Optically controlling quantum dots for quantum computing

Dan Gammon

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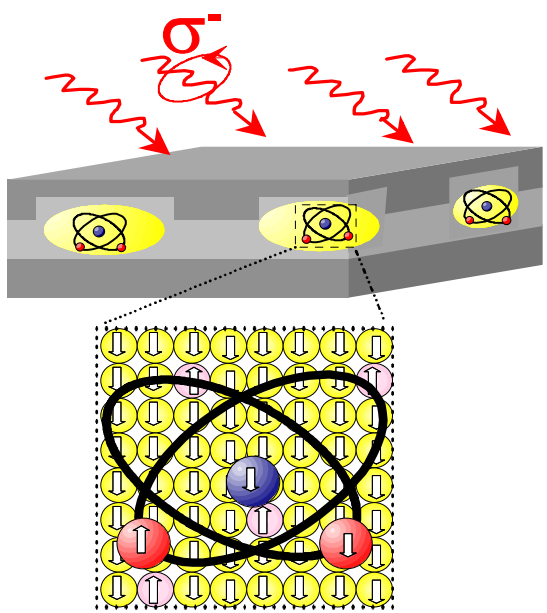
Washington DC



Collaborations

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Igor Merkulov

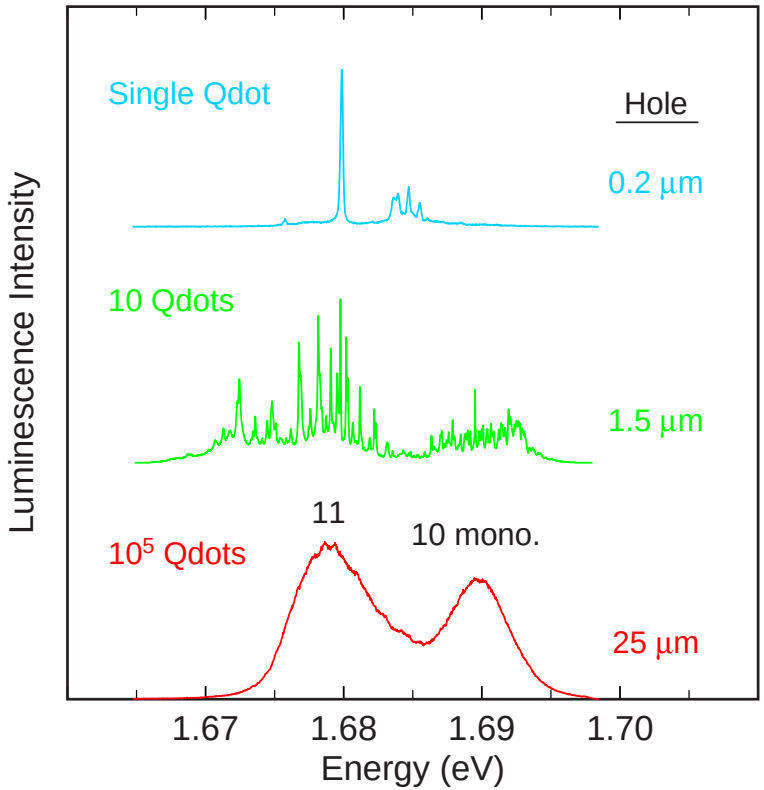
David Gershoni (Technion U.)

Lu Sham (UCSD)

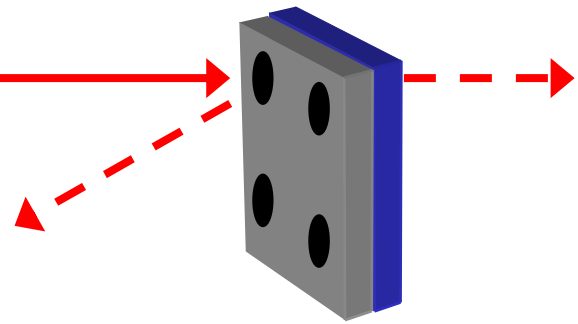
Contents

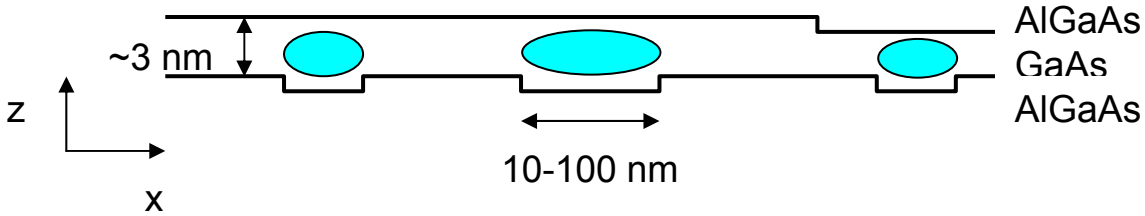
- *Exciton as qubit*
- *Spin as qubit (from the optical point of view)*
- *Hyperfine interactions and nuclear spin*

Single QD Spectroscopy



- *Apertures in Al mask directly on sample*
- *Diameters: 200 nm - 25 um*
- *Backscattering or Transmission*

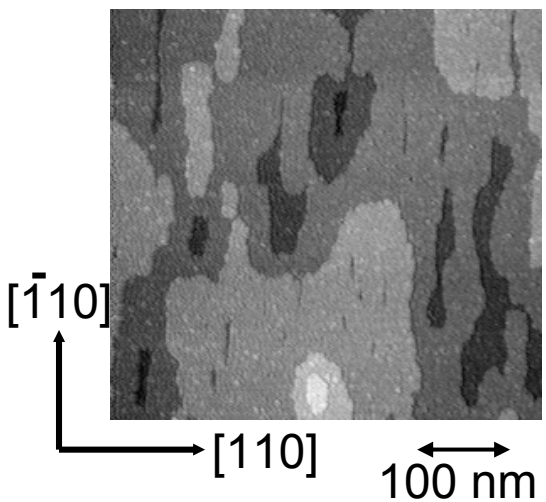


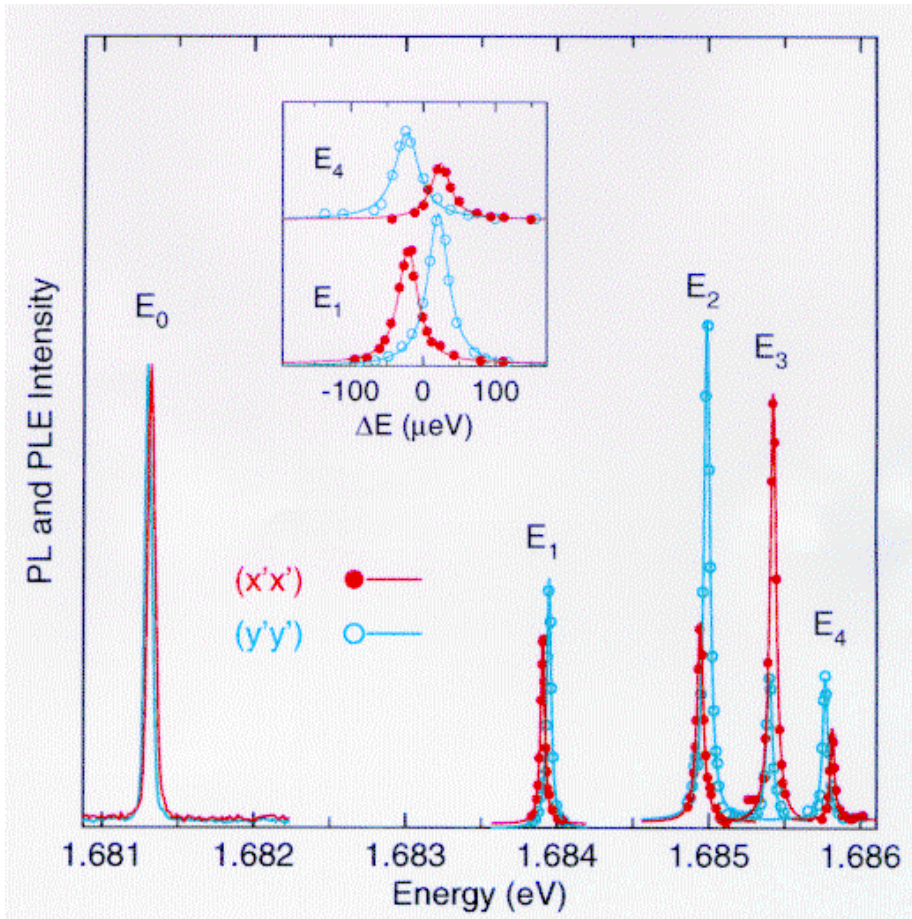


Fine Structure Splittings

- Doublets: Δ = 10 - 100 μeV
  Spin degeneracy
- Linear Polarization
  along [110] axes

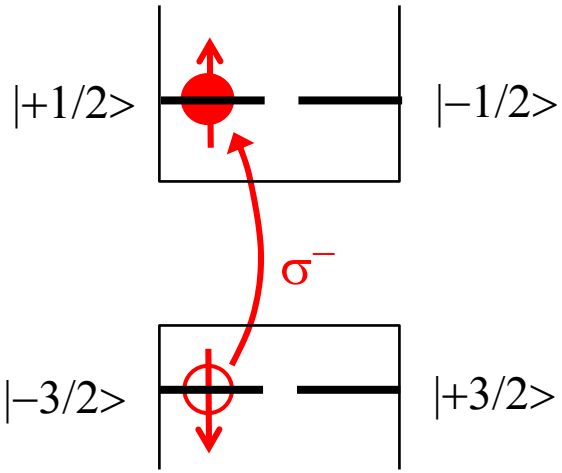
STM of GaAs

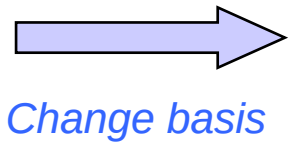




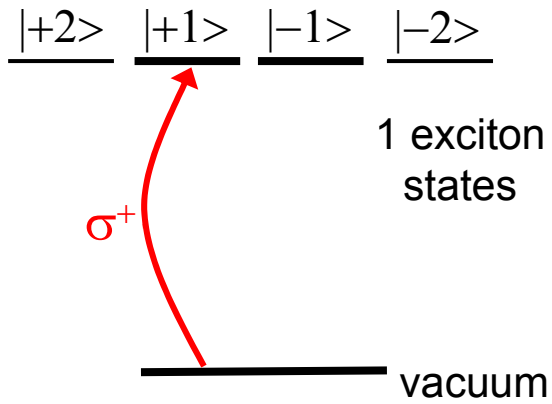
[Gammon, *et al.*, *PRL* **76**, 3005 (1996)]

