Adiabatic Passage and Noise in Quantum Dots

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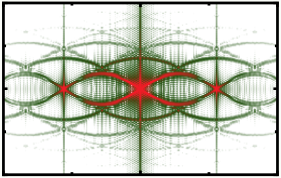
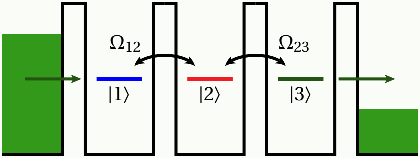


1. **Steady-state transfer passage by adiabatic passage**
   - shot noise as signal

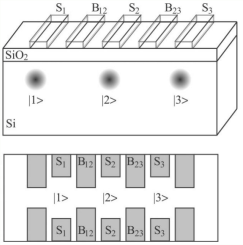
2. **Landau-Zener-(Stückelberg-Majorana) interferometry**
   - background fluctuations probed via transport

Steady-state coherent transfer by adiabatic passage



Huneke, Platero, SK, PRL **110**, 036802 (2013)

What is "coherent transfer by adiabatic passage" (CTAP)?

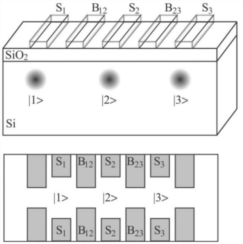


- electron transfer
  from dot 1 to dot 3
  without occupying dot 2

  Greentree *et al.*, PRB 2004

- cf. STIRAP (stimulated
  Raman adiabatic passage)

What is “coherent transfer by adiabatic passage” (CTAP)?



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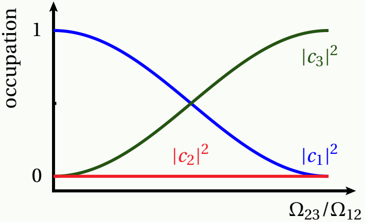
- cf. STIRAP (stimulated Raman adiabatic passage)

Hamiltonian

$$H = \begin{pmatrix} 0 & \Omega_{12} & 0 \\ \Omega_{12} & 0 & \Omega_{23} \\ 0 & \Omega_{23} & 0 \end{pmatrix}; \quad \varphi_0 \sim \begin{pmatrix} \Omega_{23} \\ 0 \\ -\Omega_{12} \end{pmatrix}$$

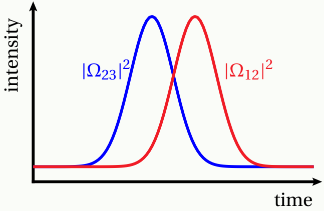
eigenvector with $E = 0$:



➔ adiabatic switching $\Omega_{ij}(t)$

$$H(t) = \begin{pmatrix} 0 & \Omega_{12}(t) & 0 \\ \Omega_{12}(t) & 0 & \Omega_{23}(t) \\ 0 & \Omega_{23}(t) & 0 \end{pmatrix}$$

Gauss pulse:



- dephasing by phonons
  ➔ small occupation of dot 2
  Greentree *et al.*, PRB 2004
- charge monitor increases dephasing
  Rech & Kehrein, PRL 2011

problem: experimental evidence for non-occupation (Zeno effect!)

CTAP — dephasing

$$H(t) = \begin{pmatrix} 0 & \Omega_{12}(t) & 0 \\ \Omega_{12}(t) & 0 & \Omega_{23}(t) \\ 0 & \Omega_{23}(t) & 0 \end{pmatrix}$$

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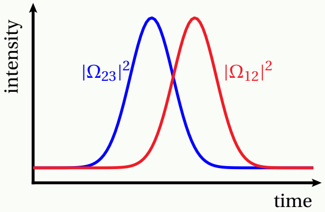

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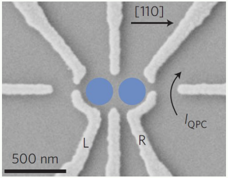

