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Modeling of relaxation in DQDs and implications for adiabaticity

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Introduction and motivation

- **Goal:**
- Characterize dissipation of a single charge DQD, in particular relaxation (T_1) processes
- Distinguish the effects of energy relaxation from those of adiabaticity
- **Motivation:** Before understanding the role of dissipation in multi-qubit charge DQD systems, an experimentally substantiated (realistic) model for single-qubit processes is needed

Model for DQD + environment

We treat the charge DQD as a two-level system coupled to a bath of acoustic phonons (spin-boson model)[1], $H = H_S \otimes \mathbb{1}_B + \mathbb{1}_S \otimes H_B + H_I$

detuning bias, tunnel coupling

System: $H_S = -\frac{1}{2}(\epsilon\sigma_z + \Delta\sigma_x)$

Phonon bath: $H_B = \sum_k \hbar\omega_k b_k^\dagger b_k$

System-bath interaction: $H_I = \sigma_z \otimes \sum_k g_k b_k^\dagger + g_k^* b_k$

Spectral density function: $J(\omega) = \sum_k |g_k|^2 \delta(\omega - \omega_k)$

(Fully characterizes system-bath interaction)

For DQD coupled to deformation acoustic phonons in Si, spectral density of form[2]:

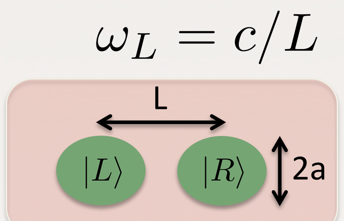
$$J(\omega) = \frac{\hbar\Xi^2}{8\pi^2\rho c^5}\omega^3\left(1 - \frac{\omega_L}{\omega}\sin\frac{\omega}{\omega_L}\right)\exp\left(-\frac{\omega^2}{2\omega_a^2}\right)$$

deformation potential: $\Xi \approx 5 - 10$ eV $\quad \omega_a = c/a$

speed of sound: $c = 9.0 \times 10^3$ m/s $\quad \omega_L = c/L$

mass density: $\rho = 2.3 \times 10^3$ kg/m^3

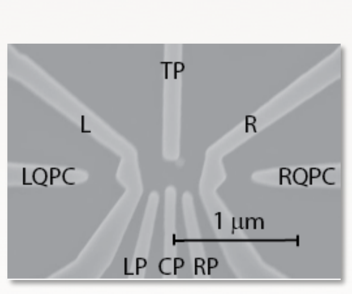
Note: $J(\omega) \propto \omega^5$ for $\omega \ll \omega_L, \omega_a$



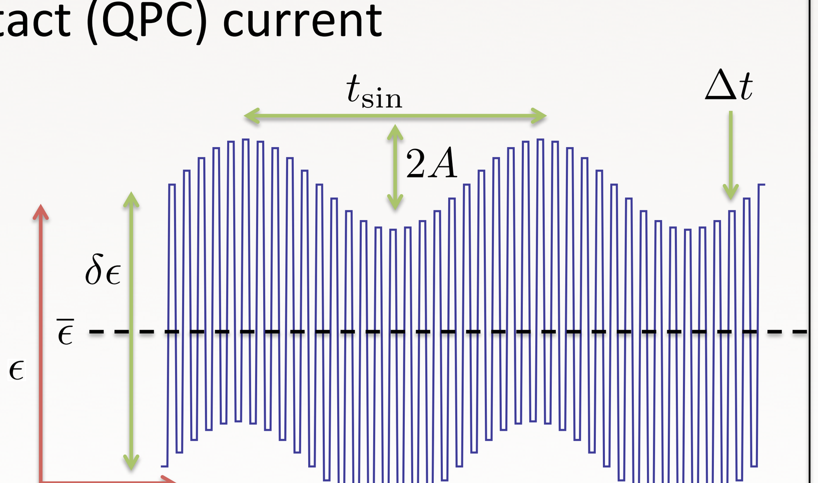
Experiment overview

Control/Measurement scheme:

Toggle voltage bias $\epsilon(t)$ as a square wave (modulated by sinusoid for lock-in), measuring time-average of quantum point contact (QPC) current



[J. Dominguez (Sandia)]