Exciton Spin Structure



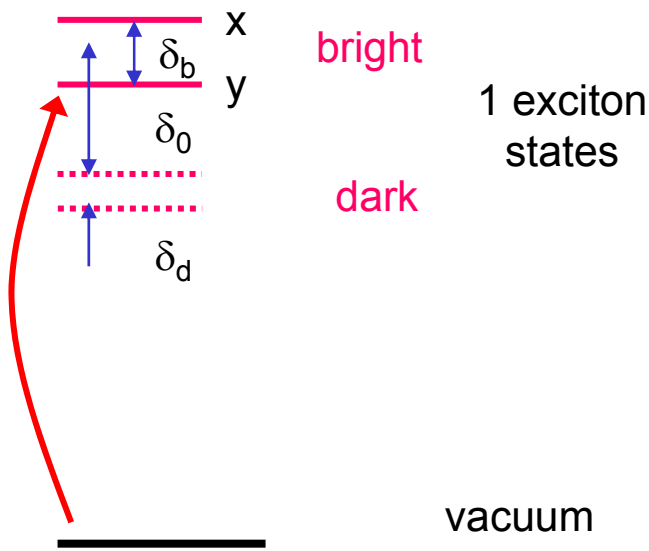


Change basis

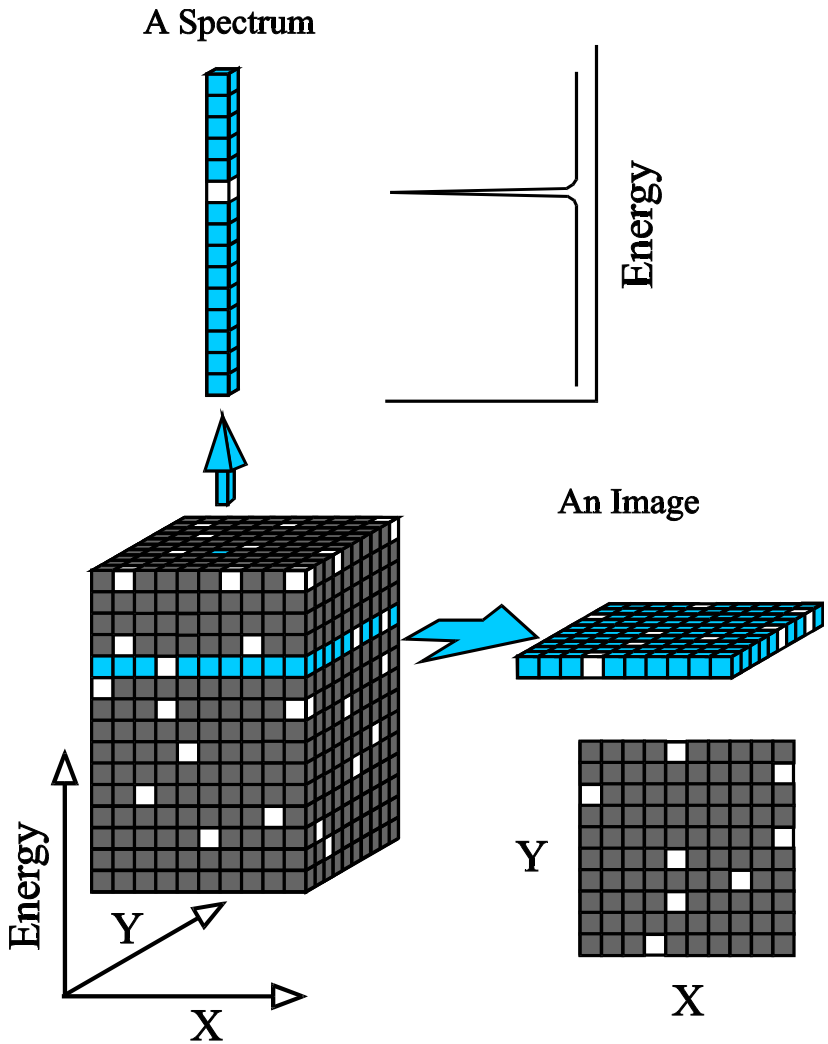


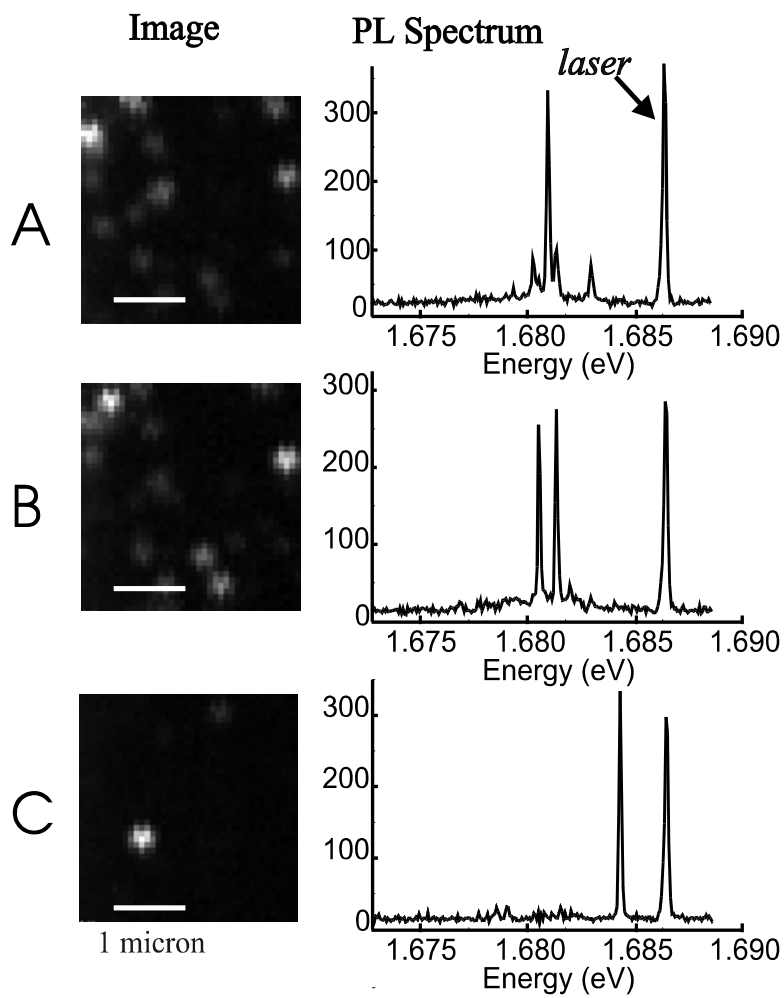
Spin interactions lift the degeneracies:

1. *Exchange*
2. *Zeeman*
3. *Hyperfine*



Spectral and spatial addressing of QDs

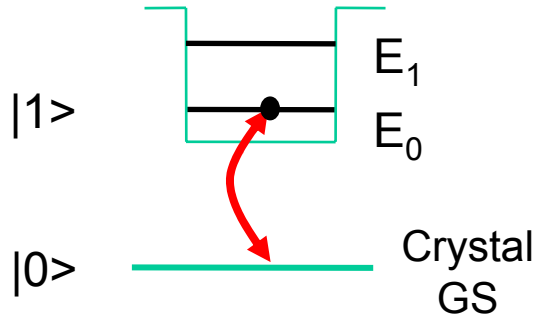




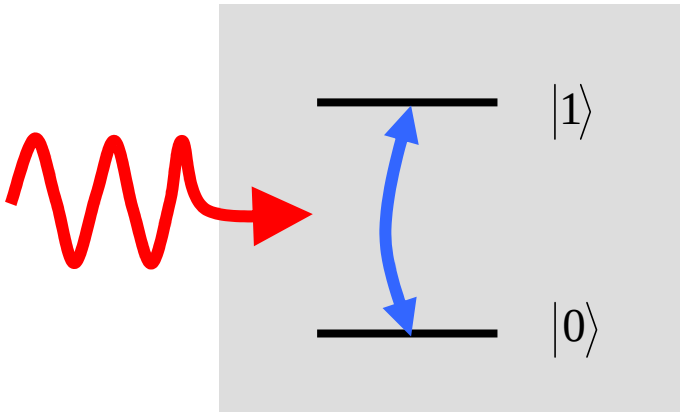
[Qiang Wu, *et al.*, *PRB* 62, 13022 (2000)]

Quantum Computing

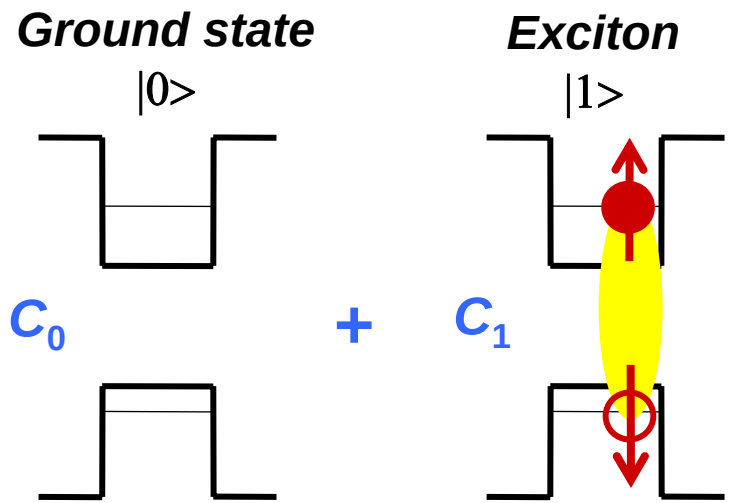
- Quantum bit
- Coherence time
- Probe and control individual qubit
  - initialize
  - “rotate”
  - measure
- Entangle and operate on two qubits
- Scalability



