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Coherent optical control of charge and spin states in quantum dots: phonon-induced dephasing

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Introduction

Quantum dots (QDs) seem to be promising candidates for quantum information storage and processing. These applications require an extremely high level of coherent control over charges and/or spins in QDs. Strong lattice response accompanying optical excitations of carriers is one of the most important obstacles on the way towards achieving the required level of coherence. Here, we present our recent theoretical results on the phonon impact on the optically controlled coherent dynamics of carriers and spins in QDs.

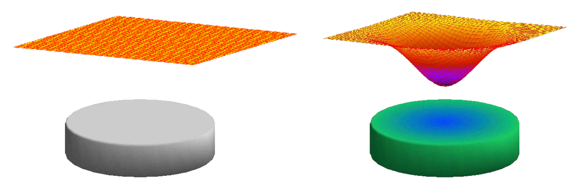
The method: Perturbation theory for an arbitrary evolution

A method to describe the phonon-induced decoherence for arbitrary control sequences, based on the 2nd Born approximation for the evolution of the density matrix.

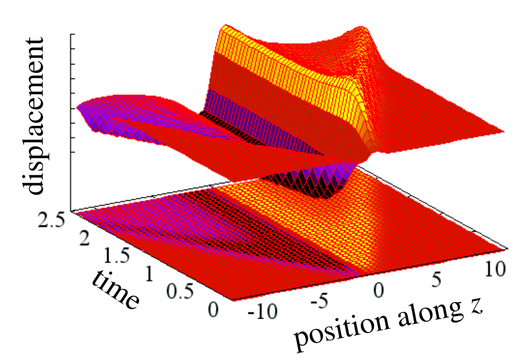
- Perturbative in phonon couplings
- Non-perturbative in driving fields
- Applicable as long as the perturbation is small
- Allowing a transparent spectral interpretation

Lattice response and *which path* information

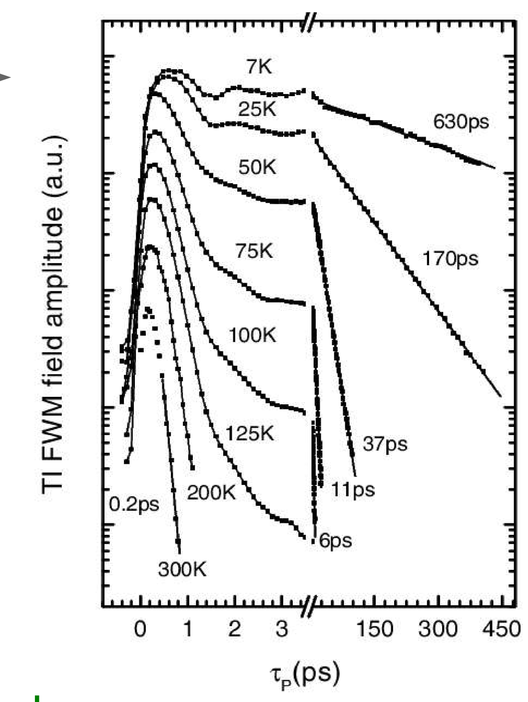
The lattice equilibrium depends on the confined charge distribution



Rapid excitation leads to spontaneous lattice relaxation (exciton dressing)



Experiment: $\varrho_{12} \sim P$ (from Borri *et al.* 2000)



- Decoherence due to LA phonons (Vagov *et al.* 2003)

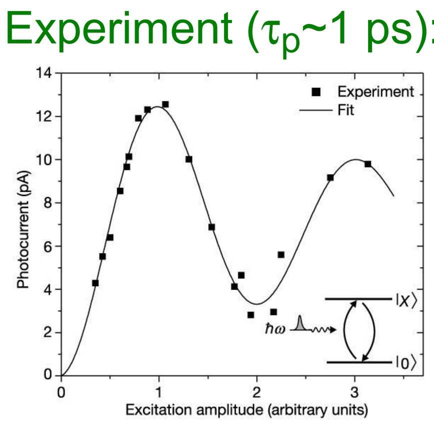
Emitted phonon wavepackets
- trace in the environment
- decoherence

Timescales:
- Optical control < 1 ps
- LO phonons ~100 fs
- LA phonons ~1 ps
- Radiative lifetime ~ 1 ns