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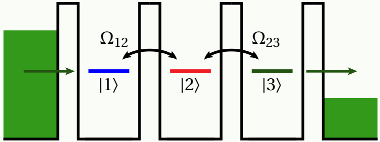
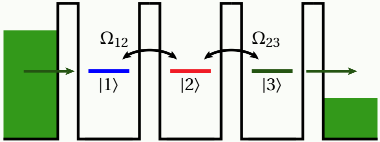
Steady-state CTAP



- leads
- → current
- → steady-state transport

Steady-state CTAP



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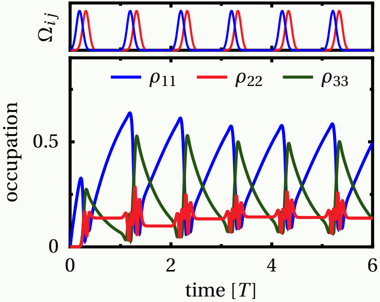

- time evolution (propagation of ρ)
- ➔ direct transition $|1\rangle \longrightarrow |3\rangle$
- ➔ ideally: 1 electron per pulse

? fingerprint: shot noise suppression

- master equation approach:
  - perturbation theory for weak wire-lead coupling Γ
  - master equation for reduced density operator:
    (Bloch-Redfield equation, consistent with equilibrium conditions)

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{\mathrm{wire}} = \frac{\mathrm{d}}{\mathrm{d}t}\mathrm{tr}_{\mathrm{leads}}\,\rho$$

- master equation approach:
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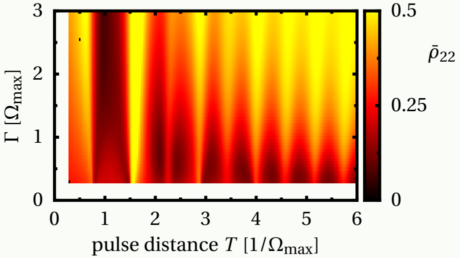
$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{\mathrm{wire}} = \frac{\mathrm{d}}{\mathrm{d}t}\mathrm{tr}_{\mathrm{leads}}\rho, \quad I \sim \frac{\mathrm{d}}{\mathrm{d}t}\mathrm{tr}_{\mathrm{leads}} N_L \rho, \quad S \sim \frac{\mathrm{d}}{\mathrm{d}t}\mathrm{tr}_{\mathrm{leads}} N_L^2 \rho$$

➔ Fano factor: Elattari & Gurvitz, Phys. Lett. (2002); Bagrets & Nazarov, PRB (2003); Novotný, Donarini, Flindt & Jauho, PRL (2004); Kaiser & SK, Ann. Phys. (2007)

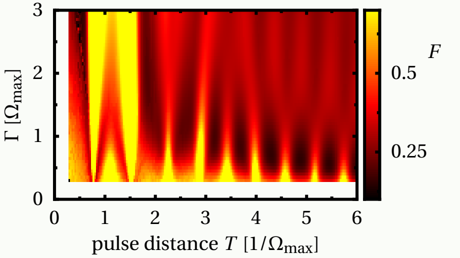
➔ iterative calculation of FCS by numerical propagation

➔ more efficient than N-resolved master equation



average occupation of dot 2

- $\rho_{22} \ll 1/3$ if
  - pulse distance $\Delta T \gtrsim 2T$
  - tunnel rate $\Gamma \approx \frac{1}{2}\Omega_{\mathrm{max}}$

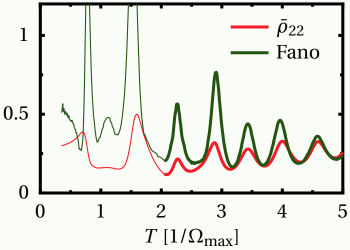


Fano factor

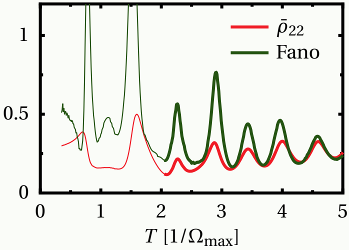
- shot noise suppression correlates with low Fano factor