Exciton qubit



$$|\Psi\rangle = c_0|0\rangle + c_1|1\rangle$$



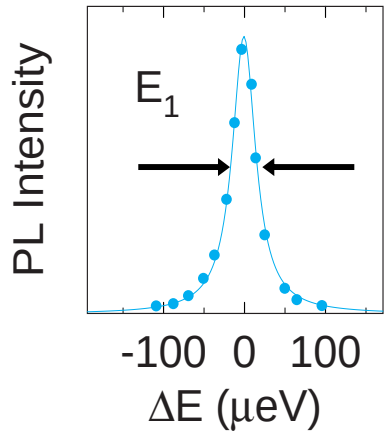
- *Gammon and Steel, Physics Today* **55(10)**, 36 (2002)
- *Xiaoqin Li, et al., Optic & Photonic News* (2004) in press

Linewidths, Dephasing, and Coherence

Homogeneous:

- No inhomogeneous broadening
- Fully resolved (fine structure?)
- No line wandering (spectral diffusion)

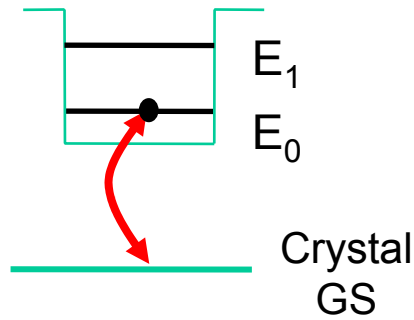
=> Linewidth is determined by coherence time (T_2)



$$\Gamma_{hom} = \frac{1}{T_2} = \frac{1}{2T_1} + \gamma_{dep}$$

Energy relaxation "inelastic"

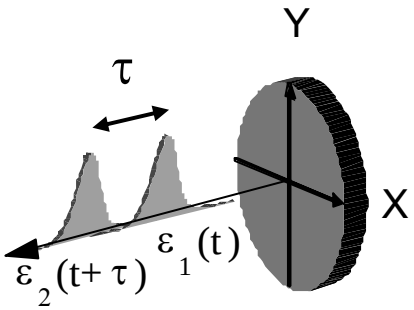
Pure dephasing "elastic"



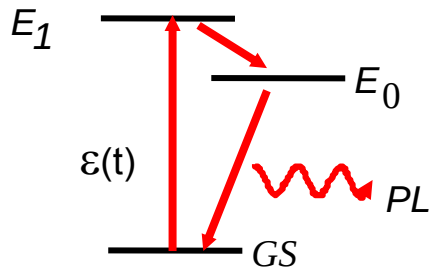
Γ_{hom}~23 μeV <=> T_2~60 ps

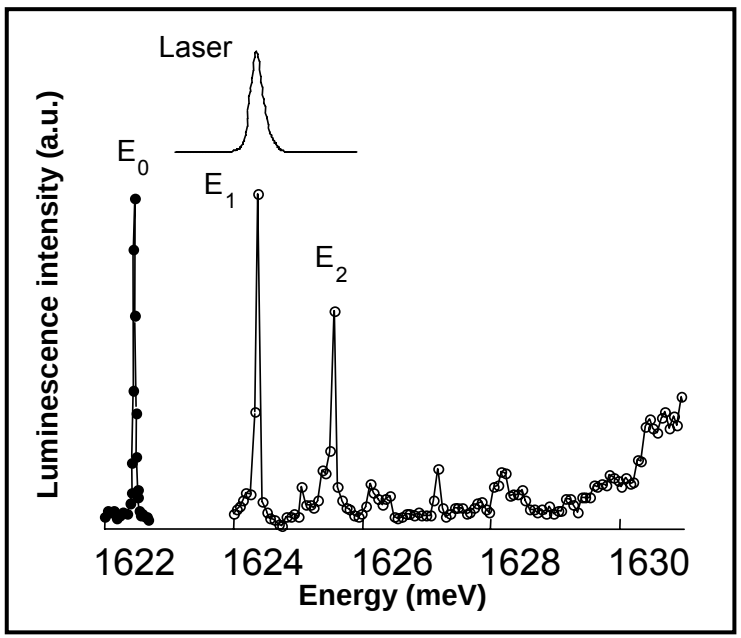
- Gammon, *et al*., *Science* **273**, 87 (1996)
- Bonadeo, *et al*., *PRL* **81**, 2759 (1998)
- Guest *et al* *PRB* **65**, 24131 (2002)

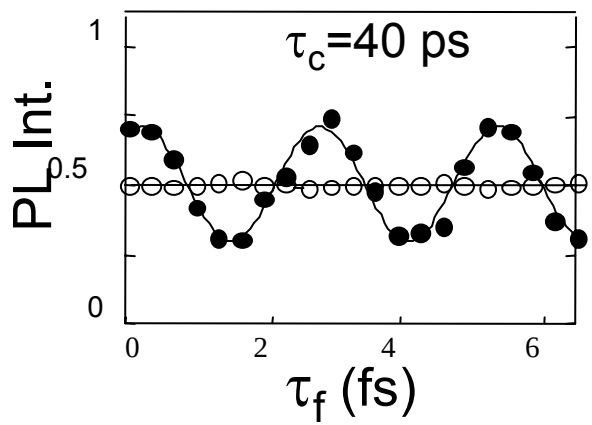
Coherent Control



- Excite QD with pair of coherent pulses (5 ps pulsewidth) as a function of delay (τ)



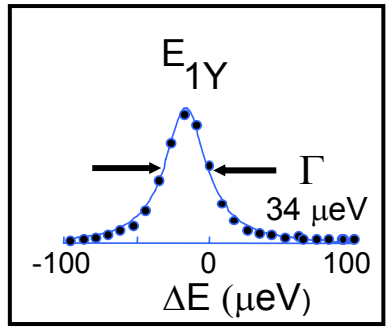


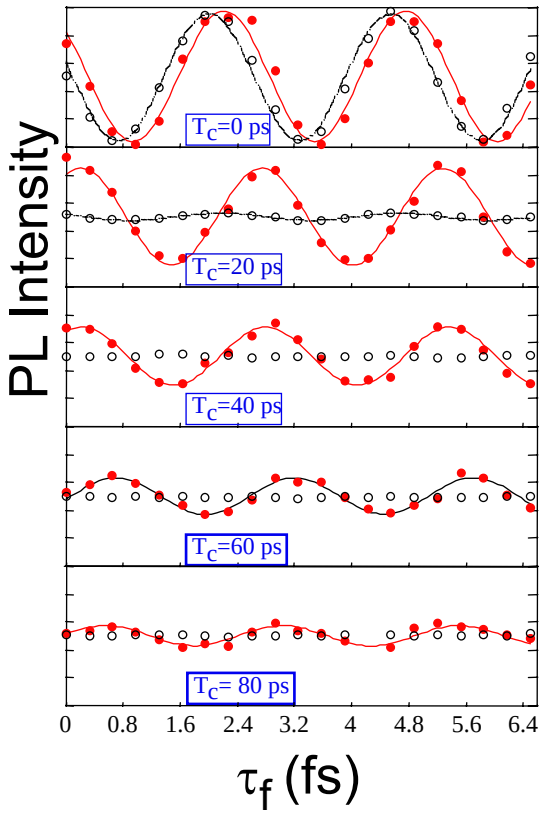


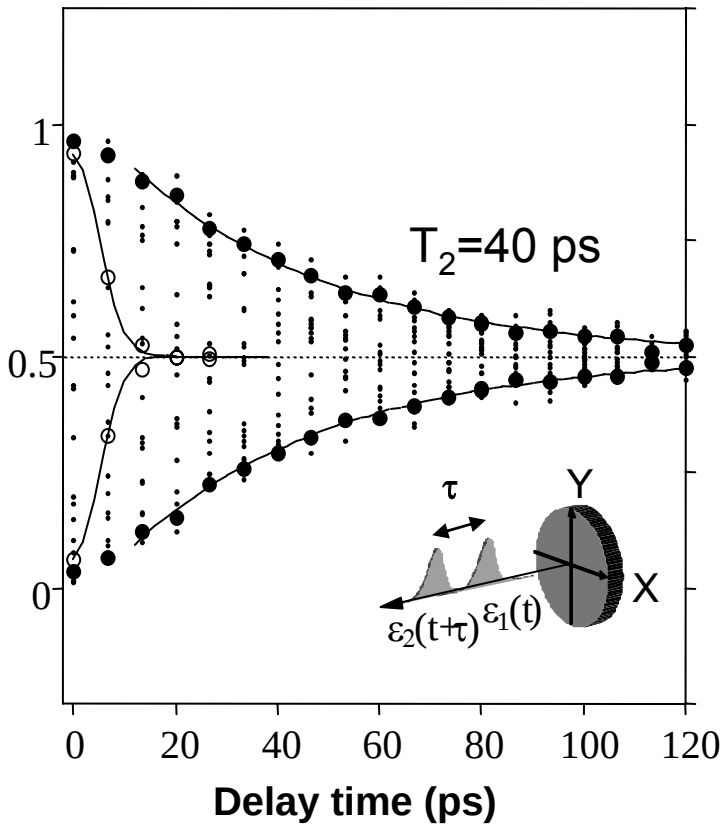
Bonadeo, *et al*., *Science* **282**, 1473 (1998)