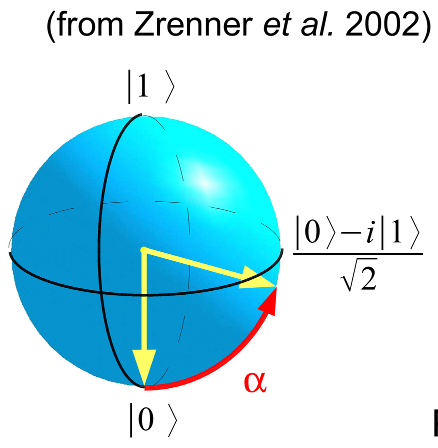
L. Jacak, P. Machnikowski, J. Krasnyj, P. Zoller, Eur. Phys. J. D **22** 319 (2003)

Rabi oscillations of exciton occupation

Experiment (τ_p~1 ps):

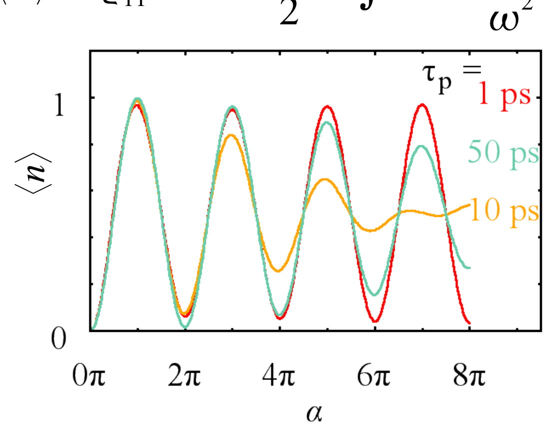


(from Zrenner *et al.* 2002)



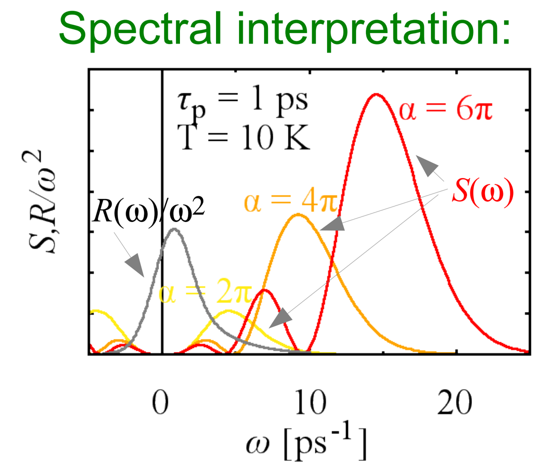
Theory:

$$\langle n \rangle = \varrho_{11} = \sin^2\frac{\alpha}{2} + \int d\omega \frac{R(\omega)}{\omega^2} S(\omega)$$



- Good quality for fast rotation
- Decoherence for τ_p ~ 1 ps
- Improvement for longer pulses
  - Resonant effect

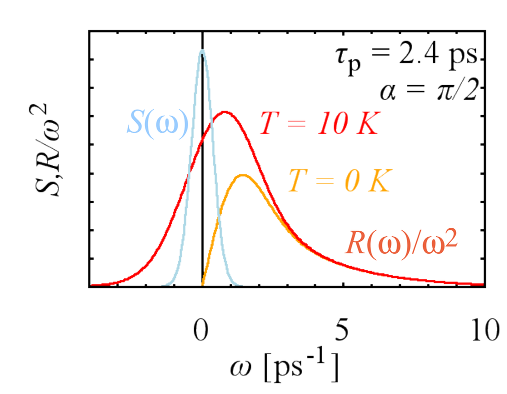
Spectral interpretation:



- $S(\omega) = f(\omega\tau_p)$ – scaling with pulse duration
- Maximum dephasing when spectral features overlap: Rabi frequency equal to phonon frequencies

P. Machnikowski, L. Jacak, Phys. Rev. B **69** 193302 (2004)

Decoherence trade-off



The error (at T = 0, for DP coupling)

$$\delta = \int d\omega \frac{R(\omega)}{\omega^2} S(\omega) \approx \frac{1}{12} R_0 \tau_p^{-2},$$

$$R_0 = \frac{(\sigma_e - \sigma_e)^2}{4\pi^2 \rho c^5}$$

Other decoherence mechanisms (finite lifetime, transitions at T > 0, ...)

$$\delta = \frac{\tau_p}{\tau_0}$$

Optimization:
- Analytical estimate at T = 0 (GaAs):