➔ Fano factor as fingerprint of CTAP

Steady-state CTAP — quantitative analysis



- for small occupation: Fano factor $F \approx 0.2$ (elsewise $F \approx 0.5$)



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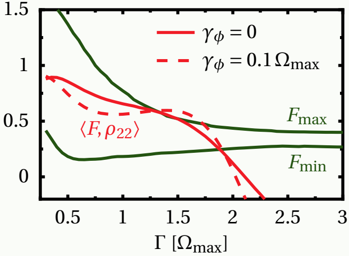
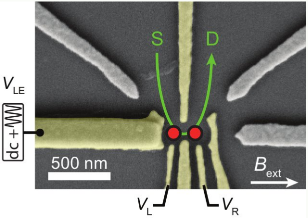


- CTAP not visible in current
- correlation $\langle F, \bar{\rho}_{22} \rangle$
- moderate dephasing γ_ϕ tolerable
- ideally: $\Gamma \approx \Omega_{max}/2$

➔ „noise is the signal“ (Landauer)

ICMM

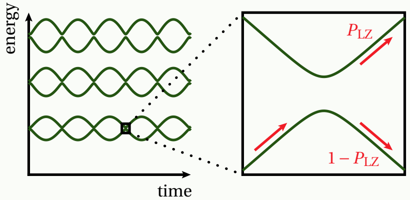
Landau-Zener-Stückelberg-Majorana Interferometry with Quantum Dots



Forster, Petersen, Manus, Hänggi, Schuh, Wegscheider, SK, Ludwig

PRL **112**, 116803 (2014)

Quantum system in AC-field, $H(t)$



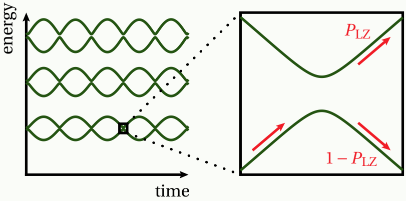
- non-adiabatic transition probability

$$P_{LZ} = e^{-\pi\Delta^2/2\hbar v}$$

Landau, Zener, Stückelberg, Majorana, 1932

AC-driving and Landau-Zener transitions

Quantum system in AC-field, $H(t)$



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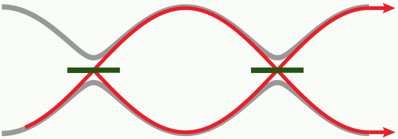
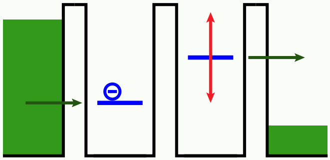
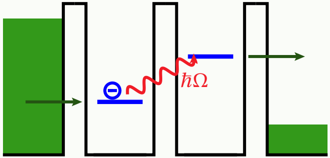


➔ beam splitter, interference

➔ Landau-Zener-(Stückelberg-Majorana) interferometry

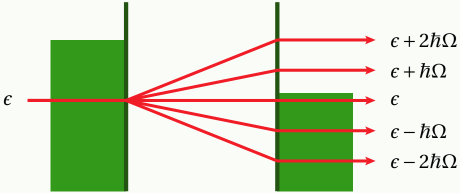


- LZSM interference
  „avoided crossings“



- photon-assisted tunneling
  „dipole excitations“

„Conductance is transmission“ (Landauer, 1957)

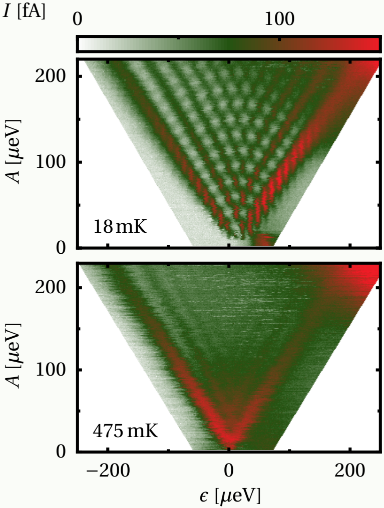


➔ scattering process

➔ with rf-field: resonances

LMU experiment: interference pattern

Experimental LZSM pattern (Ludwig group, LMU Munich)

