$

leading to $\phi_B = \phi + \phi_A = \left(1 + \frac{L_g}{L_J}\right) \phi \approx \phi \quad (L_J \gg L_g)$

$$\left.\mathcal{L} = \frac{1}{2} C \left(\frac{L_J + L_g}{L_J} \right)^2 \dot{\phi}^2 + E_J(\phi_e) \cos\left(\phi \cdot \frac{2\pi}{\Phi_0} \right) - \frac{L_g}{2L_J^2} \phi^2 \right\} - \frac{1}{2} \frac{L_J + L_g}{L_J^2} \phi^2$$

Model (2)

martes, 23 de febrero de 2016 19:14



2) We couple the qubits with a junction that is influenced by an external current through some mutual inductance

$$\mathcal{L} = \frac{1}{2} C (\dot\phi_B)^2 + \frac{1}{2}(\dot\phi_C)^2 - \frac{1}{2L_g}\phi_A^2 - \frac{1}{2}\phi_D^2$$
$$+ E_J(\phi_e)\cos\left(\frac{\phi_B-\phi_A}{\phi_0}2\pi\right) + E_J(\phi_e')\cos\left(\frac{\phi_C-\phi_D}{\phi_0}2\pi\right)$$
$$+ E_c\cos\left(\frac{\phi_D-\phi_A}{\phi_0}2\pi\right)$$

Note that because $\phi_A \propto \phi_B$, $\phi_D \propto \phi_C$, the connection between both is a qubit qubit coupling.

$$\frac{1}{L_J}(\phi_B-\phi_A) = \frac{\phi_A}{L_g} + \frac{1}{L_c}(\phi_A-\phi_D) \equiv \frac{1}{L_J}\phi_1$$

$$\frac{1}{L_J}(\phi_C-\phi_D) = \frac{\phi_D}{L_g} + \frac{1}{L_c}(\phi_D-\phi_A) \equiv \frac{1}{L_J}\phi_2$$

$L_c \propto E_c(\delta)$
$\uparrow$
ext. flux

Model (3)

martes, 23 de febrero de 2016 21:16

Stationary solution

$$\phi_D = \frac{L_g}{L_J} \cdot \frac{1}{L_c + 2L_g} \cdot \left[(L_c + L_g)\phi_2 + L_g \phi_1 \right]$$

$$\phi_A = \frac{L_g}{L_J} \cdot \frac{1}{L_c + 2L_g} \left[(L_c + L_g)\phi_1 + L_g \phi_2 \right]$$

We plug this into the lagrangian and

M = mutual inductance

$$\frac{1}{2L_g}\phi_A^2 + \frac{1}{2L_g}\phi_D^2 + \frac{1}{2L_c}(\phi_D - \phi_A)^2 \sim \frac{L_g^2}{L_c + 2L_g} \frac{1}{L_J^2} \phi_1 \phi_2 + \left(\text{qubit terms like before}, \phi_1^2, \phi_2^2\right)$$

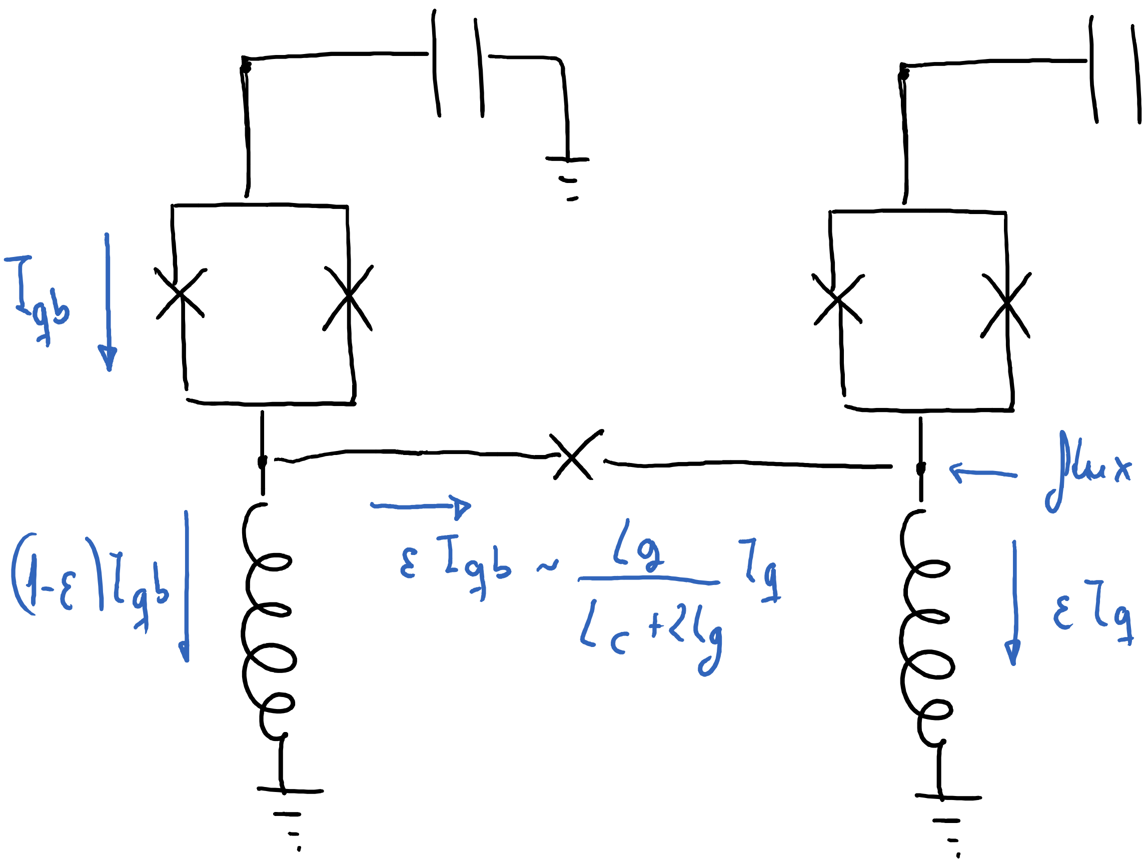
When we plug in the quantized expressions

$$\phi_{1,2} = \sqrt{\frac{\omega L_{eff}}{2}} \left(a_{1,2} + a_{1,2}^{+}\right) \approx \sqrt{\frac{\omega}{2} \frac{L_J^2}{L_J + L_g}} \left(a_{1,2} + a_{1,2}^{+}\right)$$

This results into a coupling $\frac{\omega}{2} \frac{M}{L_J + L_g} \left(a_1^{+} a_2 + a_2^{+} a_1\right)$

