Introduction to Decoherence and How To Fight It

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Why is decoherence so difficult?

Because $\tilde{\hbar}$ is so small!

Charge qubits:

$\tilde{\hbar} \equiv 10^{-15}$ eV·s $= (1e)(1nV)(1\mu s)$

[$\equiv$ in red]

Flux qubits:

$\tilde{\hbar} \equiv (1 \text{nT})(1 \text{nA})(10 \mu m)^2 (1 \mu s)$
SENSITIVITY OF BIAS SCHEMES TO NOISE (EXPD)

Junction noises

<table>
<thead>
<tr>
<th></th>
<th>(\Delta Q_{\text{off}})</th>
<th>(\Delta E_J)</th>
<th>(\Delta E_C)</th>
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</thead>
<tbody>
<tr>
<td>bias</td>
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<td>charge</td>
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<td>flux</td>
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<td>phase</td>
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CHARGED IMPURITY
TUNNEL CHANNEL
ELECTRIC DIPOLES

Charge qubit

Flux qubit

Phase qubit
What can we do about environmental decoherence?

1. Choose materials and fabrication techniques which minimize $1/f$ noise, two-level fluctuators, dielectric loss, etc.

2. Use quiet dispersive readouts that leave no energy behind and which do not heat up the dirt or the q.p.’s (And: Develop low noise pre-amps so fewer photons needed for read out.)

3. Design using symmetry principles which immunize qubits against unavoidable environmental influences (e.g. sweet spots, topological protection)
\[ H = \frac{\omega_0}{2} \sigma^z + \frac{1}{2} \left( Z(t)\sigma^z + X(t)\sigma^x + Y(t)\sigma^y \right) \]

\[ \frac{1}{T_2^*} = \frac{1}{2T_1} + \frac{1}{T_\varphi} \]

Review of NMR language

\( Z(t) \) causes transition frequency to fluctuation in time
\( X(t), Y(t) \) cause diabatic transitions between eigenstates
\[ H = \frac{\omega_0}{2} \sigma^z + \frac{1}{2} \left( Z(t)\sigma^z + X(t)\sigma^x + Y(t)\sigma^y \right) \]

\[ \omega_0 + Z(t) \]

Fluctuations in transition frequency make the phase of superpositions unpredictable.

Gaussian white noise leads to homogeneous broadening (Lorentzian line shape)

\[ \frac{1}{T_\varphi} = \frac{1}{2} S_{ZZ}(0) \]

\[ \rho_{\uparrow\downarrow}(t) = \rho_{\uparrow\downarrow}(0) e^{-i\omega_0 t} \left\langle e^{-i\int_0^t d\tau Z(\tau)} e \right\rangle \]

\[ \rho_{\uparrow\downarrow}(t) \approx \rho_{\uparrow\downarrow}(0) e^{-i\omega_0 t} e^{-\frac{1}{2}\int_0^t d\tau_1 \int_0^t d\tau_2 \left\langle Z(\tau_1)Z(\tau_2) \right\rangle} \]

\[ \rho_{\uparrow\downarrow}(t) \approx \rho_{\uparrow\downarrow}(0) e^{-i\omega_0 t} e^{-\frac{1}{2}[S_{ZZ}(0)]t} \]
Low frequency 1/f noise leads to inhomogeneous broadening (gaussian line shape)

Spin echo can help in some cases.

\[ H = \frac{\omega_0}{2} \sigma^z + \frac{1}{2} \left( Z(t) \sigma^z + X(t) \sigma^x + Y(t) \sigma^y \right) \]

\[ \omega_0 + Z(t) \]

\[ \rho_{\uparrow \downarrow}(t) = \rho_{\uparrow \downarrow}(0) e^{-i\omega_0 t} \left\langle e^{-i \int_0^t d\tau Z(\tau)} \right\rangle \]

\[ \rho_{\uparrow \downarrow}(t) \approx \rho_{\uparrow \downarrow}(0) e^{-i\omega_0 t} \left\langle e^{-itZ} \right\rangle \]

\[ \rho_{\uparrow \downarrow}(t) \approx \rho_{\uparrow \downarrow}(0) e^{-i\omega_0 t} e^{-\frac{1}{2}\langle Z^2 \rangle t^2} \]
Dephasing of CPB qubit due to gate charge $n_g$ noise