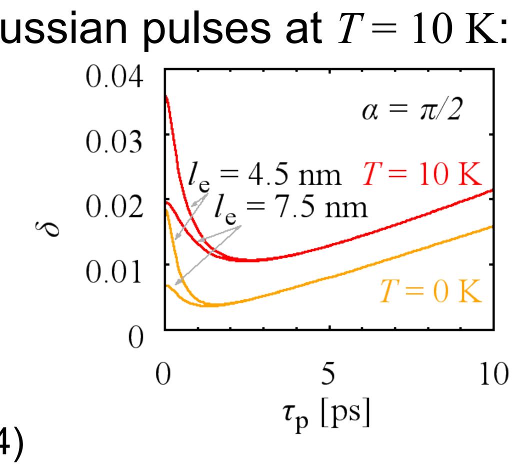
$$\delta_{\min} = \frac{3}{2}\left(\frac{\alpha^2 R_0}{6\tau_0^2}\right)^{1/3} = \alpha^{2/3}\, 0.0035$$

This is above the QEC threshold

$$\tau_{\rm opt} = \left(\frac{1}{6}\alpha^2 R_0 \tau_0\right)^{1/3} = \alpha^{2/3}\, 1.47\,\mathrm{ps}$$

Experimentally accessible

- Numerical results for Gaussian pulses at T = 10 K:

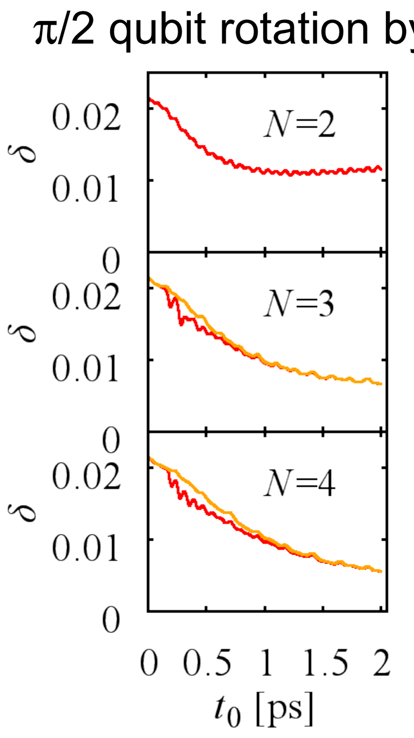


R. Alicki, M. Horodecki, P.Horodecki, R. Horodecki, L. Jacak, P. Machnikowski, Phys. Rev. A **70** 010501 (2004)

Pulse optimization

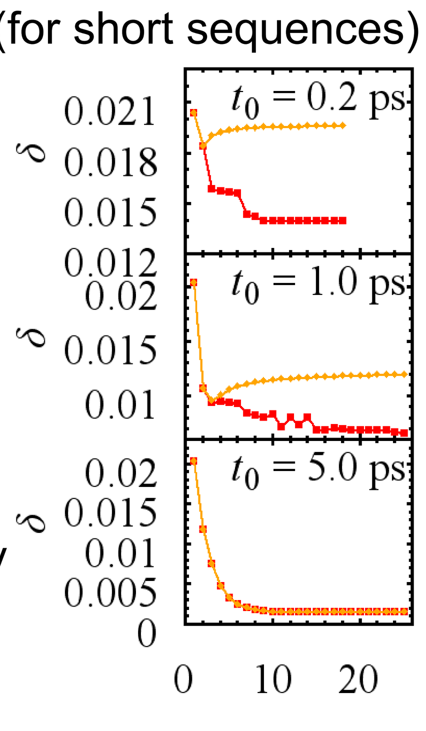
- Is it possible to reduce decoherence by pulse-shaping?
- Is full control over the pulse shapes necessary?