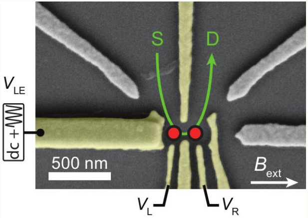


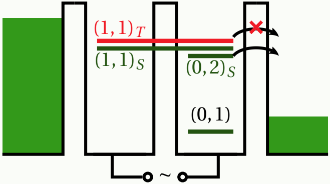
- resonance peaks
- with increasing temperature: pattern blurred

→ phonons

→ pattern contains information about decoherence

LMU experiment: realistic modelling

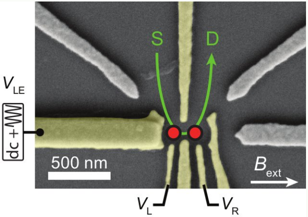


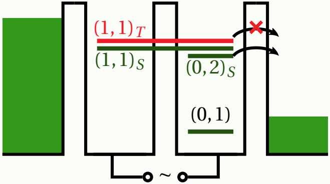


single-particle terms

- ✓ dot-lead tunneling
- ✓ detuning
- ✓ AC gate voltage
  $H_{rf}(t) \propto \cos(\Omega t)$
- ✓ Zeeman splitting

LMU experiment: realistic modelling





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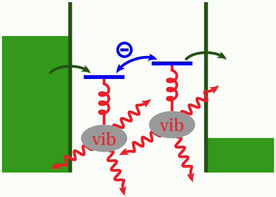
two-particle interaction

- ✗ spin relaxation
  (resolves spin blockade)
- ✗ Coulomb repulsion
- ✗ coupling to phonons
- ➔ master equation for
  many-body states

Decoherence: Caldeira-Leggett model



- $H_{\text{DQD-bath}} = (n_L - n_R)\xi$
- Ohmic spectral density
  $J(\omega) = \frac{\pi}{2}\alpha\omega \exp(-\omega/\omega_{\text{cutoff}})$
  dissipation strength α

Slow fluctuations

- time scale < dwell time
- ϵ Gauss distributed
  $w(\epsilon) \propto \mathrm{e}^{-\frac{1}{2}(\Delta\epsilon/\lambda^*)^2}$

➔ convolution of $I(\epsilon, A)$ with Gauss
inhomogeneous broadening λ^*

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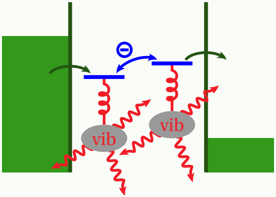

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inhomogeneous broadening λ^*

Central idea

- comparison experiment/theory
  - $I(\epsilon, A)$ ➔ λ^*
  - $W(\tau_\epsilon, \tau_A)$ ➔ α

➔ determine dissipative parameters

Floquet-Bloch-Redfield master equation

Perturbation theory in DQD-environment coupling V

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho = -\frac{\mathrm{i}}{\hbar}\left[H_{\mathrm{DQD}}(t),\rho\right] - \int_0^\infty \mathrm{d}\tau \left\langle [V,[V(t-\tau,t),\rho]] \right\rangle_{\mathrm{env}}$$

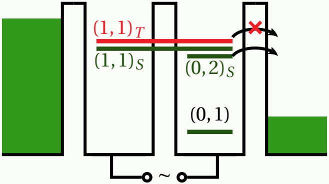
- Floquet theory (Bloch theory in time) ➔ rf-field exact

$$\left(\mathrm{i}\hbar\frac{\partial}{\partial t} - H_{\mathrm{DQD}}(t)\right)\phi_\alpha(t) = \epsilon_n\phi_n(t), \quad \text{mit} \quad \phi_n(t) = \phi_n(t+2\pi/\Omega)$$

