Controlling dissipation and decoherence in nanodevices

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Themes

- Connection between dissipation and decoherence
- Role of localization
- Control of coupling to the bath
- Example of nuclear spin relaxation in quantum dot
- Role of symmetry
- Critical issues
Mechanisms of dissipation

1. DC signal
2. AC excitation

   1. Resonant
   2. Relaxation

Energy levels oscillate with frequency
Population follows Non-equilibrium distribution
Its relaxation gives absorption
Connection between dissipation and decoherence

1. DC Transport, weak localization

\[ \frac{\delta \rho}{\rho} = \ln \frac{\tau_\phi}{\tau} \]

Role of localization

2D conductor: insulator if no decoherence (P. Anderson)
Finite decoherence gives conductivity, i.e. dissipation.
Connection between dissipation and decoherence

2. AC absorption

\[ E_1 \quad \uparrow \quad \hbar \omega \quad \downarrow \quad E_2 \]

Rabi oscillations, if no decoherence

Decoherence (relaxation) needed even in “resonant” case
Nuclear spin relaxation in Quantum Dots

- Transitions in discrete spectrum
- Beating energy mismatch
- Energy-conserving transitions
- Tunneling on and off the dot
- Coulomb blockade
- Role of spin-orbit interactions
- Relaxation mechanism

(YLG, Aleiner, Altshuler, 2003)
Creating and sustaining nuclear spin polarization in QD

- Quickly polarize nuclear spins (Overhauser effect)
- Sustain long-lived polarization
Quantum dots

1. Discrete spectrum: artificial atoms

2. Connection to leads

3. Electronic interactions: Coulomb blockade

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Coulomb blockade

Electrostatic energy of the dot

\[ H = E_c \ (n - N)^2 \]

\[ N = CV_g / e \]

\[ E_c = \frac{e^2}{2C} \]

Charging effect on tunneling rate

Maximum: \( N - \) half integer

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Nuclear spin relaxation

1. Dipole–dipole nuclear interaction

\[ H = \overrightarrow{S_1} \cdot \overrightarrow{R} \overrightarrow{S_2} \cdot \overrightarrow{R} - \overrightarrow{R}^2 / 3 \]

Inhomogeneous magnetic field (external B + electrons)

2. Hyperfine interaction of electron and nuclear spins

\[ H = A \overrightarrow{S} \cdot \overrightarrow{\sigma} \]

Contact interaction
Korringa mechanism of nuclear spin relaxation

Hyperfine interaction

\[ V = \sum_i A \bar{s} \bar{I} \delta(r - R_i) \]

\[ W_{\bar{s}, \bar{k}, \bar{I}; \bar{s}', \bar{k}', \bar{I}'} = \frac{2\pi}{\hbar} \left| V_{\bar{s}, \bar{k}, \bar{I}; \bar{s}', \bar{k}', \bar{I}'} \right|^2 \delta(E_{\bar{s}, \bar{k}, \bar{I}} - E_{\bar{s}', \bar{k}', \bar{I}'}) \]

Kinetic energy reservoir

\[ E_{\bar{k}} \]

Bulk metal

\[ E_F \]

\[ W \propto T \text{ – creation of electron-hole pair} \]
Nuclear spin relaxation in QD

Beating energy mismatch by contacts with continuum spectrum
Nuclear Relaxation Rate in QD
Nuclear spin relaxation in QD
Coulomb blockade valley: third order

\[ M_{ll} = \frac{V_{l1} A_{12} V_{2r}}{(E_N - E_{N+1})(E_1 - E_2)} \]

Weak spin–orbit

Contact

Dot

Contact
Applicability of perturbative approach

**Strong spin–orbit:**

Peak

- Not applicable
- Derivation and solution of kinetic (master) equation
- Non-equilibrium Keldysh GF

![Diagram showing nuclei, electrons, a dot, and contact with tunneling label.](Image)
Qualitative Picture, Strong Spin-orbit

Nuclei

Electrons

Peak

\[ \Omega = A \sigma_{11} \]

\[ \Phi = \frac{\Omega}{\Gamma} \]

\[ \langle \Phi^2 \rangle = \left( \frac{\Omega}{\Gamma} \right)^2 \Gamma \]

\[ \frac{1}{T_1} = \frac{\Omega^2}{\Gamma} \]
Estimates

I: 0.25 Hz
II: $2 \times 10^{-3}$ Hz
III: $1.6 \times 10^3$ Hz
IV: $4 \times 10^{-4}$ Hz
V: $4 \times 10^{-6}$ Hz

Parameters:
$A = 43 \, \mu \text{eV (As)}$
$E_c = 0.5 \, \text{meV}$
$a = 0.1 \, \mu \text{m}$
$w = 50 \, \text{A}$
Transition from zero to weak spin-orbit interactions

\[ \lambda/L < \left( \frac{E_c}{\Gamma_t} \right)^{2/3} \left( \frac{E_T}{T} \right)^{1/6} \]

Condition for valley maximum

\[ \lambda = \text{is the spin-orbit length,} \]

Spin-orbit interaction

\[ H_{so} = (\sigma_x p_y - \sigma_y p_x)/m \lambda \]

\[ \gamma_{so} \approx g^4 \Delta, \quad g \text{ is the dot conductance} \]

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Critical Issues

• Control of coupling to the bath
• Role of correlations in the bath
• Localization in (Fock) state space

• Localization problems for various many-body interactions.
Role of Localization in Fock space

Lifetime in many-electron QD (Altshuler, Gefen, Kamenev, Levitov)

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