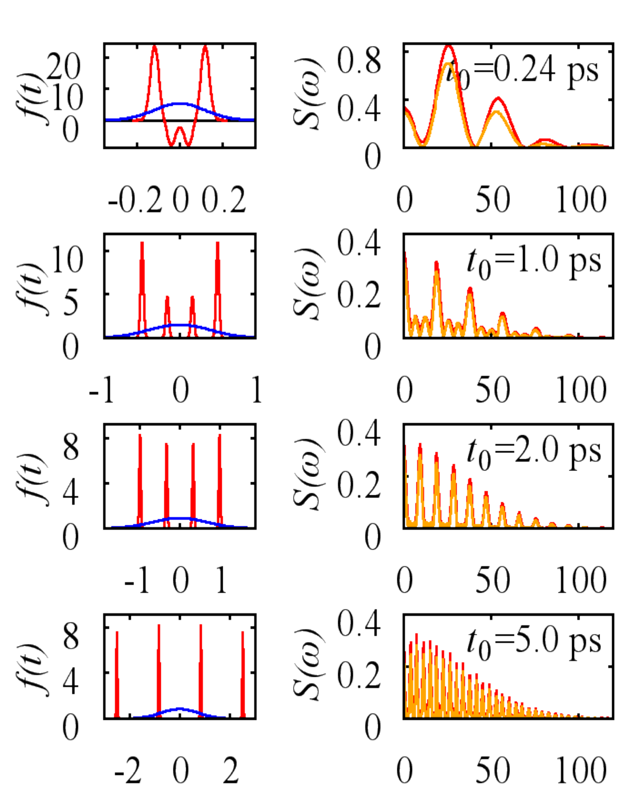
π/2 qubit rotation by series of pulses (identical or optimized):



Most improvement already for a few pulses.

- “Diffraction” pattern
- Pulse broadening ⇛ envelope
- Error lower than for Gaussians (for short sequences)





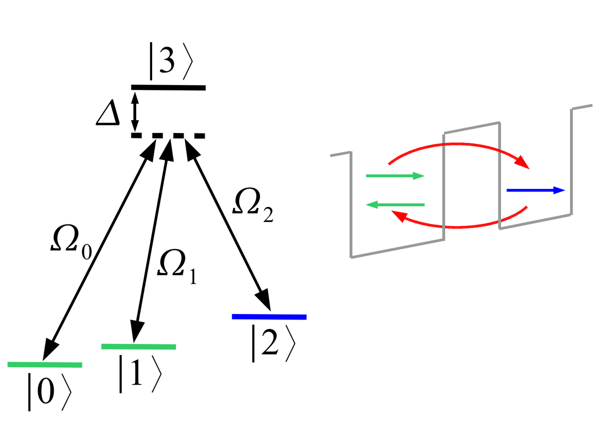
V. M. Axt, P. Machnikowski, T. Kuhn, Phys. Rev. B. **71** 155305 (2005)

Phonon dephasing of a spin-charge qubit

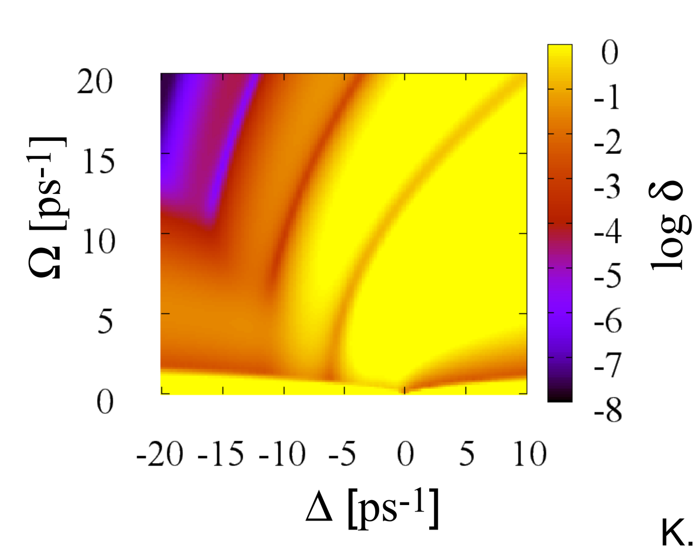
Charge: ultrafast optical control
Spin: ultralong decoherence times.

Use spin for storage and couple to charge for control (Imamoglu *et al.* 1999, Pazy *et al.* 2003).

The stimulated Raman adiabatic passage may be used for an arbitrary spin rotation (Troiani *et al.* 2003).



Charge transfer in real space ⇛ strong lattice response (piezoelectric).



Error sources:
- Nonadiabatic transitions
- Pure dephasing
- Transitions between trapped states

High-fidelity operation possible in narrow parameter areas.

K. Roszak, A. Grodecka, P. Machnikowski, T. Kuhn, Phys. Rev. B **71** 195333 (2005)

Conclusions

- Interactions with phonons lead to trace in the environment and to decoherence.
- The quality of Rabi oscillations improves both for slow and fast evolution.
- The control over a charge qubit is restricted by the trade-off with slow decoherence processes.
- The effect of decoherence may be reduced by pulse shape optimization.
- Spin-charge qubits are subject to strong phonon dephasing during driving but for certain parameters high coherence may be achieved.