Alternative explanation

jueves, 25 de febrero de 2016 11:00



$$\text{flux} \propto l_g I_g \varepsilon \sim \underbrace{\frac{l_g^2}{l_c + 2 l_g}}_{\text{mutual inductance}} I_{gb}$$

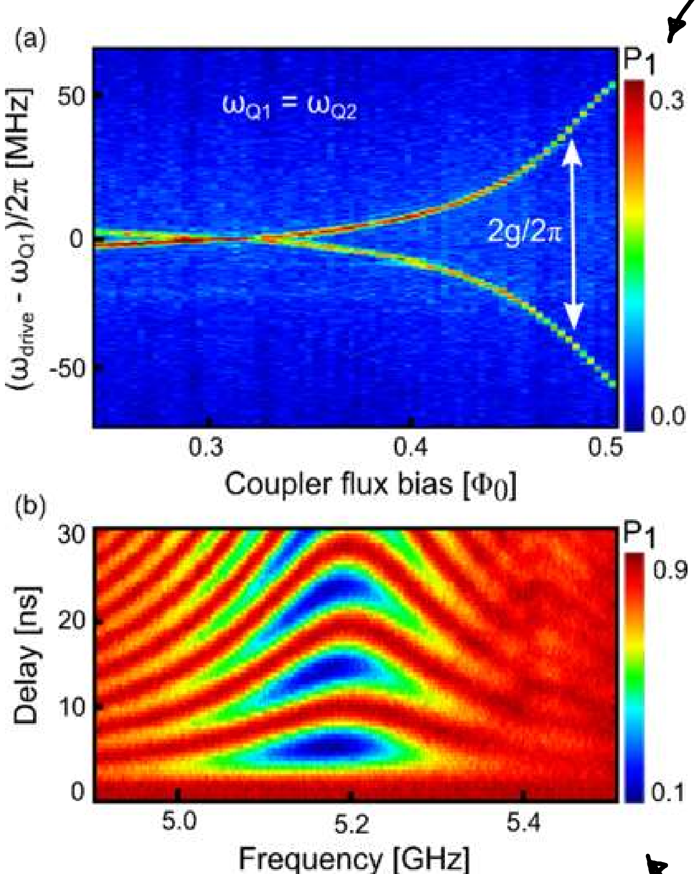
$$\Downarrow$$

$$E_{ind} \sim - M I_{gb}^1 I_{gb}^2 \sim M \frac{\phi_1}{l_g} \frac{\phi_2}{l_g}$$

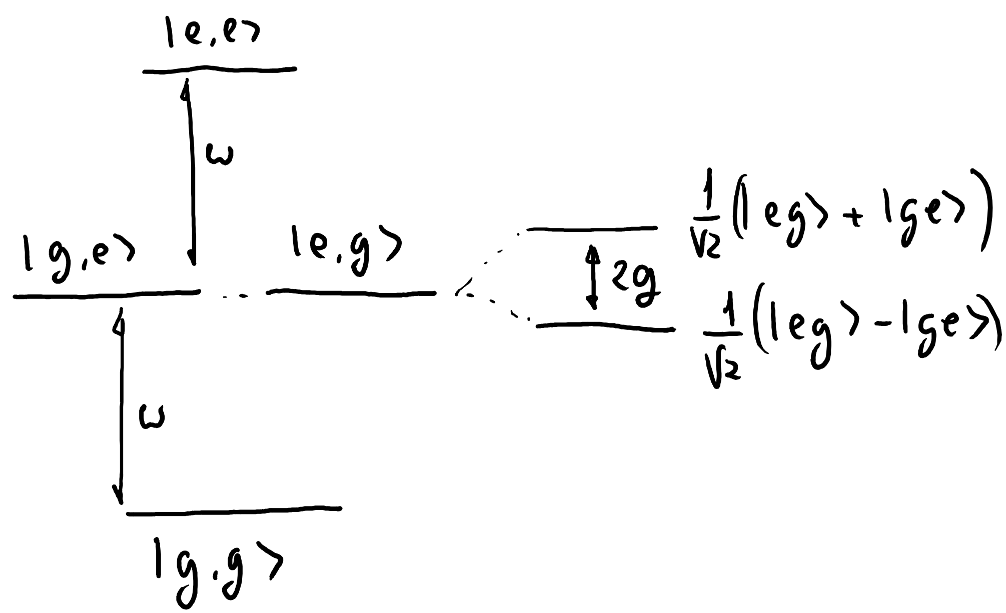
Tuneable coupling

martes, 23 de febrero de 2016 21:28

On-off ratio ~ 1000



$$H \sim \omega\left(\frac{\sigma_1^z+1}{2}\right) + \omega\left(\frac{\sigma_2^z+1}{2}\right) + g\left(\sigma_1^+\sigma_2^- + \sigma_1^-\sigma_2^+\right)$$