$\hat{H} = \hat{H}(n_g), \quad n_g = n_g(t)$ → charge fluctuations

$\omega(t) = \omega_0 + Z(t)$

$Z(t) \approx \frac{\partial Z}{\partial n_g} \delta n_g(t) + \frac{1}{2} \frac{\partial^2 Z}{\partial n_g^2} \delta n_g(t)^2 + ...$

$\frac{1}{T_\varphi} = \frac{1}{2} S_{ZZ} (0) \approx \frac{1}{2} \left( \frac{\partial Z}{\partial n_g} \right)^2 S_{\delta n_g \delta n_g} (0) + ...$
Outsmarting noise: CPB sweet spot

\[ \hat{H} = \hat{H}(n_g), \quad n_g = n_g(t) \]

charge fluctuations

\[ \omega_\alpha = \omega_\alpha(t) \]

-best CPB performance @ sweet spot:

\[ T_1 \sim 7\mu s, \quad T_2 > 500\,\text{ns} \]

(Schoelkopf Lab)

DISTRIBUTION OF RAMSEY RESULTS at Charge Sweet Spot

(Devoret group, fast CBA readout)

Lopsided frequency fluctuations

\[ E_{J}/E_{C} = 3.6 \]

\[ S_{N_g}(\omega) = \frac{\alpha^2}{\omega}, \quad \alpha \approx 1.9 \times 10^{-3} \] 

Charge noise!

value OK
DISTRIBUTION OF RAMSEY RESULTS

Second order (curvature) effects limit coherence times to 500-600 ns

Lopsided frequency fluctuations

Need larger $E_J/E_C$ for less curvature

$S_{N_g}(\omega) = \frac{\alpha^2}{\omega}, \alpha \not= 1.9 \times 10^{-3} e$

value OK
Comparison of superconducting qubits

$E_J/E_C \sim 0.1-10 \quad E_J/E_C \sim 30-100 \quad E_J/E_C \sim 10,000$

Cooper pair box

Transmon

Phase qubit

Cooper pair box

Transmon

Phase qubit
Transmon qubit: Sweet Spot Everywhere

\[ \hat{H} = 4E_C (\hat{n} - n_g)^2 - E_J \cos \varphi \]

\begin{align*}
\text{E}_J / E_C & = 1 \\
\text{E}_J / E_C & = 5 \\
\text{E}_J / E_C & = 10 \\
\text{E}_J / E_C & = 50
\end{align*}

\[ \epsilon_m \rightarrow (-1)^m E_C \frac{2^{4m+5}}{m!} \sqrt{\frac{2}{\pi}} \left( \frac{E_J}{2E_C} \right)^{\frac{m}{2} + \frac{3}{4}} e^{-\sqrt{8E_J / E_C}} \]

\[ \text{Exponentially small charge dispersion!} \]
quantum rotor
(charged, in constant vector potential ∼ n_g)

\[ \left[ 4E_C \left( -i \frac{d}{d\varphi} - n_g \right)^2 - E_J \cos \varphi \right] \psi(\varphi) = E \psi(\varphi) \]

Offset charge = ‘vector potential’

\[ \epsilon_m \rightarrow (-1)^m E_C \frac{2^{4m+5}}{m!} \sqrt{\frac{2}{\pi}} \left( \frac{E_J}{2E_C} \right)^{\frac{m}{2} + \frac{3}{4}} e^{-\sqrt{8 E_J/E_C}} \]
T2 and Larmor Frequency Statistics

1st generation transmon with on Si
with $E_J/E_C \sim 50$, flux sweet spot
20 hours of Ramsey experiments, no retuning