Square wave frequency: f

Avg. detuning bias: $\bar{\epsilon}$

Toggling amplitude: $\delta\epsilon$

Experiment: Sweep over $\bar{\epsilon}$

Open system dynamics

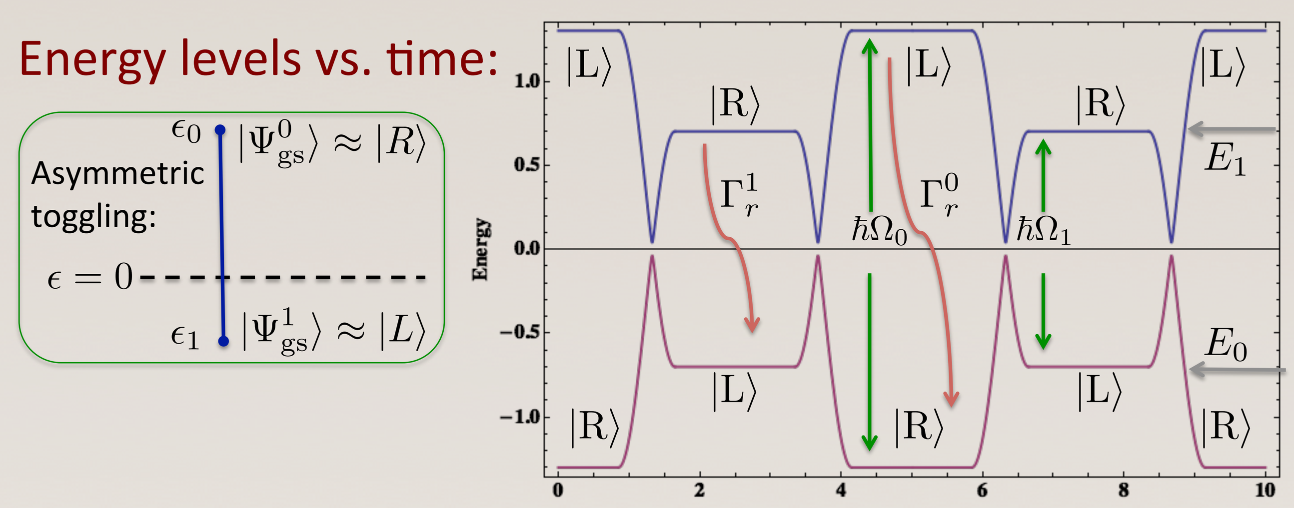
Take Born-Markov approximations to get a master equation for DQD in Lindblad form—obtain a rate equation for ground/first excited state occupations (relaxation rate depends on gap energy)

Relaxation rate: $\Gamma_r(\Omega) = \frac{2\pi}{\hbar^2}\left(\frac{\Delta}{\hbar\Omega}\right)^2 J(\Omega)\coth\left(\frac{\beta}{2}\hbar\Omega\right)$

where: energy gap = $\hbar\Omega = \sqrt{\epsilon^2 + \Delta^2}$

lattice temperature = β^{-1}

Energy levels vs. time:

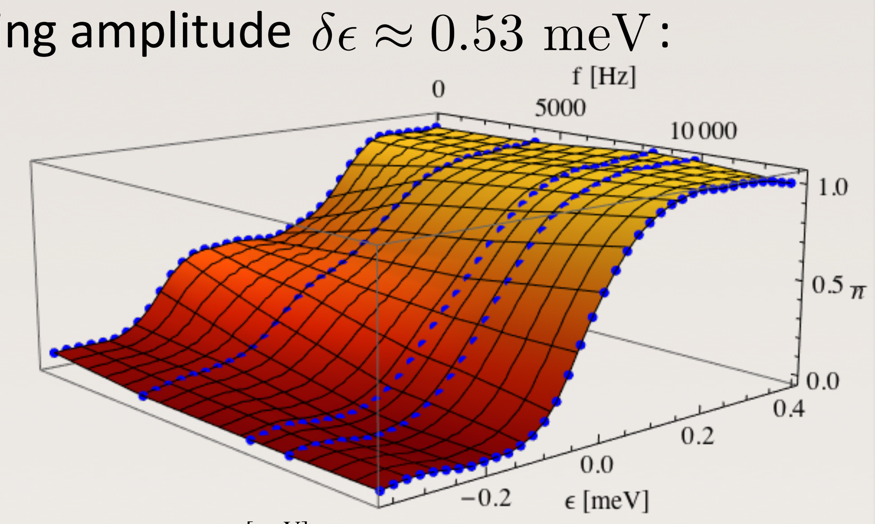


From rate equation, compute time-averaged ground state occupation assuming dynamic equilibrium

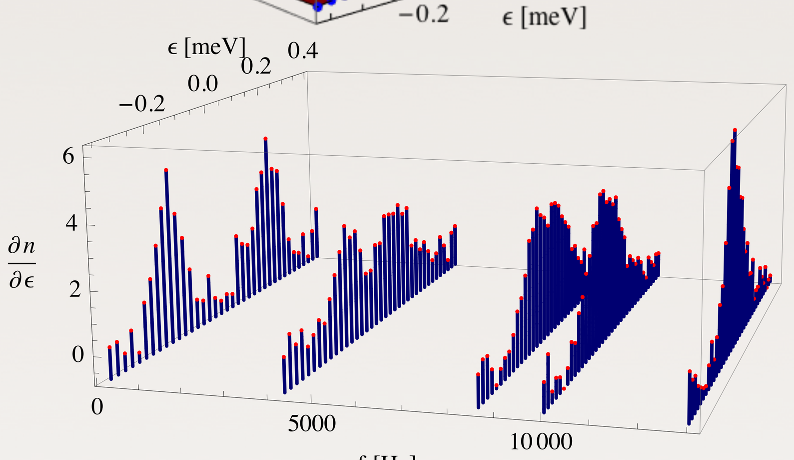
Experimental results

Results for toggling amplitude $\delta\epsilon \approx 0.53$ meV:

Time-averaged dot localization: $\bar{n}(\bar{\epsilon}, f)$

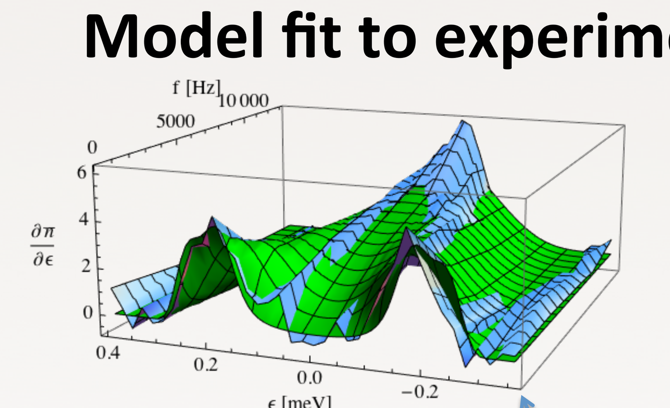


Time-averaged differential dot localization: $\partial\bar{n}(\bar{\epsilon}, f)/\partial\bar{\epsilon}$

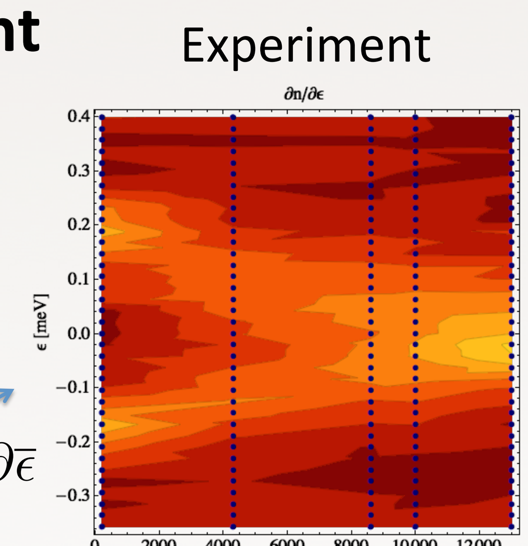


Notice: merging of peaks as frequency f increased

Model fit to experiment

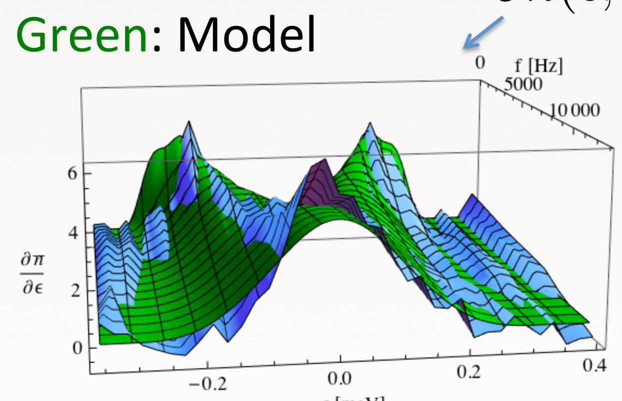


Experiment

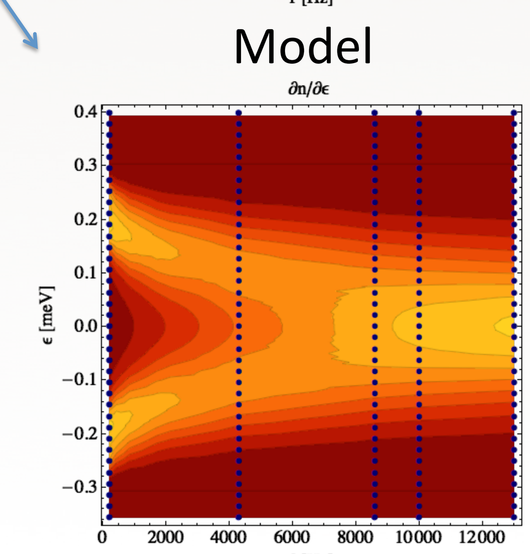


Blue: Experiment
Green: Model

$\partial\bar{n}(\bar{\epsilon}, f)/\partial\bar{\epsilon}$



Model



Fitting with:
$\Gamma_r(\Omega) = \gamma(\hbar\Omega)^3$
$\gamma \approx 3 \times 10^6$ meV^{-3}s^{-1}

Distinguishing adiabaticity from relaxation?