Decoherence

- PL oscillations decay because of dephasing

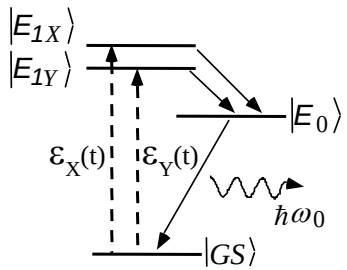


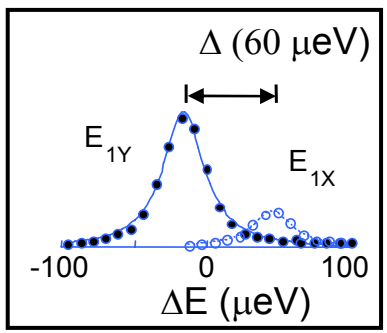


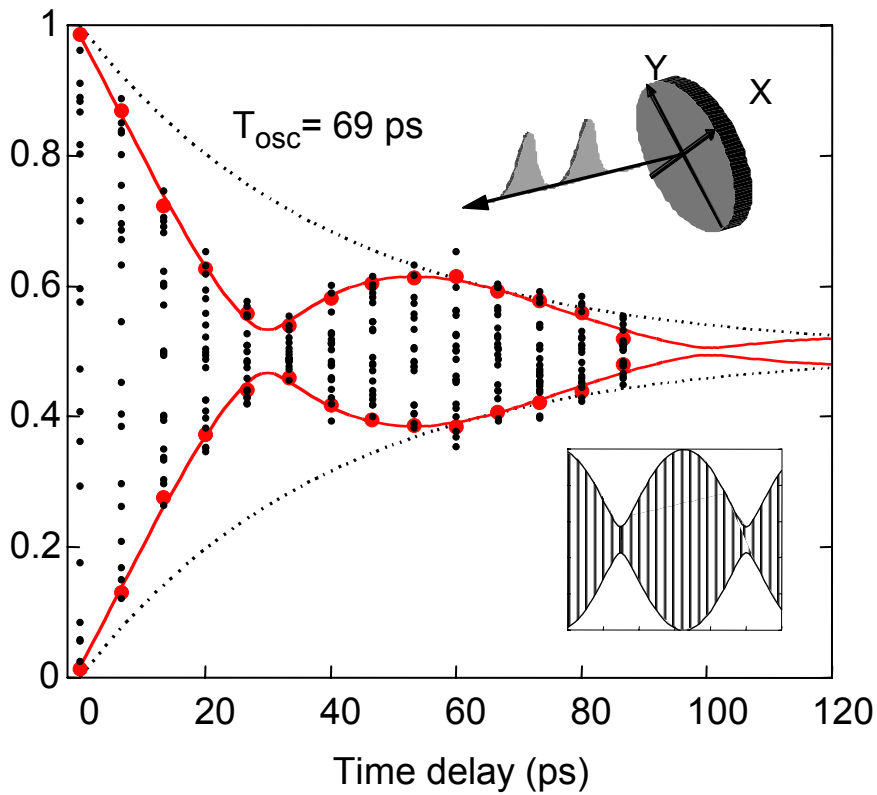


Quantum Superposition of Spin States

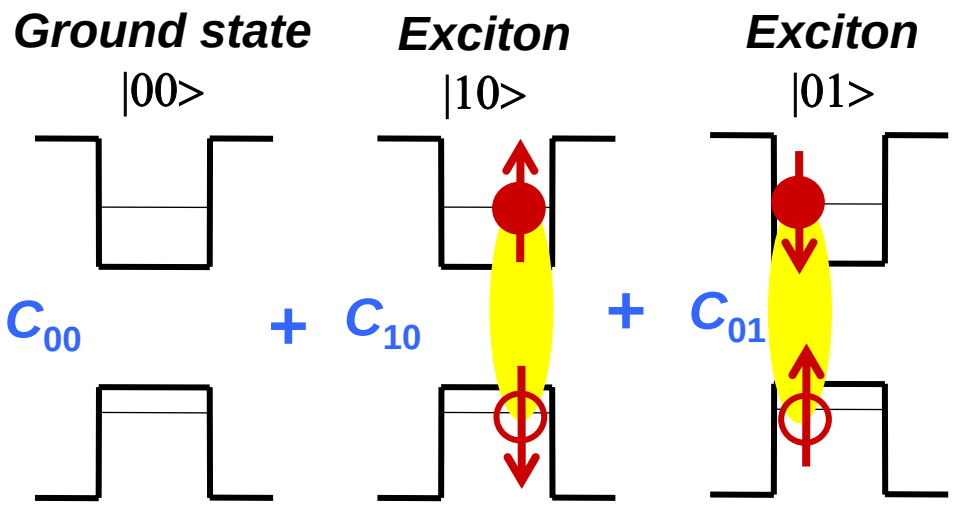
- Rotate polarization to create superposition of x and y states

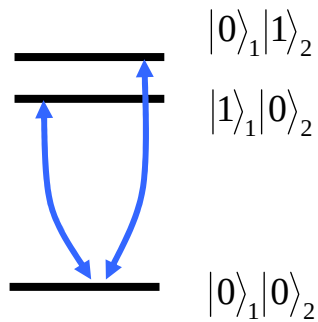






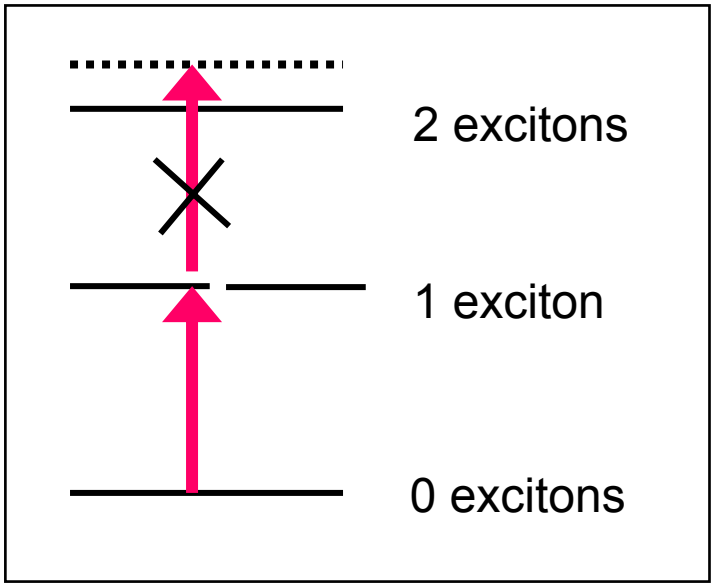
3-level coherence





$$|\Psi\rangle = c_0|0\rangle_1|0\rangle_2 + c_1|1\rangle_1|0\rangle_2 + c_2|0\rangle_1|1\rangle_2$$

Biexciton

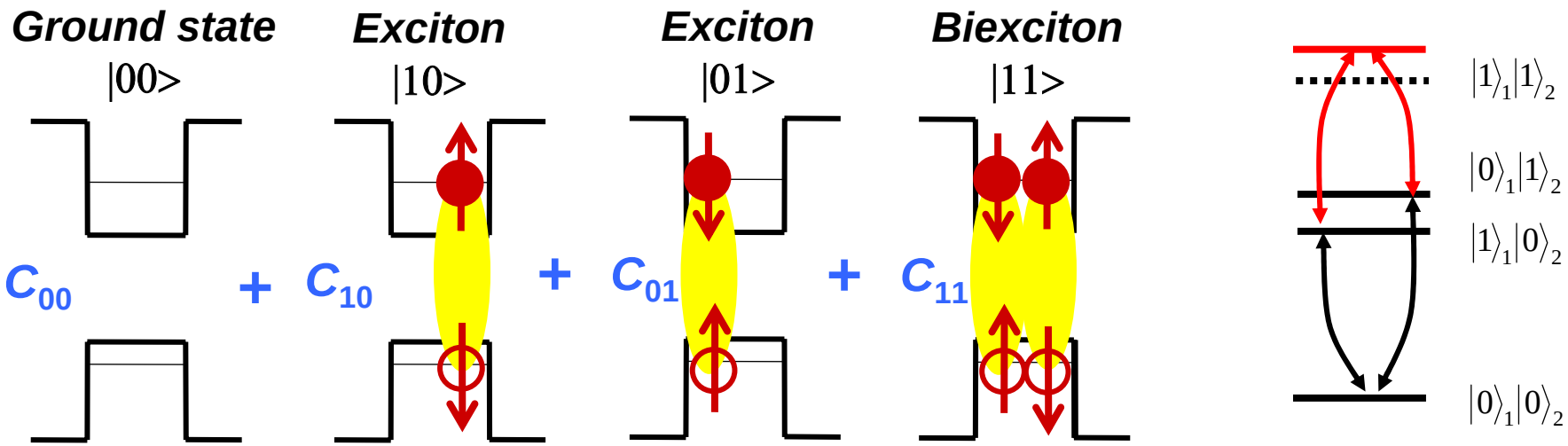


- Biexciton state is shifted down by ~4 meV

  [Brunner *et al*., *PRL* **73**, 1138 (1994)]

  [Gang Chen *et al., PRL* **88**,117901 (2002)]

Biexciton



If no biexciton shift, then no entanglement: the excitons factor!

$$|\Psi\rangle = c_{00}|0\rangle_1|0\rangle_2 + c_{10}|1\rangle_1|0\rangle_2 + c_{01}|0\rangle_1|1\rangle_2 + c_{11}|1\rangle_1|1\rangle_2$$

$$= (c_0|0\rangle_1 + c_1|1\rangle_1)(c_0|0\rangle_2 + c_1|1\rangle_2)$$

For a short discussion along these lines, see; Gammon, et al. Physica E **9**, 99 (2001).