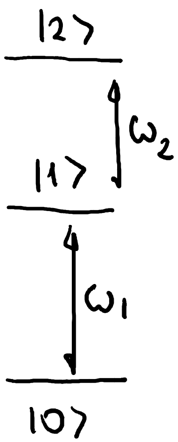


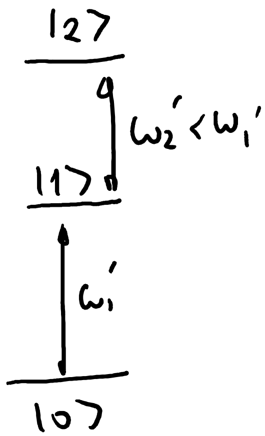
Hopping of excitations

Two-qubit gate

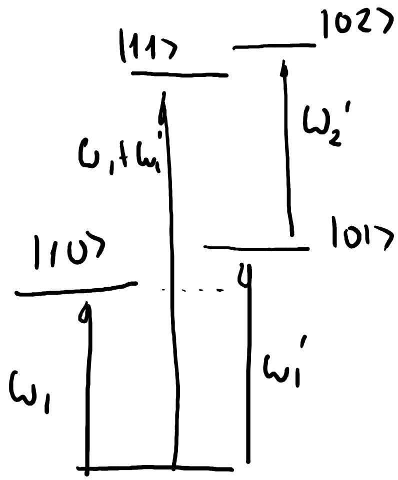
martes, 23 de febrero de 2016 21:55

Qubit 1

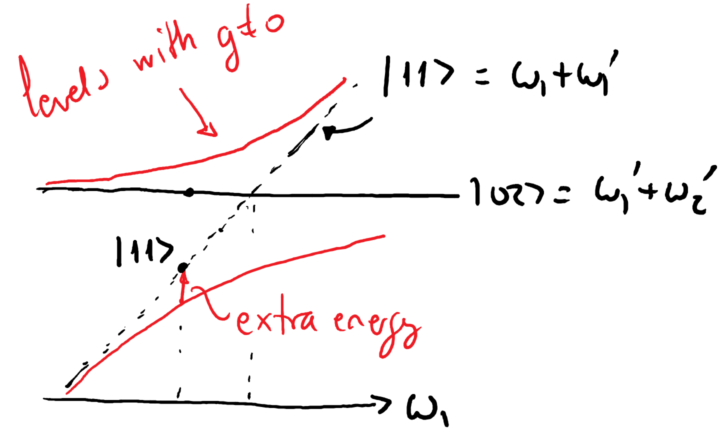




Qubit 2



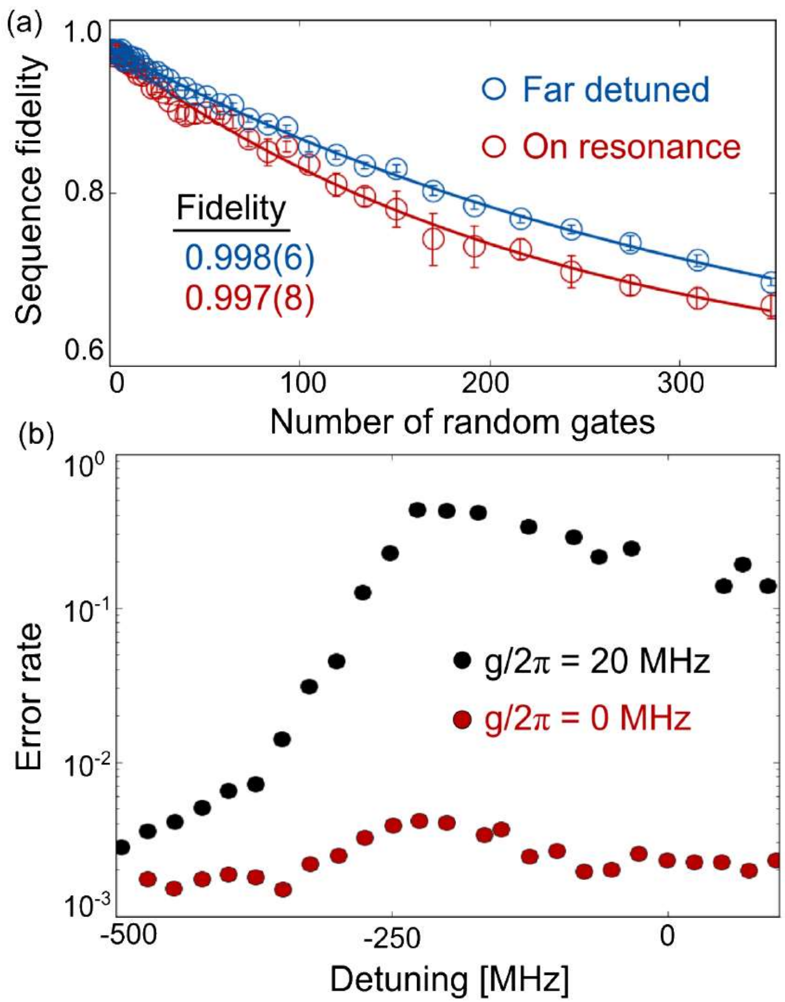
$|\omega_1' - \omega_1| \gg 2g$ to avoid direct tunneling



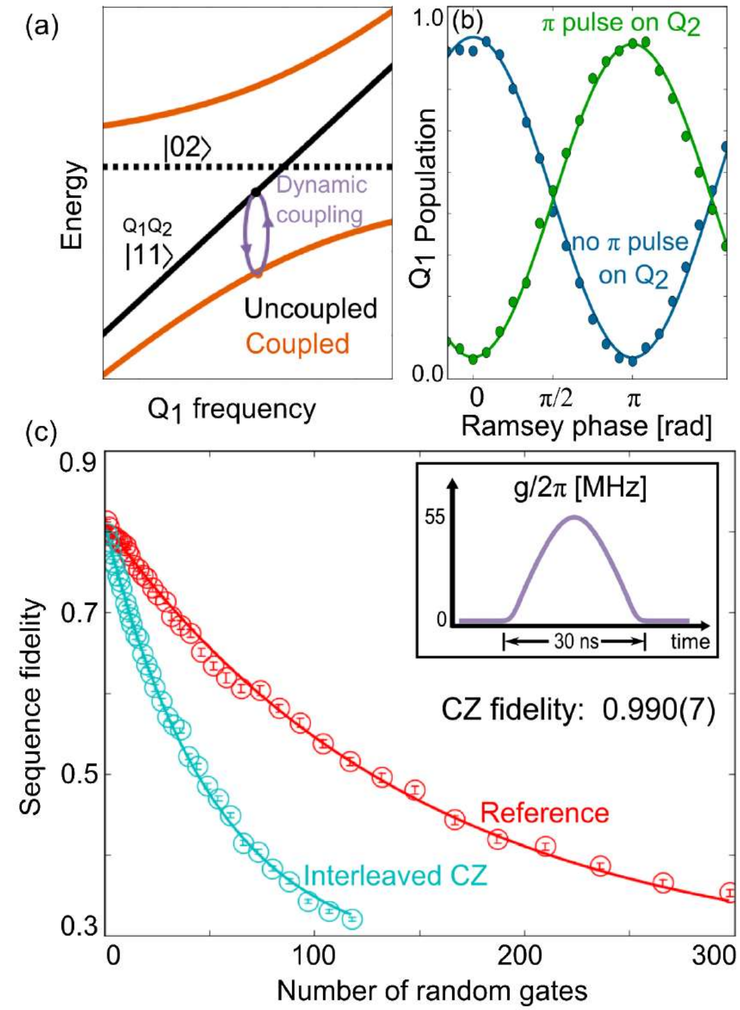
Because $\omega_1 < \omega_2'$, when we connect and disconnect "g" all what happens to the $|11\rangle$ state is that it returns back to the same configuration with a phase that accounts for the extra interaction energy