- rate equation for occupations

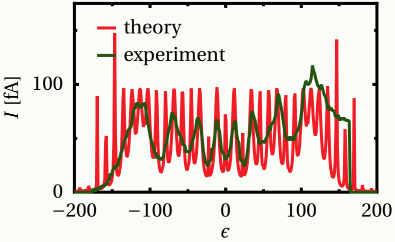
$$\dot{P}_n = \left(W_{n\leftarrow n'}P_{n'} - W_{n'\leftarrow n}P_n\right)$$

$$W = W^{\mathrm{leads}} + W^{\mathrm{spinflip}} + \alpha W^{\mathrm{bath}}$$



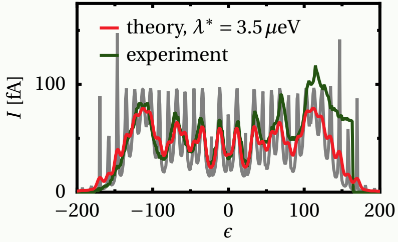
➔ determination of α requires knowledge of W^{leads} and W^{spinflip}

Inhomogeneous broadening



- resonance peaks
  - singlet-triplet mixing
  - inter-dot excitations

Inhomogeneous broadening

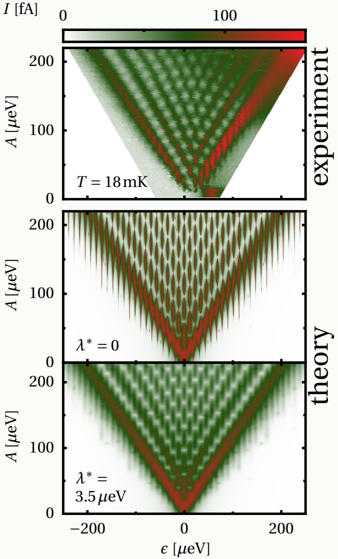


- resonance peaks
  - singlet-triplet mixing
  - inter-dot excitations

➔ $\lambda^* = 3.5\,\mu\text{eV}$

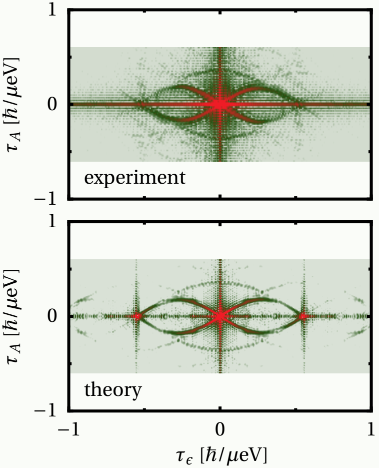
in agreement with e.g.