•For a review; Gang Chen et al., Coherence in Semiconductor Q.Wires and QDs, ed. T. Takagahara (Gordon and Breach 2003). Chapter 9

Qubit Rotations

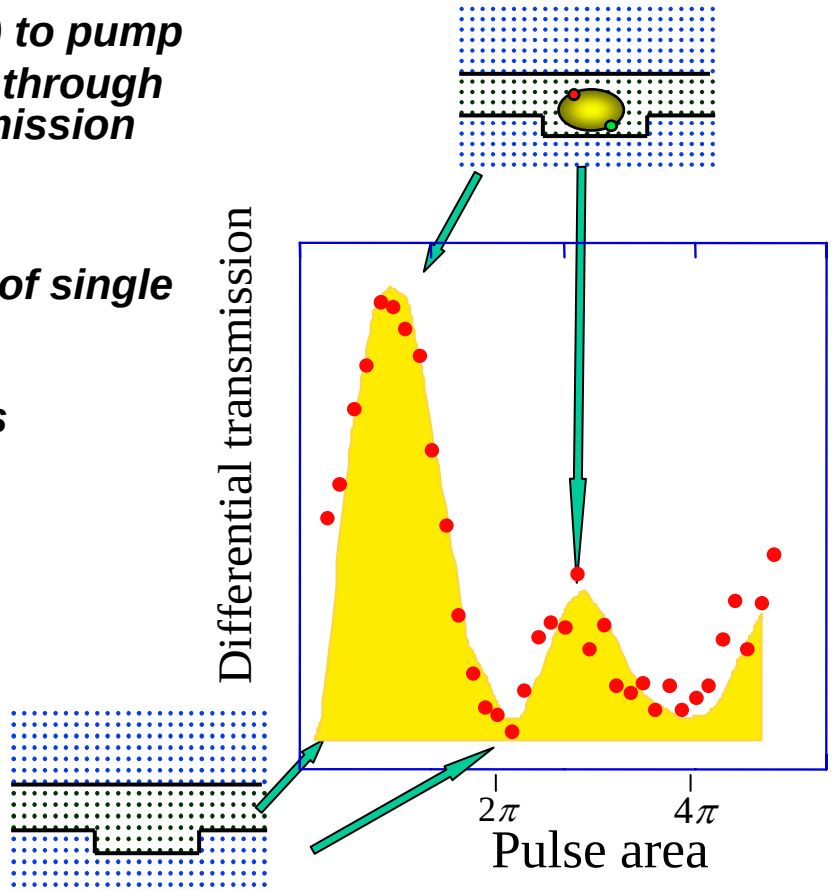
Ground State ⇔ Exciton Rabi Oscillations

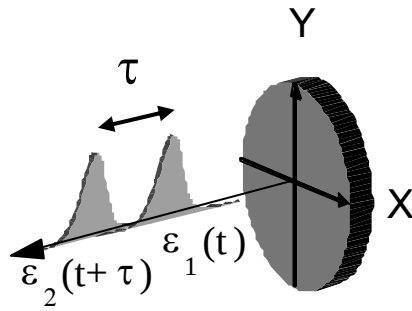
Approach

- *Laser pulse (4 ps) to pump*
- *Probe population through differential transmission*

Results

- *Rabi Oscillations of single exciton*
- *4 ps Π pulse => fast operations*



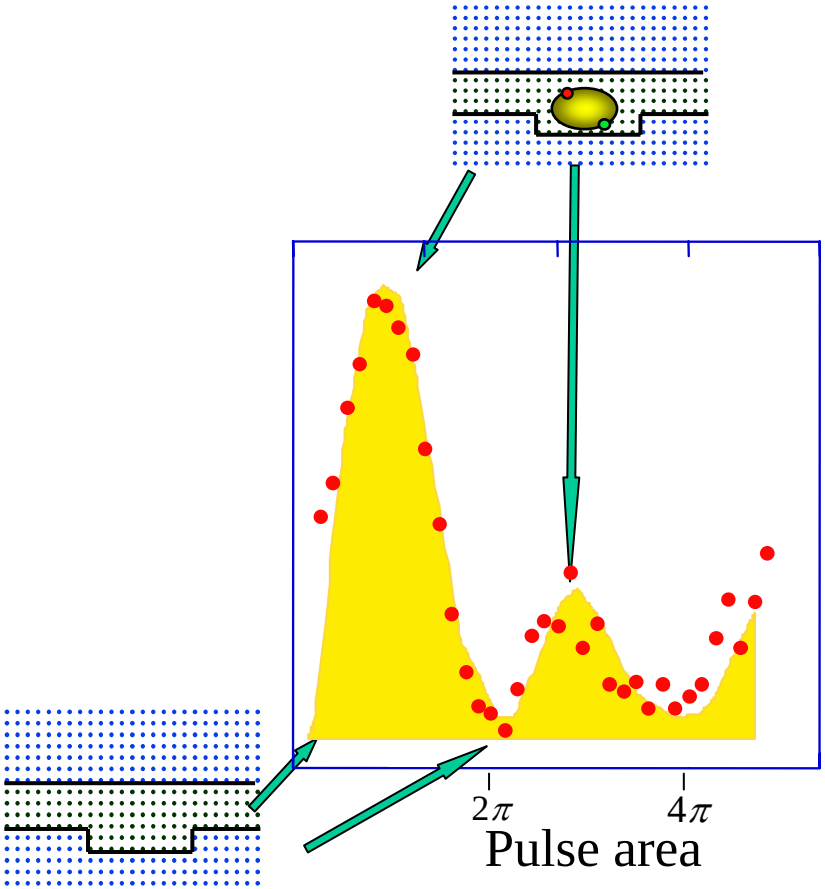


Stievater et al. PRL **87**, 133603 (2001).

See also:
Kamada et al. PRL (2001)
Htoon et al., PRL (2001)
Zrenner et al., Nature (2002)

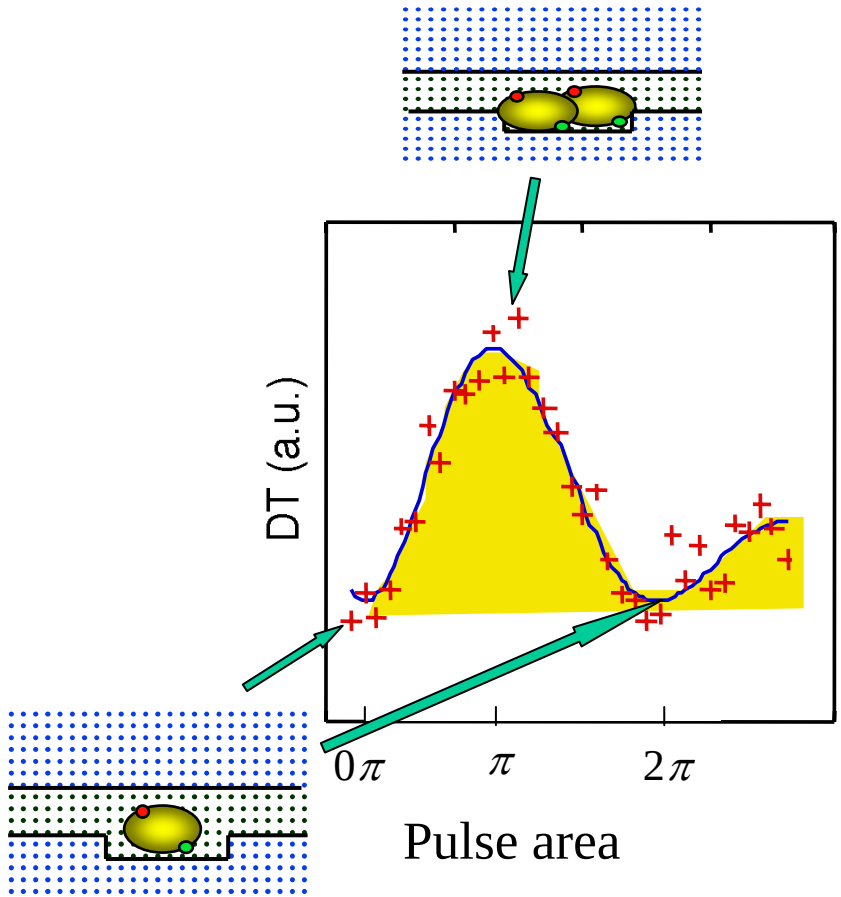
Rabi Oscillations

Ground State ⇔ Exciton Rabi Oscillations



Stievater et al., PRL **87**, 133603 (2001).

Exciton ⇔ Biexciton Rabi Oscillations

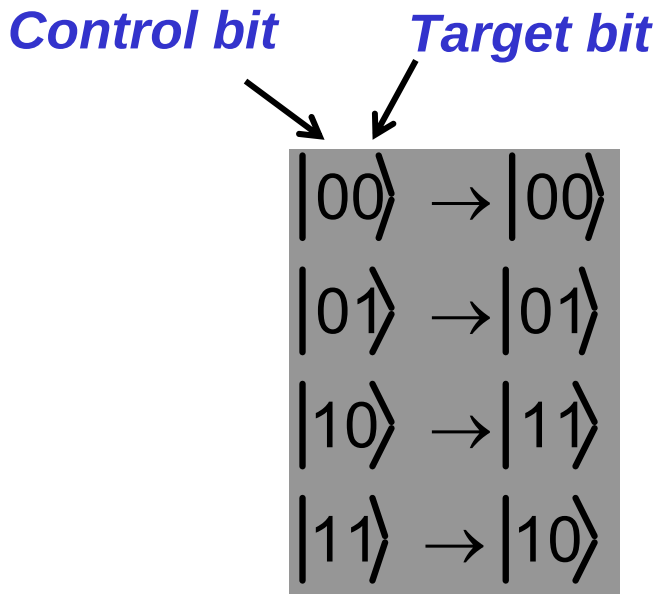


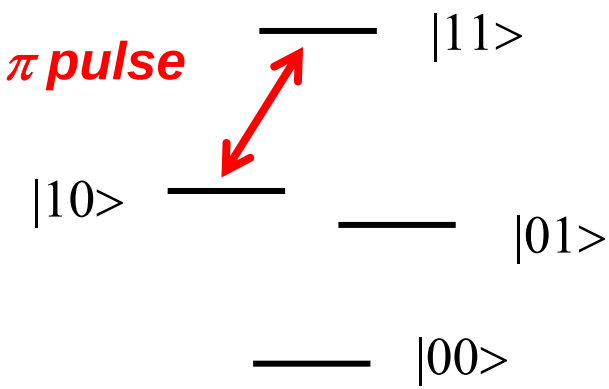
Elaine Wu et al., Science **301**, 809 (2003).