Gate fidelities

martes, 23 de febrero de 2016 21:51



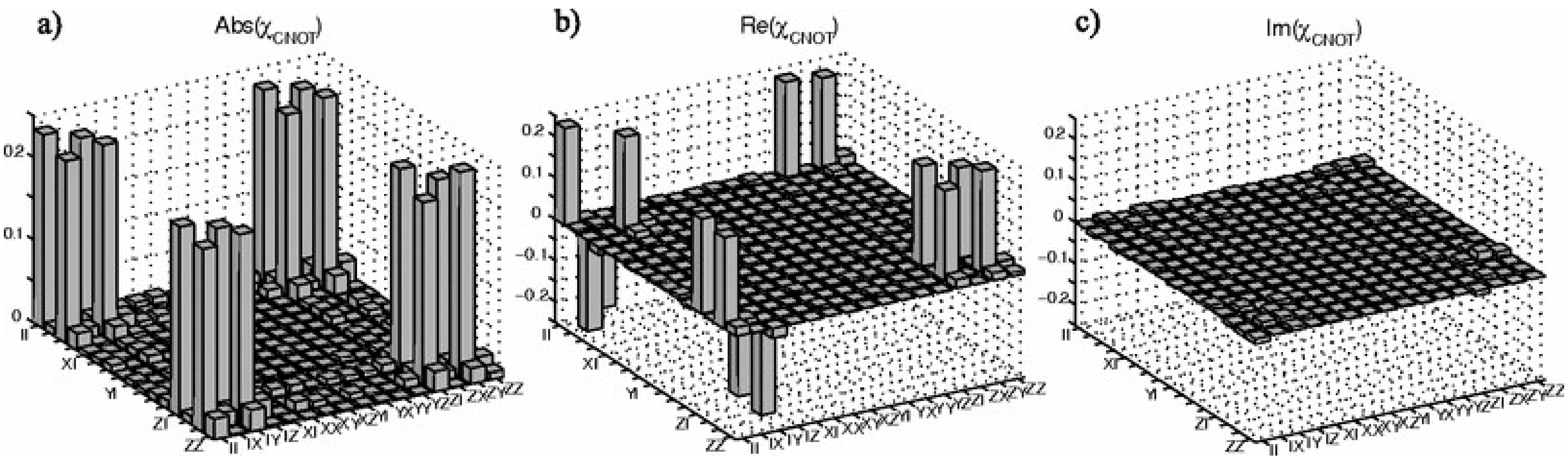
Single qubit fidelites



Two-qubit gates

Tomography

jueves, 25 de febrero de 2016 14:44



Process Tomography of Ion Trap Quantum Gates
M. Riebe, K. Kim, P. Schindler, T. Monz, P. O. Schmidt, T. K. Körber, W. Hänsel, H. Häffner, C. F. Roos, and R. Blatt, Phys. Rev. Lett. 97, 220407 2006

Is the experimental procedure to reconstruct either a quantum state

$$\rho \sim \sum_{\alpha_1 \ldots \alpha_N} C_{\alpha_1 \ldots \alpha_N} \sigma^{\alpha_1} \cdots \sigma^{\alpha_N}$$

or a physical transformation

$$\mathcal{E}(\rho) \sim \sum_{\lambda} A_\lambda \rho A_\lambda^\dagger \quad \text{or} \quad \sum_{mn} \chi_{mn} A_m \rho A_n^\dagger \qquad A_m \propto \sigma^{\alpha_m} \cdots \sigma^{\gamma_m}$$

Tomography (2)

jueves, 25 de febrero de 2016 14:56

PROS: It seems to give very detailed information about what "goes on" beyond just a global error measure

CONS: - It is very costly

N qubits $\Rightarrow \sim 4^N$ measurement setups for state tomography

$\Rightarrow \sim 2^{4N}$ input states for process tomography

- It demands a-priori information about errors in state preparation, process, and measurement phase

- Even after that, needs interpreting the tomography coefficients + errors through some "maximum likelyhood" approximation method

Noise channels

jueves, 25 de febrero de 2016 15:00

Assume our operation errors are not systematic

When we prepare a state $|\psi\rangle$, how it is distorted does not depend on the state

1) Spontaneous emission

$$\mathcal{E}(\rho) \approx \begin{pmatrix} \rho_{00} + \rho_{11}(1-e^{-\gamma t}) & \rho_{01} e^{-\gamma t/2} \\ \rho_{10} e^{-\gamma t/2} & \rho_{11} e^{-\gamma t} \end{pmatrix} \approx \sum_{s,r=0,1} |s\rangle\langle s|\rho|r\rangle\langle r| (1-p)^{\frac{r+s}{2}} + p\,\sigma^-\rho\,\sigma^+$$

$1-p$

2) Dephasing

$$\mathcal{E}(\rho) = \begin{pmatrix} \rho_{00} & \rho_{01} e^{-t/T_2} \\ \rho_{10} e^{-t/T_2} & \rho_{11} \end{pmatrix} = (1-p)\rho + \sum_{s=0,1} p\,|s\rangle\langle s|\rho|s\rangle\langle s|$$

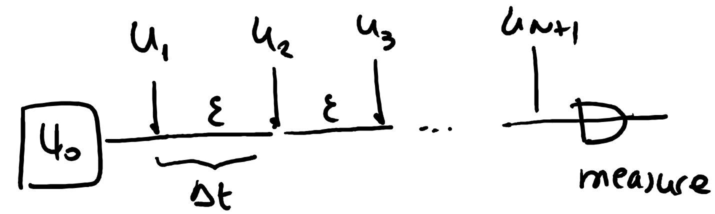
3) Depolarising

$$\mathcal{E}(\rho) = p\frac{\mathbb{1}}{2} + (1-p)\rho = \left(1 - \frac{3}{4}p\right)\rho + \sum_{\alpha=1}^{3} p\,\sigma^\alpha \rho\,\sigma^\alpha$$

Randomized benchmarking

jueves, 25 de febrero de 2016 19:42

Let's assume $\mathcal{E}(\rho) \equiv \mathcal{E}(\rho, \Delta t)$ describes noise over a time Δt, and we have a large group of unitaries $\mathcal{G} = \{U_1 \dots U_L\}$ s.t. random products of them quickly cover the whole space of unitaries



1) For each sequence length $n = 1 \dots M$

   a) For N repetitions

      1) Prepare state ψ_0

      2) Apply a random sequence of gates $\{U_1 \dots U_N\}$ waiting a time Δt

      3) Apply one gate $U_{N+1} = \Pi\, U_N^{-1} \dots U_1^{-1} \in \mathcal{G}$

      4) Measure $|\psi_0\rangle\langle\psi_0|$

   b) Store the average success probability F_N

Randomized benchmarking (2)

jueves, 25 de febrero de 2016 19:50

When $\mathcal{G}$ is a unitary 2-design, quickly converges to averaging over unitaries

$$W(\rho) = \frac{1}{M} \sum_k U_k \rho U_k^\dagger$$

$$W^N[\rho] \sim \int dU \cdot U \rho U^{-1}$$

We then expect an exponential decay of the fidelity

$$F_N \sim A + B f^N, \quad f = \frac{d \times F_{avg}(\mathcal{E}) - 1}{d - 1}$$