Experimental prescription:

- Adjust square wave frequency f so that only a single peak appears in differential measurement
- While obeying constraint that square wave is sufficiently square, increase rise time τ. If peak splits in two, this suggests adiabaticity has driven system into ground state

Condition to be adiabatic[3-5]: $2\hbar\delta\epsilon/\pi\Delta^2 \ll \tau$

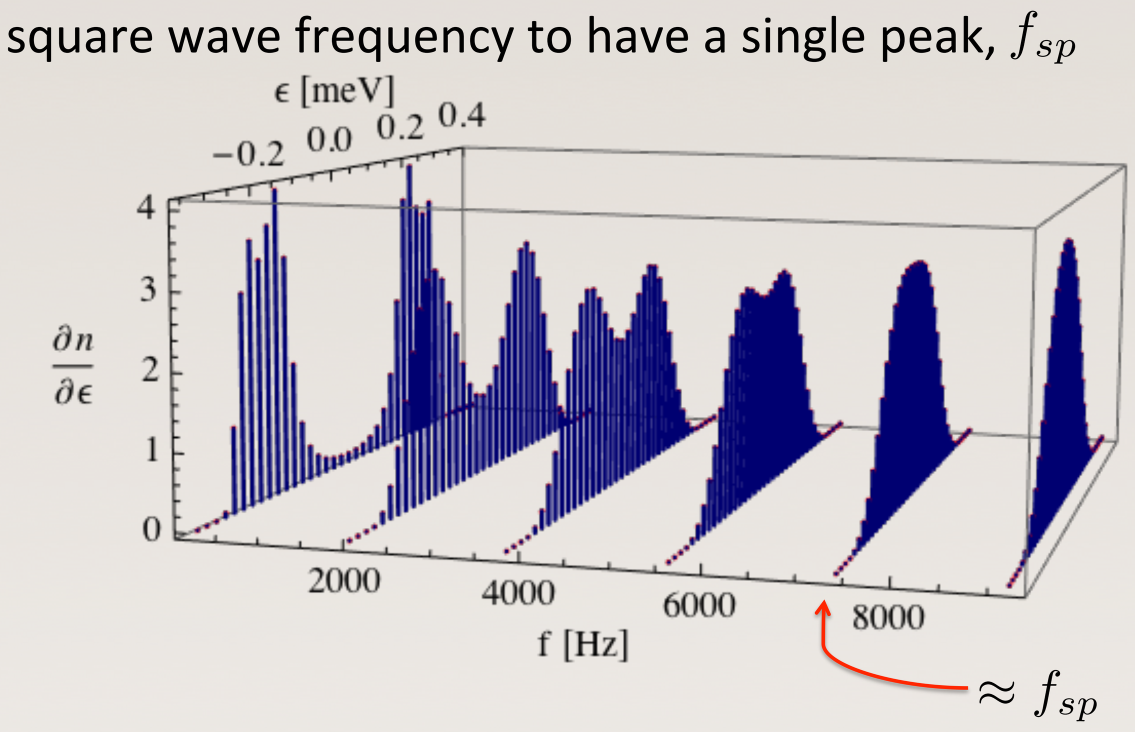
Squareness of control signal: $\tau \ll \Delta t$

$\Longrightarrow$ Necessary condition for both: $\delta\epsilon \ll \pi\Delta^2/4\hbar f$

where $f = (2\Delta t)^{-1}$

Note: Criterion for single/double peak: sign of $\partial^3\bar{n}/\partial\bar{\epsilon}^3|_{\bar{\epsilon}=0}$

Easiest to satisfy both conditions at the minimum square wave frequency to have a single peak, f_{sp}



Experimental resource required: High measurement resolution with respect to bias voltage, ϵ

Discussion and future directions

Observations

- Experimental data are consistent with a gap-dependent relaxation rate
- Gap-dependence for relaxation is compatible with spin-boson model for a bath of acoustic deformation phonons
- We've constructed a test for distinguishing whether the ground state is populated due to adiabaticity or simply relaxation

To do

- With more experimental data, continue refining fit and check for agreement with microscopic derivation of system-bath coupling (agreement with known material parameters, etc.)
- Implement adiabaticity test in lab
- Obvious next step: do similar analysis for a pair of DQDs, simple two-qubit AQC problem

References

[1] Leggett, et al. Rev. Mod. Phys. **59**, 1 (1987)
[2] Fedichkin & Fedorov, IEEE Trans. Nano. **4**, 65 (2005)
[3] L.D. Landau, Phys. Z. Sow. **2**, 46 (1932)
[4] C. Zener, Proc. R. Soc. A **137**, 696 (1932)
[5] E. Majorana, Nuovo Cimento **9**, 43 (1932)

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