A QNOT gate (exciton)

QNOT Gate

- *Coherent control of two interacting excitons provides an example of a QNOT gate*





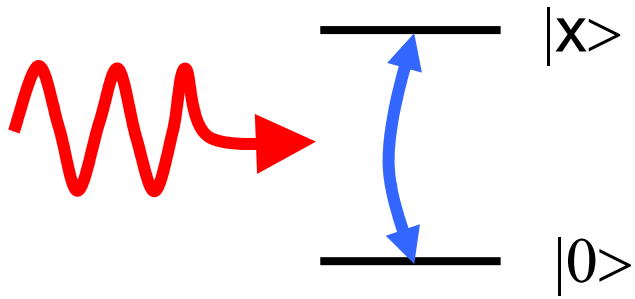
Qubit: exciton

Exciton decoherence / π pulse

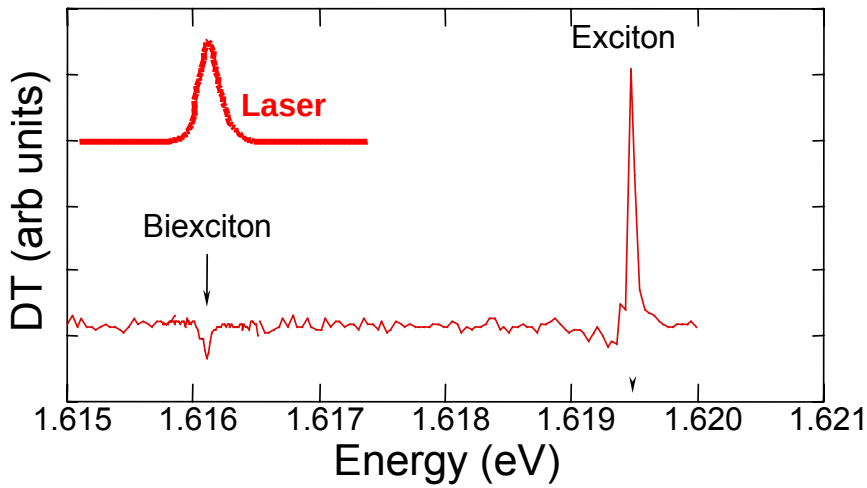
T_2 ~ 60 ps → **1 ns**

τ_{pulse} ~ 4 ps → **100 fs**

T_2/τ_{pulse} ~ 10 pulses → **10^4**



Use Spin!?

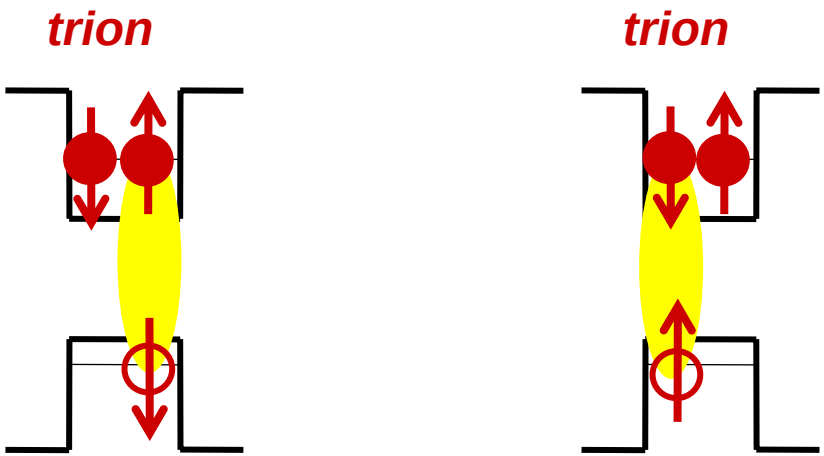


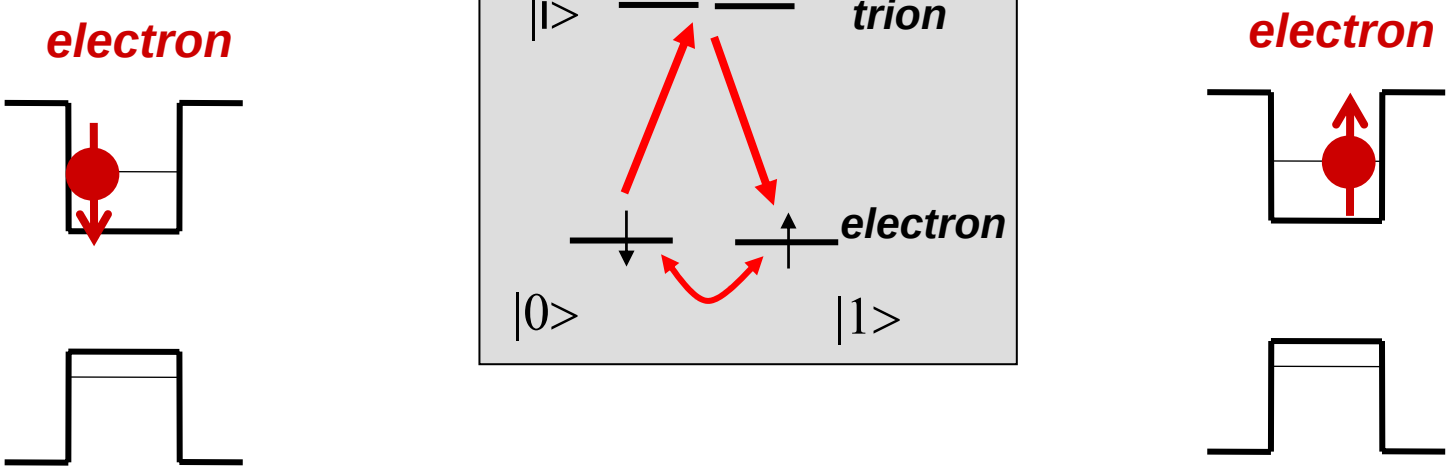
Contents

- *Exciton as qubit*
- *Spin as qubit (from the optical point of view)*
- *Hyperfine interactions and nuclear spin*