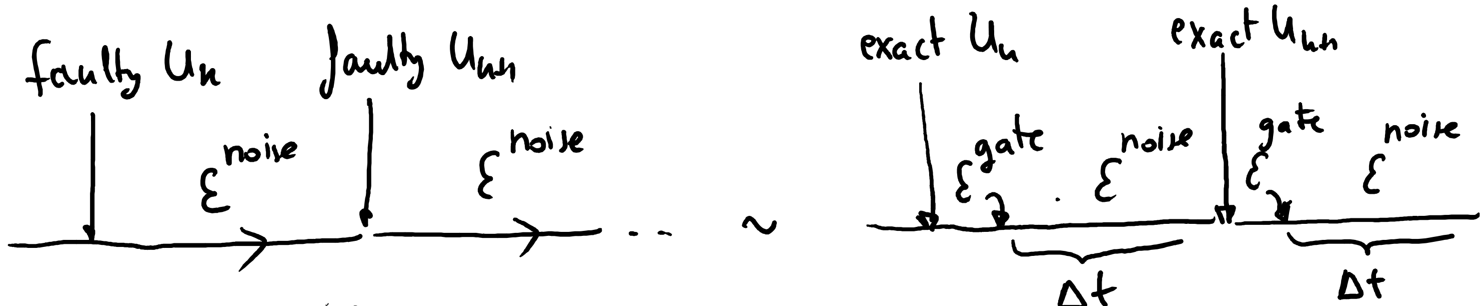
$$F_{avg}(\mathcal{E}) = \int dU \, \mathrm{tr}\left[U^{-1} |\psi_0\rangle\langle\psi_0| U \, \mathcal{E}(U |\psi_0\rangle\langle\psi_0| U^{-1}) \right]$$ ← avg. over unitaries

$$= \int d|\psi\rangle \, \mathrm{tr}\left[|\psi\rangle\langle\psi| \, \mathcal{E}(|\psi\rangle\langle\psi|) \right]$$ ← avg. over states

Benchmarking of gates

Question 1: What if we cannot implement the unitaries U_n accurately in the experiments

a) If there are no systematic errors we can incorporate those errors into the budget of $\mathcal{E}$



$$\mathcal{E}(\rho) \approx \mathcal{E}^{noise}\left(\mathcal{E}^{gate}(\rho), \Delta t\right)$$

b) If there are systematic errors, they should pop up as strange correlations bw. U_n and F_N, deviations from exponential law, etc.

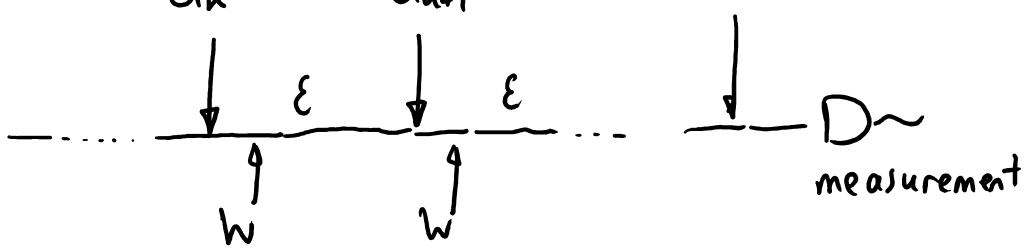
Benchmarking of actual gates

jueves, 25 de febrero de 2016 20:05

QUESTION 2: Can I use this to estimate the fidelity of some particular gate?

Yes, this involves interleaving

$$U_{N+1} = \prod U_N^{-1} W^{-1} U_{N-2} W^{-1} \dots U_1^{-1}$$



$$r_{ref} \sim \left(1 - f_{ref}\right)\frac{d-1}{d} \rightarrow \text{average error per gate in } \mathcal{G}$$

$$r_{gate} \sim \left(1 - \frac{f_G}{f_{ref}}\right)\frac{d-1}{d} \rightarrow \text{average error per application of } W$$

These are estimates and once more assume independence between $\mathcal{E}, W, \mathcal{G}$.

Improvements

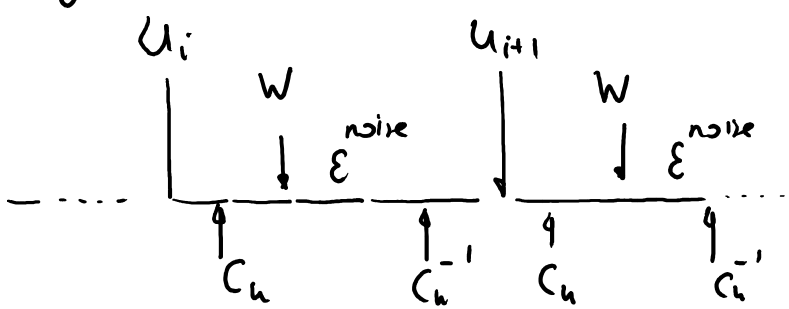
jueves, 25 de febrero de 2016 20:14

* Some groups do not use the complete unitary 2-design, such as a Clifford group for N qubits

$$\mathcal{C} = \left\{ 1,\ e^{\pm i \sigma^\alpha \pi/4},\ e^{\pm i \sigma^\alpha \pi/2} \,/\, \forall \alpha \right\}$$

↳ reduced set of gates based on assumptions about error model or just to get estimates