$T_1 = 79 \pm 3 \text{ ns}$

$T_2 = 140 \pm 10 \text{ ns} = 2T_1$

$\omega_{01} = 7350495 \pm 90 \text{ kHz}$

There is no significant drift or 1/f dephasing on these scales!
Coherence in Second Generation Transmon

**Rabi experiment**

- 12 ns $\pi$-pulses
- Rabi visibility 100.4% ± 1%

**Ramsey experiment**

- $T_2^* = 2 \mu s$
- No echo, at flux sweet spot

**T1 Measurement**

- $T_1 = 1.5 \mu s$

\[
\frac{1}{T_2^*} = \frac{1}{2T_1} + \frac{1}{T_\phi}
\]

- $T_\phi = 6 \mu s$

- Consistent with ~ 20 kHz of residual charge dispersion at $E_J/E_C = 50$
NO Echo:

\[ T_2^* = 2.05 \pm 0.1 \mu s \]
\[ T_1 = 1.5 \mu s \]

consistent with ~ 20 kHz of residual charge dispersion at \( E_J/E_C = 50 \)

\[ \frac{1}{T_2^*} = \frac{1}{2T_1} + \frac{1}{T_\phi} \]

\[ \epsilon_m \rightarrow (-1)^m E_C \frac{2^{4m+5}}{m!} \sqrt{\frac{2}{\pi}} \left( \frac{E_J}{2E_C} \right)^{\frac{m}{2}} + \frac{3}{4} e^{-\sqrt{8E_J/E_C}} \]

Phase coherence time becomes exponentially larger for only modest increase in \( E_J/E_C \)

Quasiparticles plentiful but non-poisoning. See Rob Schoelkopf's talk.

Is \( T_1 \) the only remaining problem???
\[ H = \frac{\omega_0}{2} \sigma^z + \frac{1}{2} \left( Z(t)\sigma^z + X(t)\sigma^x + Y(t)\sigma^y \right) \]

\[ \frac{1}{T_1} = \Gamma_\uparrow + \Gamma_\downarrow \]

\[ \Gamma_\downarrow = \frac{1}{4} \left[ S_{XX} (+\omega_0) + S_{YY} (+\omega_0) \right] \]

\[ \text{emission into environment} \]

\[ \Gamma_\uparrow = \frac{1}{4} \left[ S_{XX} (-\omega_0) + S_{YY} (-\omega_0) \right] \]

\[ \text{absorption from environment} \]
Environment = Junction Loss??

\[ C = C_1 - jC_2 = C_1 (1 - j \tan \delta) \]

\[ Q = \frac{1}{\tan \delta} \]

\[ S_{ii}(\omega) = \frac{2}{R} \hbar \omega (1 + n_B) \]

\[ \omega_0 = \frac{1}{\sqrt{LC_1}} \]

\[ \frac{1}{T_1} = \omega_0 \tan \delta (2n_B + 1) \]
Reduce Junction Participation Ratio

\[ Q = \frac{1}{\tan \delta} \]

\[ \tan \delta' = \frac{C}{C_S + C} \tan \delta \]

If shunt capacitance is lossless then:

UCSB: overlap shunt capacitor
Nori et al. proposal: shunt capacitance in flux qubits
Yale: single layer transmon shunt capacitance

Qubit is simply an anharmonic oscillator. A necessary but not sufficient condition to achieve high \( Q \) is to be able to make high \( Q \) resonators on the same substrate.
Purcell Effect:
Engineering Spontaneous Emission from Cavity

Substrate losses
Junction losses
Shunt capacitance
Density of EM States Seen by Qubit Weakly Coupled to Cavity

Cavity filtering enhances qubit decay rate

Cavity filtering reduces qubit decay rate

50 ohm background decay rate

This picture only valid in the ‘bad cavity’ limit: \( g \square \kappa = \frac{\omega_{\text{cavity}}}{Q} \)
Strong Qubit-Cavity Coupling: ‘Good Cavity’ Limit

In limit of large detuning: \( \Delta \gg g \)

\[
\frac{1}{T_1} \approx \frac{1}{T_1^{\text{NR}}} + \left( \frac{g}{\Delta} \right)^2 \kappa
\]
$T_\varphi$ again...