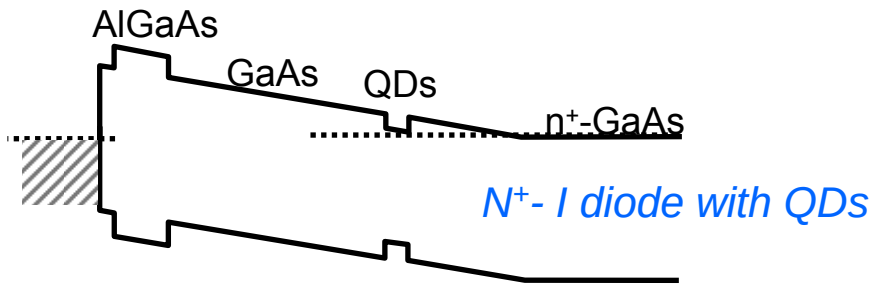
A spin qubit

qubit: spin

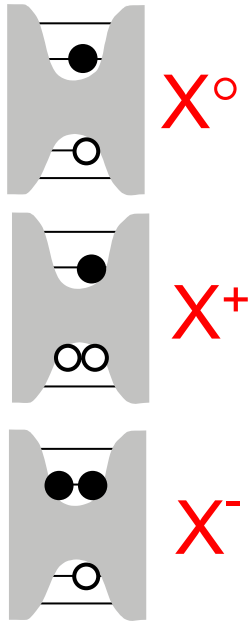


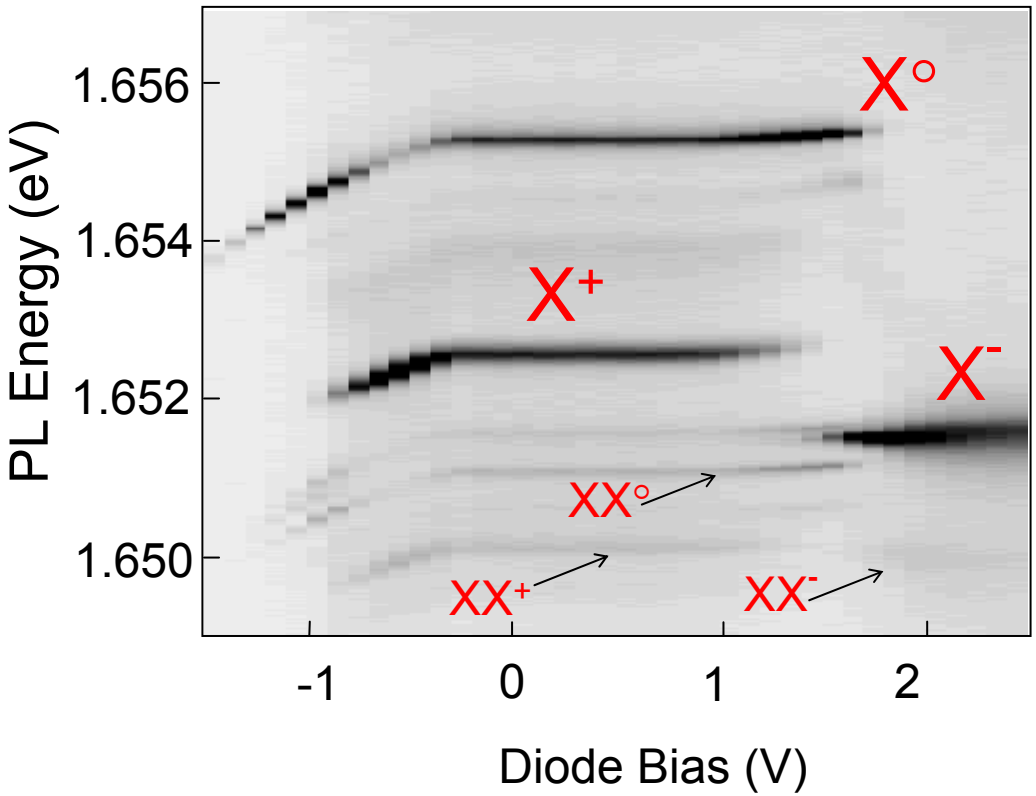


Luminescence from single dot in a diode



N+- I diode with QDs

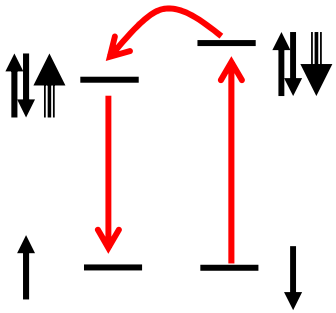




The quantum toolbox

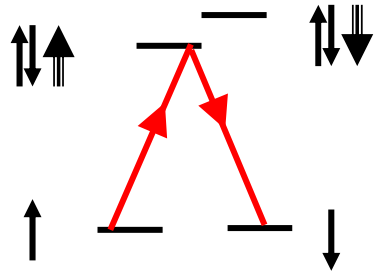
Quantum Toolbox

Initialization (Optical Pumping)



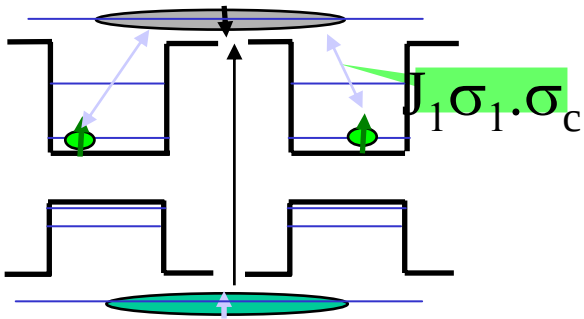
A. Shabaev, et al. PRB 68, 201305 (2003).

Rotations (coherent Raman)



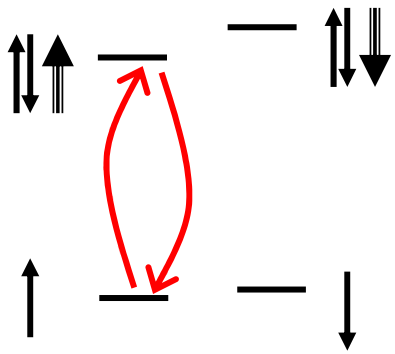
P. Chen et al., PRB 69, 075320 (2004).

Entanglement



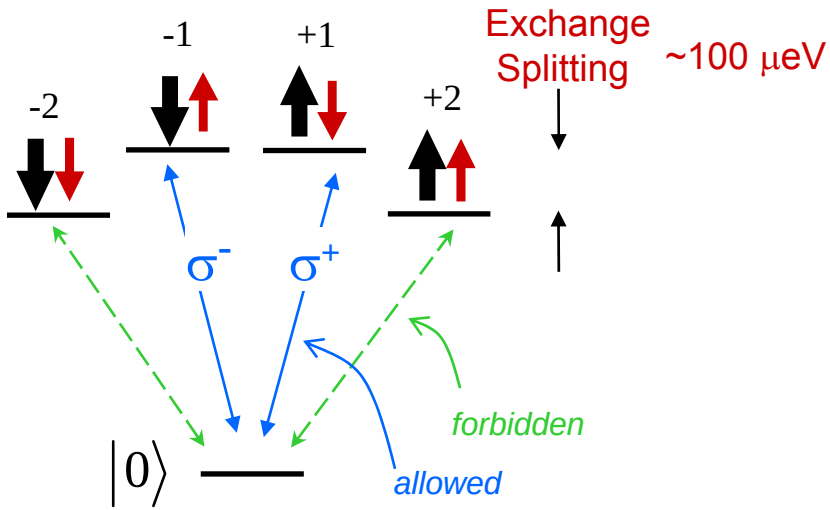
Immamoglu et al PRL 83, 4204 (1999)
Piermarcchi et al., PRL 89, 167402 (2002)
Troiani et al., PRL 90, 206802 (2003)
Pazy et al., Europhysics Lett.62, 175 (2003)

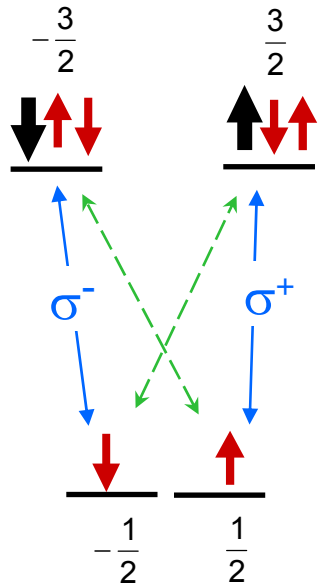
Measurement (recycling transitions)



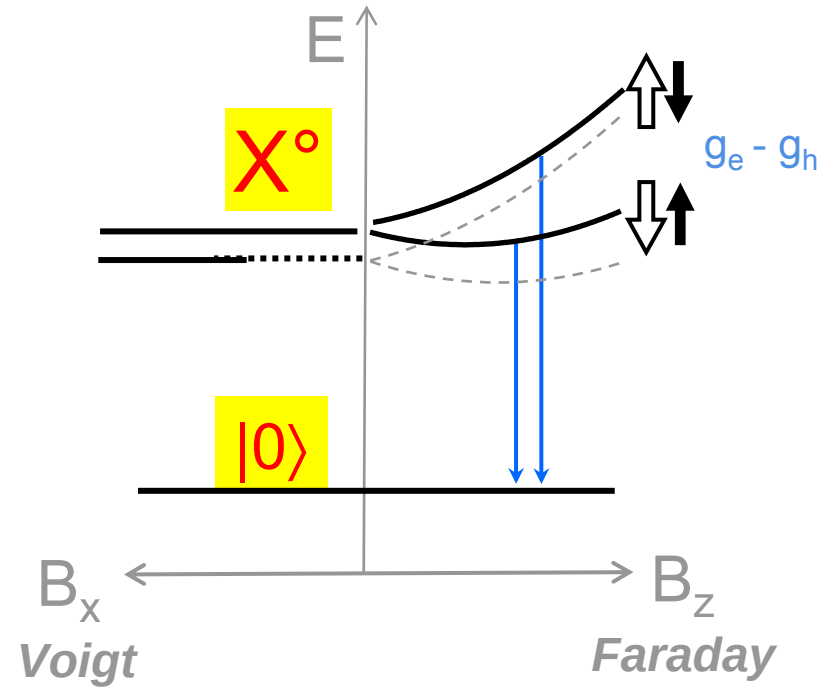
Shabaev et al., PRB (2003)
Calarco et al., PRA 68, 12310 (2003)