* Other groups (BBN) use the full group and study $F^{(k)}$ for



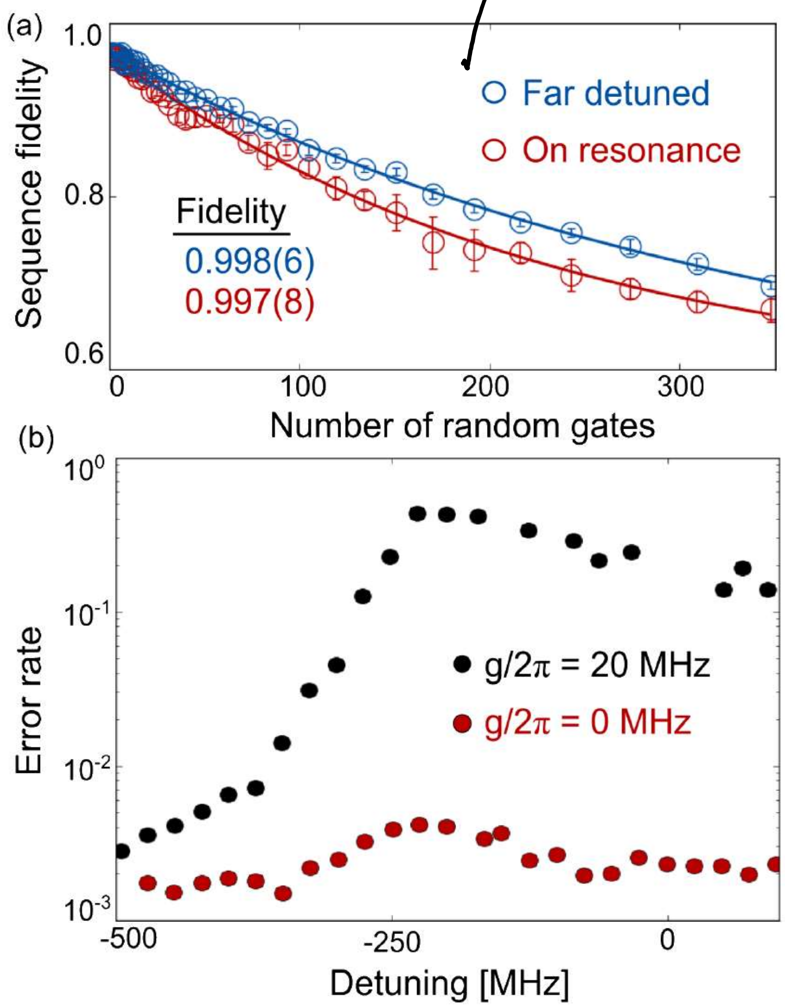
This allows expanding the unital part of the composite map $\mathcal{E}_W \equiv \mathcal{E}^{noise} \circ W$ in terms of Clifford gates $\{C_k\}$

* Analysis of systematic errors, length of sequences, convergence..

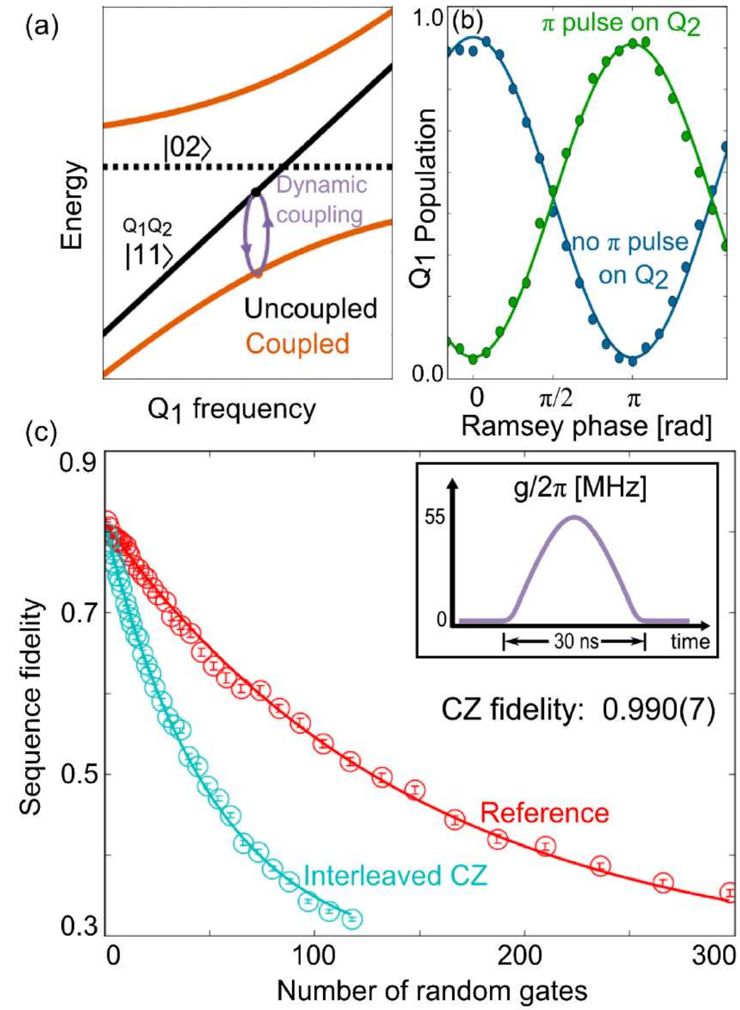
Gate fidelities

martes, 23 de febrero de 2016 21:51

$(0.998)^{10} \sim 0.81$ fidelity!



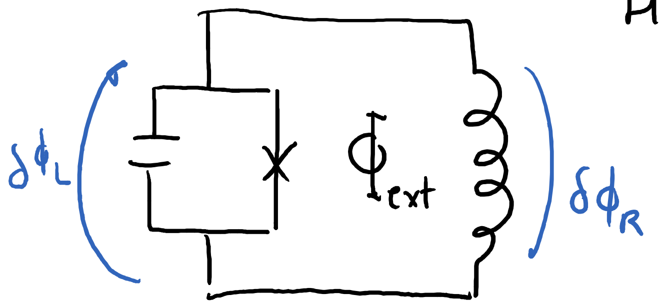
Single qubit fidelities



Two-qubit gates

Current states

lunes, 22 de febrero de 2016 9:18

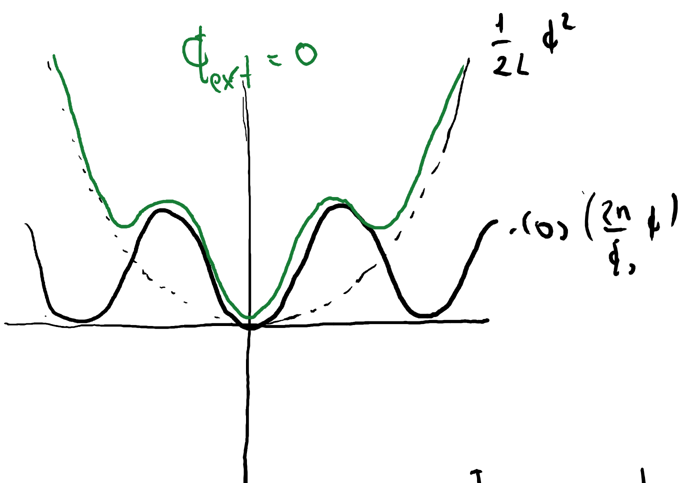


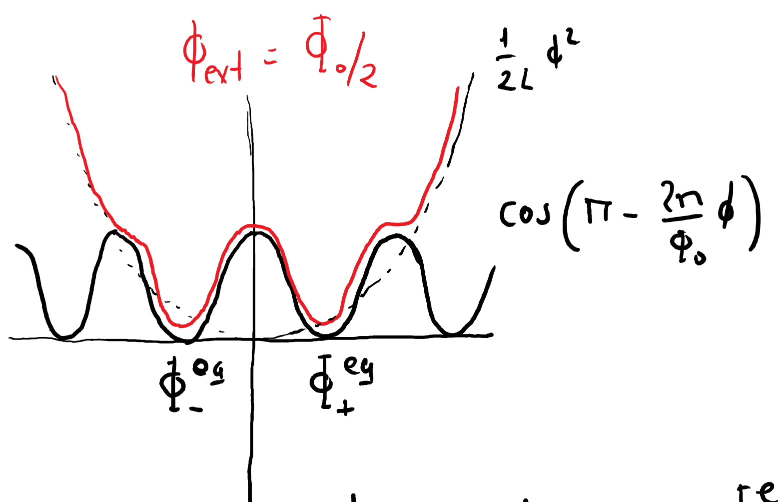
$$\delta\phi_L + \delta\phi_R = \Phi_{ext} + \cancel{2\pi m}\,\Phi_0$$