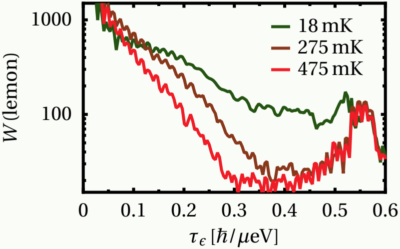
Petersson *et al.* PRB 2010



LZSM pattern in Fourier space: decaying arcs

Rudner *et al.*, PRL 2008

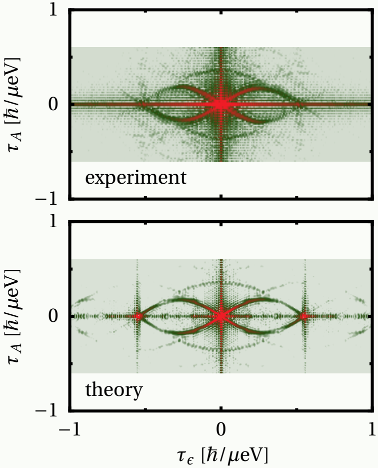


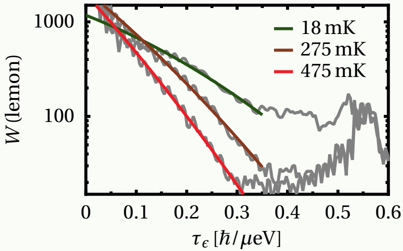


Analysis in Fourier space

LZSM pattern in Fourier space: decaying arcs

Rudner *et al.*, PRL 2008





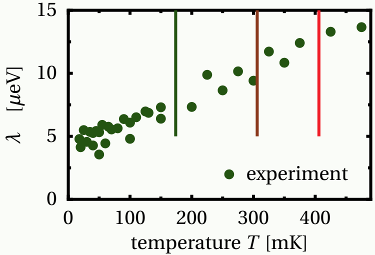
- arc decay

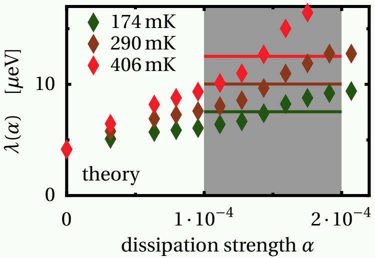
$$f(\tau_\epsilon) \propto \mathrm{e}^{-\lambda\tau_\epsilon - \frac{1}{2}(\lambda^*\tau_\epsilon)^2}$$

→ compare λ_{exp} and λ_{theo}

→ determine α

Temperature dependence

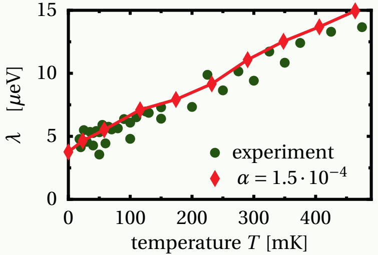




- λ grows with temperature
- fit parameter: dissipation strength

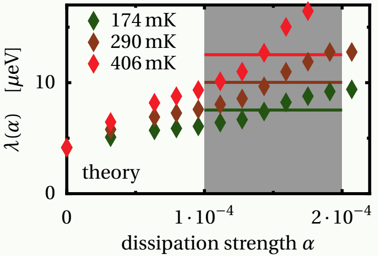
$\alpha = 1.5 \cdot 10^{-4}$ (±30%)

Temperature dependence



- λ grows with temperature

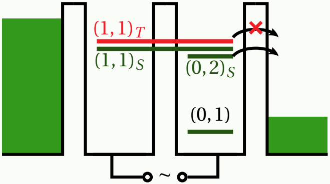
➔ Ohmic dissipation consistent with measured temperature dependence

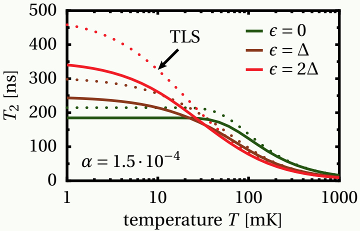


- fit parameter: dissipation strength

$$\boxed{\alpha = 1.5 \cdot 10^{-4}} \ (\pm 30\%)$$

Application: Charge qubit





$(1,1)_S$–$(0,2)_S$ qubit

- for spin-boson model
  Weiss & Wollensak, PRL 1989

$$T_2^{-1} = \frac{\pi \alpha}{\hbar}\left(\frac{2kT\epsilon^2}{E^2} + \frac{\Delta^2}{2E}\coth\left(\frac{E}{2kT}\right)\right),$$

- here: T_2 from full Bloch-Redfield equation

- $\alpha = 1.5 \cdot 10^{-4}$ ➔ $T_2 \sim 200\,\text{ns}$
- $T_2^* = 200\,\text{ps} \ll T_2$

Summary

- **Noise as signal for adiabatic passage**
  - leads allow steady-state operation
  - current noise indicates non-local transport
    ➔ avoids measurement and its backaction
- **Landau-Zener interference to probe noisy environment**
  - temperature dependence consistent with Ohmic dissipation
  - Floquet approach
  - determine bath coupling strength
    (Caldeira-Leggett parameter α)

? propagation method for finite voltage

? charge monitor: controlled decoherence

Thanks to . . .

- Jan Huneke
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- Gunnar Petersen
- Stefan Ludwig (Munich / Berlin)