Measurement Induced Dephasing

Photons intentionally or accidentally introduced into the cavity cause a light shift (ac Stark shift) of the qubit frequency

$$H_{\text{eff}} = \hbar \omega_r a^\dagger a + \left( \frac{\hbar}{2} \omega_0' + \frac{\hbar g^2}{\Delta} a^\dagger a \right) \sigma_z$$

$g = \text{atom-cavity coupling}$

$\Delta = \text{atom-cavity detuning}$
Measurement induced dephasing

\[ \Delta \hat{g} : \]

\[ H_{\text{eff}} = \hbar \omega_r a^\dagger a + \left( \frac{\hbar}{2} \omega_{01} + \hbar \frac{g^2}{\Delta} a^\dagger a \right) \sigma_z \]

AC Stark shift of qubit by photons

Phase shift induced by passage of a single photon

\[
\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)|1_{\text{in}}\rangle \rightarrow \frac{1}{\sqrt{2}} \left( e^{i\theta/2} |\uparrow\rangle + e^{-i\theta/2} |\downarrow\rangle \right)|1_{\text{out}}\rangle
\]

\[
\frac{\theta}{2} = \arctan \left( \frac{2g^2}{\Delta \kappa} \right) \quad \kappa = \text{resonator decay rate}
\]

For strong coupling, even a single photon measures the state of the qubit and destroys the superposition:

\[
\frac{1}{T_\phi} \sqrt{\bar{n} \kappa}
\]
What can we do about environmental decoherence?

1. Choose materials and fabrication techniques which minimize 1/f noise, two-level fluctuators, dielectric loss, etc.

2. Use quiet dispersive readouts that leave no energy behind and which do not heat up the dirt or the q.p.’s (And: Develop low noise pre-amps so fewer photons needed for read out.)

3. Design using symmetry principles which immunize qubits against unavoidable environmental influences (e.g. sweet spots, topological protection)
The End
## Coherence Limits for SC Qubits

<table>
<thead>
<tr>
<th>Noise source</th>
<th>transmon $E_J/E_C=85$</th>
<th>CPB $E_J/E_C=1$</th>
<th>flux qubit</th>
<th>phase qubit</th>
</tr>
</thead>
<tbody>
<tr>
<td>dephasing 1/f amplitude</td>
<td>$T_2 [\text{ns}]$</td>
<td>$T_2 [\text{ns}]$</td>
<td>$T_2 [\text{ns}]$</td>
<td>$T_2 [\text{ns}]$</td>
</tr>
<tr>
<td>charge $10^{-4} - 10^{-3} e$ [1]</td>
<td>400,000</td>
<td>1,000*</td>
<td>1,500</td>
<td>$\infty$</td>
</tr>
<tr>
<td>flux $10^{-6} - 10^{-5} \Phi_0$ [2,3]</td>
<td>3,600,000*</td>
<td>1,000,000*</td>
<td>1,000 - 2,000*</td>
<td>300</td>
</tr>
<tr>
<td>critical current $10^{-7} - 10^{-6} I_0$ [4]</td>
<td>35,000</td>
<td>17,000</td>
<td>1,500</td>
<td>1,000</td>
</tr>
<tr>
<td>measured $T_2$ [ns] this year</td>
<td>2,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>measured $T_1$ [ns] last year</td>
<td>90</td>
<td>~ 7,000 [5]</td>
<td>2,000 - 4,000 [3,6]</td>
<td>110 [7]</td>
</tr>
<tr>
<td>measured $T_1$ [ns] this year</td>
<td>4,000</td>
<td></td>
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* values evaluated at sweet spots
† value away from flux sweet spot at $\Phi_0/4$