Hamiltonian $\quad \mathcal{H} \sim \frac{1}{2C} q^2 + \frac{1}{2L} \underbrace{(\phi)}_{\delta\phi_R}^2 - E_J \cos\left[\frac{2\pi}{\Phi_0} \underbrace{(\Phi_{ext} - \phi)}_{\delta\phi_L}\right]$

When $\Phi_{ext} = 0$, the minimum energy is obtained for $\phi \approx 0$, no flux difference

$$I(\Phi_{ext} = 0) = I_c \sin\left(\frac{2\pi}{\Phi_0} \cdot (\phi = 0)\right) = 0$$



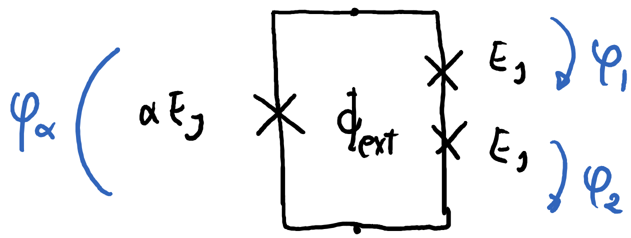


But when $\Phi_{ext} \sim \frac{\Phi_0}{2}$ we have two quasi-degenerate ground states $\Phi_\pm^{eq}$

3 junction flux qubit

lunes, 22 de febrero de 2016 9:29

A similar design, but we do not rely on the small inductance L.



$$\varphi_\alpha = \phi_{ext}\frac{2\pi}{\phi_0} - \varphi_1 - \varphi_2 \sim \pi - (\varphi_1 + \varphi_2)$$

Working in the limit of one smaller junction $\alpha \sim (0.7 - 0.9) E_J$ the inductive energy reads

$$E_J\Big[\underbrace{\cos(\varphi_1) + \cos(\varphi_2)}_{2\cos\left(\frac{\varphi_1+\varphi_2}{2}\right)\cos\left(\frac{\varphi_1-\varphi_2}{2}\right)} + \alpha\cos\big(\pi - (\varphi_1+\varphi_2)\big)\Big]$$

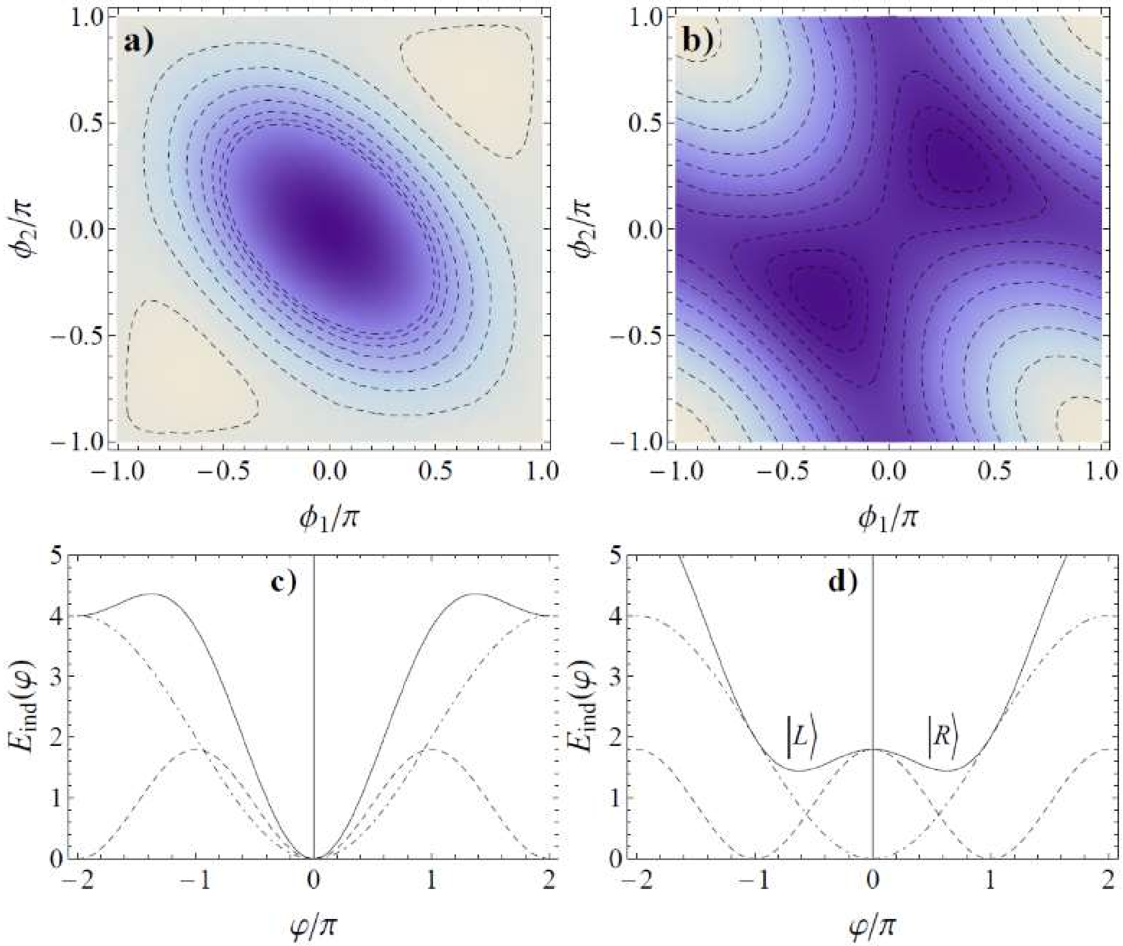
$$2\cos\left(\frac{\varphi_1+\varphi_2}{2}\right)\cos\left(\frac{\varphi_1-\varphi_2}{2}\right) - \alpha\cos(\varphi_1+\varphi_2)$$

The minima are located along $\varphi_1 = \varphi_2$,

$$E_J\left(2\cos(\varphi_+) - \alpha\cos(2\varphi_+)\right)$$

Degenerate ground states

lunes, 22 de febrero de 2016 9:52



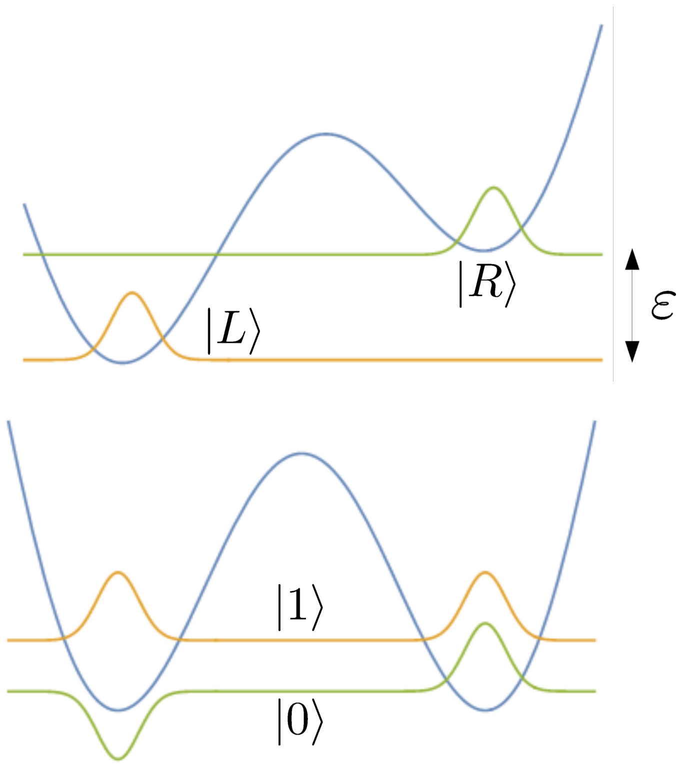
$\leftarrow \cos(\varphi_+)$

$\leftarrow \alpha \cos(2\varphi_+)$

φ_+/π

Effective Hamiltonian

lunes, 22 de febrero de 2016 9:53



$$H = \frac{\Delta}{2}\left(|L\rangle\langle R| + |R\rangle\langle L|\right) + \varepsilon\left(|R\rangle\langle R| - |L\rangle\langle L|\right)$$

$\Delta \propto E_J \times$ overlap bw. $|L\rangle$ and $|R\rangle$

$$\varepsilon \sim \frac{2\pi}{\Phi_0}\left(\Phi_{ext} - \Phi_0/2\right)$$

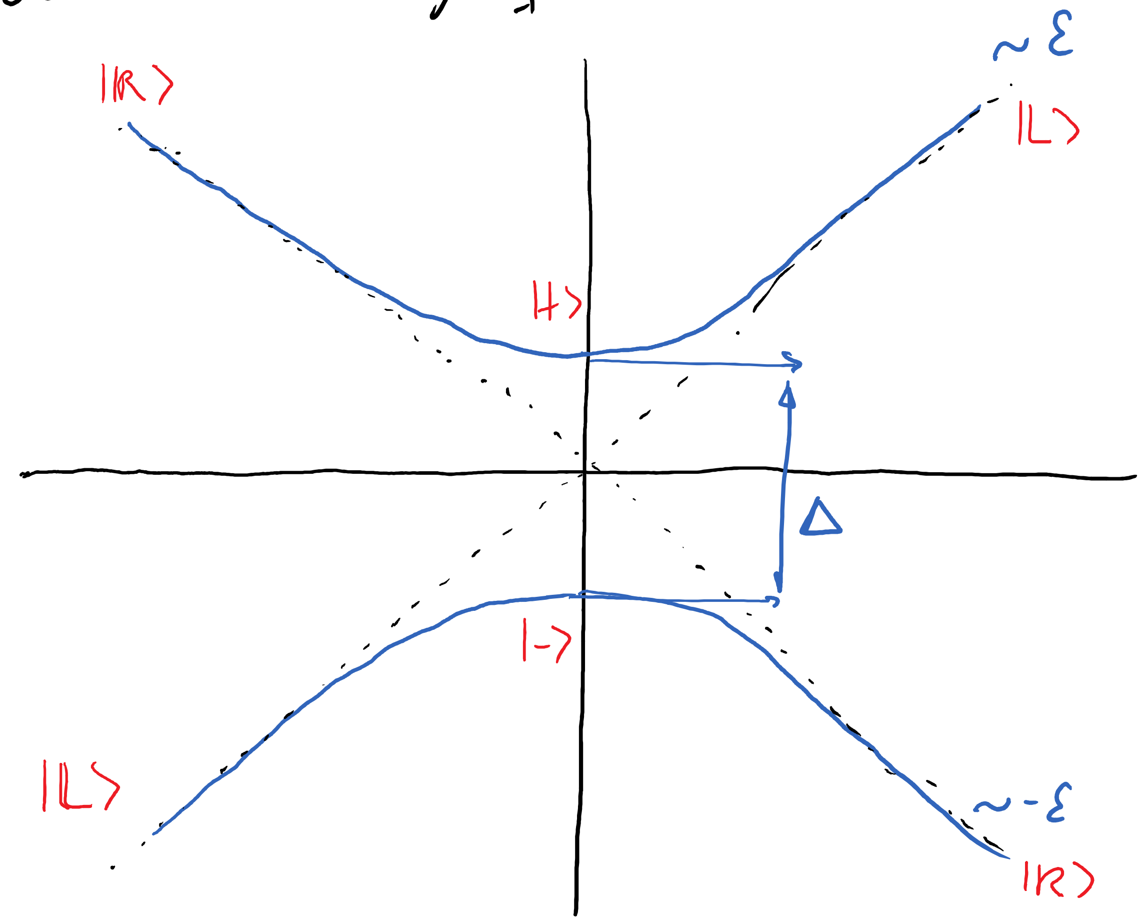
The two minima are connected due to quantum tunneling, Δ. This amplitude decreases exponentially with $E_J/E_C \Rightarrow$ very hard to "tune" or design

In addition to this, changes in the magnetic flux act as an effective magnetic field on the dipole $|L\rangle\langle L| - |R\rangle\langle R|$

Qubit hyperbola

lunes, 22 de febrero de 2016 10:04

Just like the charge qubit



- For large bias field ε the states are well defined current states, clock- or anticlockwise, $|L\rangle, |R\rangle$
- The symmetry point $\varepsilon = 0$ ($\Phi_{ext}/\Phi_0 = \pi \cdot n$) has a superposition of current states
- As with the charge qubit, this point is where dephasing is minimized