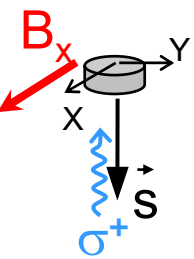
Selection Rules

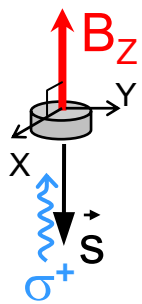


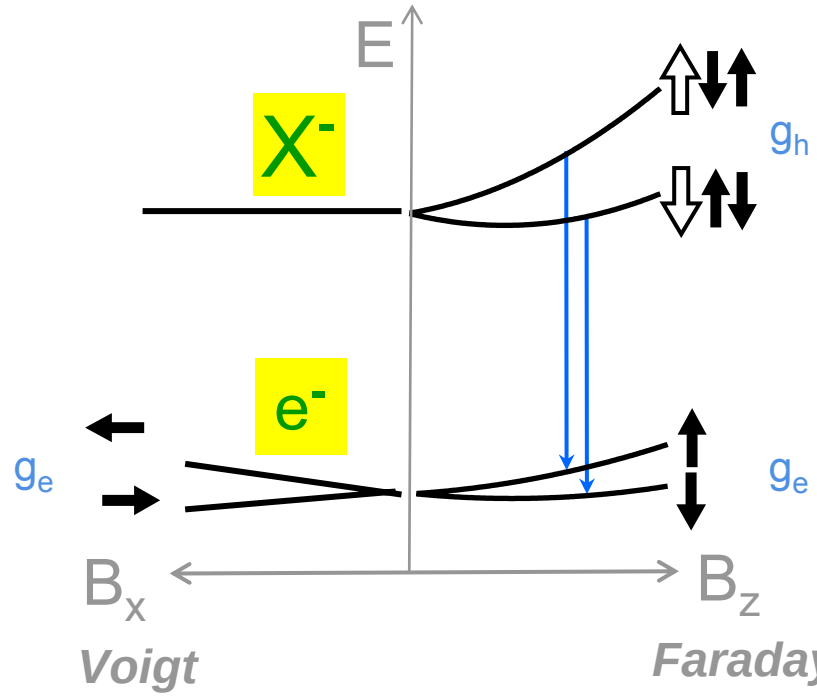


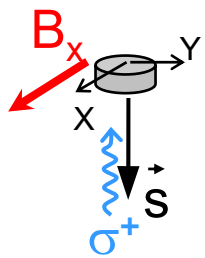
Exciton (X0) vs. Trion (X-) in B-field

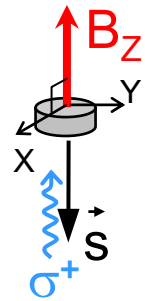












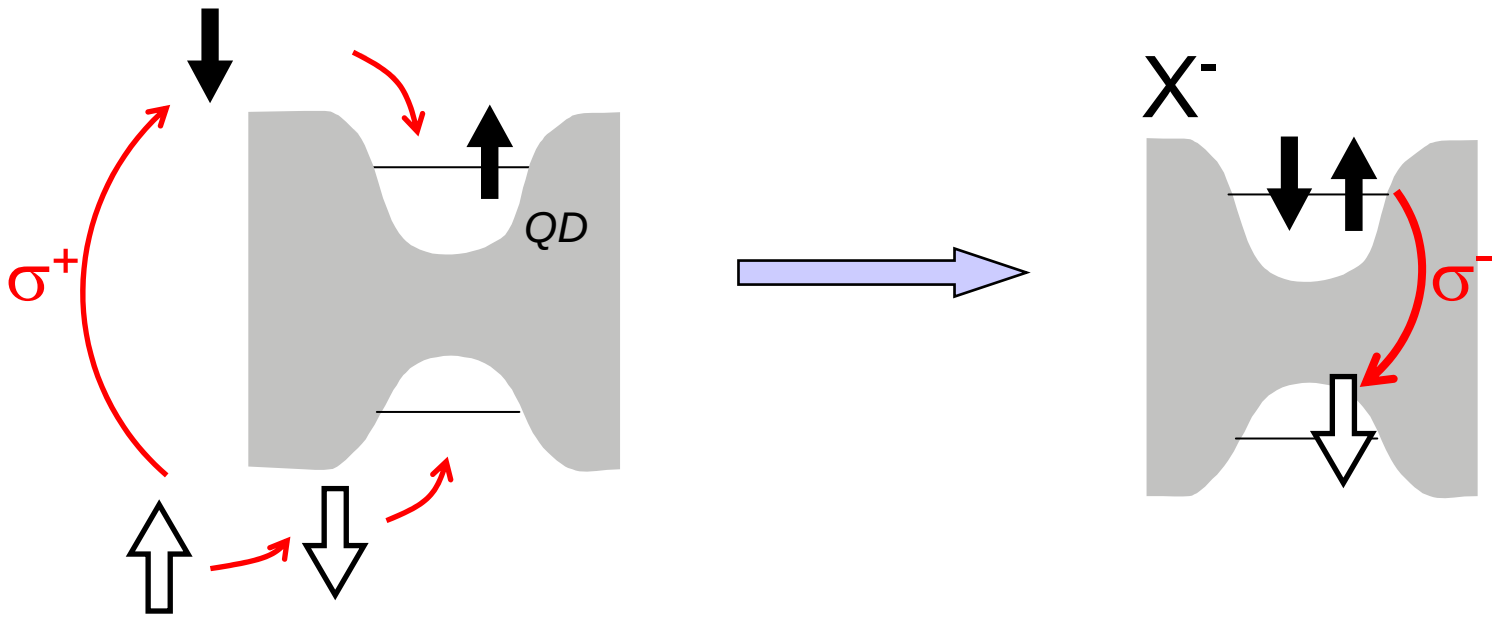
[Tischler, *et al.*, *PRB* **66**, 08131 (2002)]
[M. Bayer, *et al.*, *PRB* **65**, 195315 (2002)]

Optical Orientation

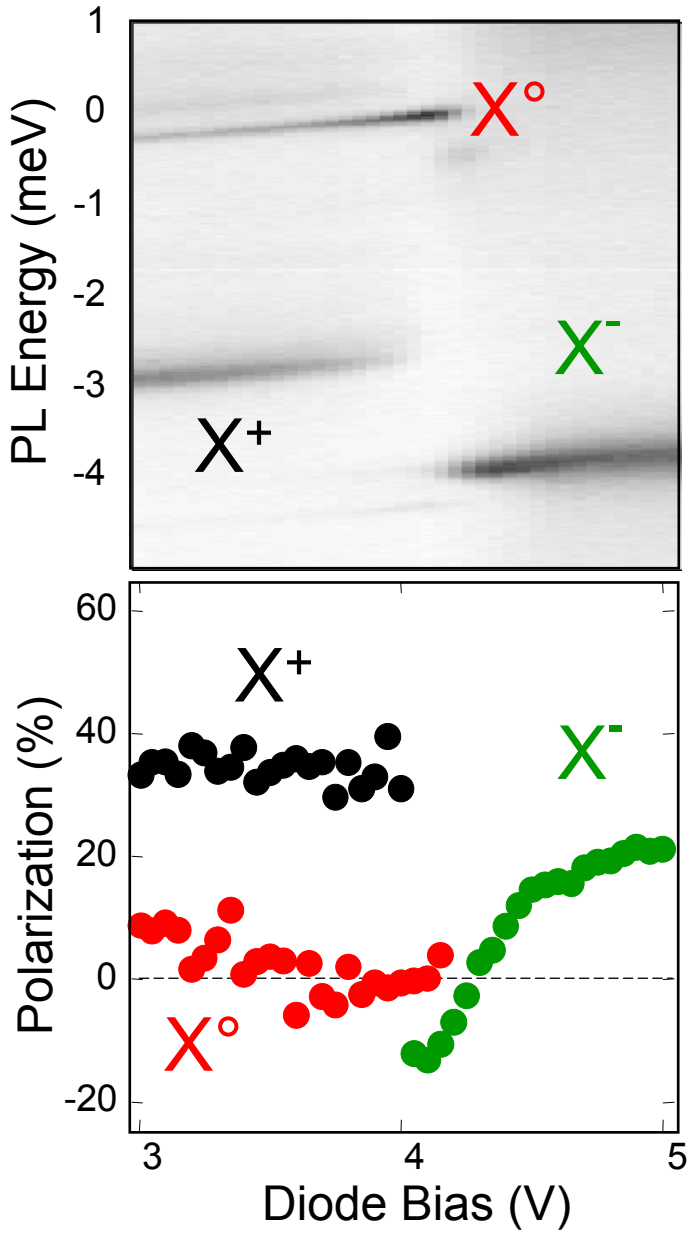
For GaAs quantum dots:

Nonresonant excitation into QW
~30 meV above QD energy

Fast hole spin flip, Slow electron spin flip



PL polarization of X°, X⁺, X⁻



PL polarization

$$P = \frac{I^+ - I^-}{I^+ + I^-}$$

X⁺ Large positive
(long e-spin lifetime)

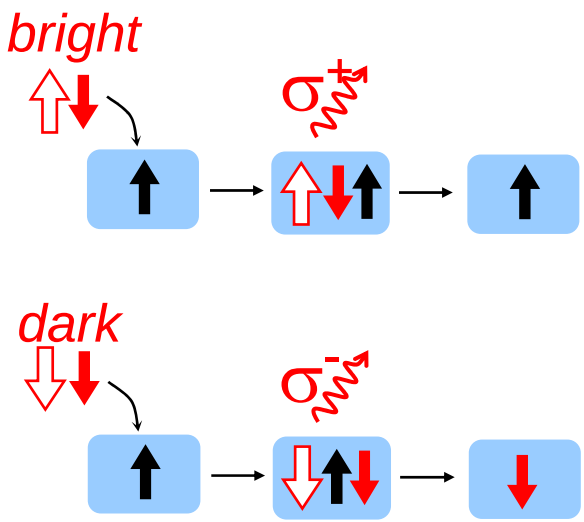
X° Zero or small positive at B_z=o
(anisotropic exchange)

X⁻ Positive or negative,
depends on conditions

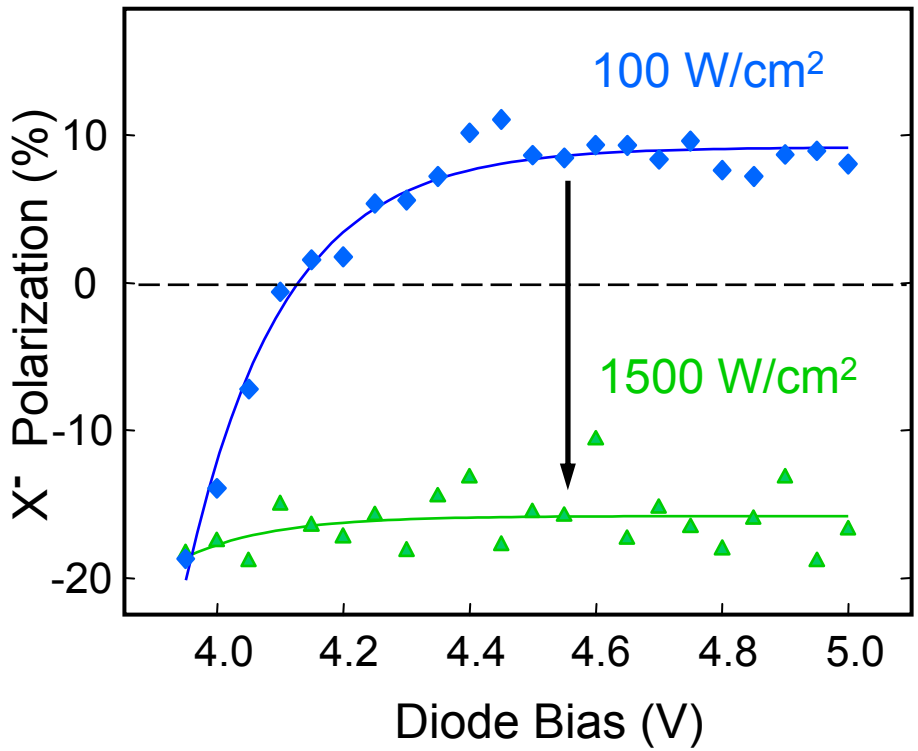
Optical pumping of electron spin

X^- polarization:

1. *h*-spin orientation
2. Ground state *e*-spin pumping



Need fast hole flip rate compared to electron spin flip rate

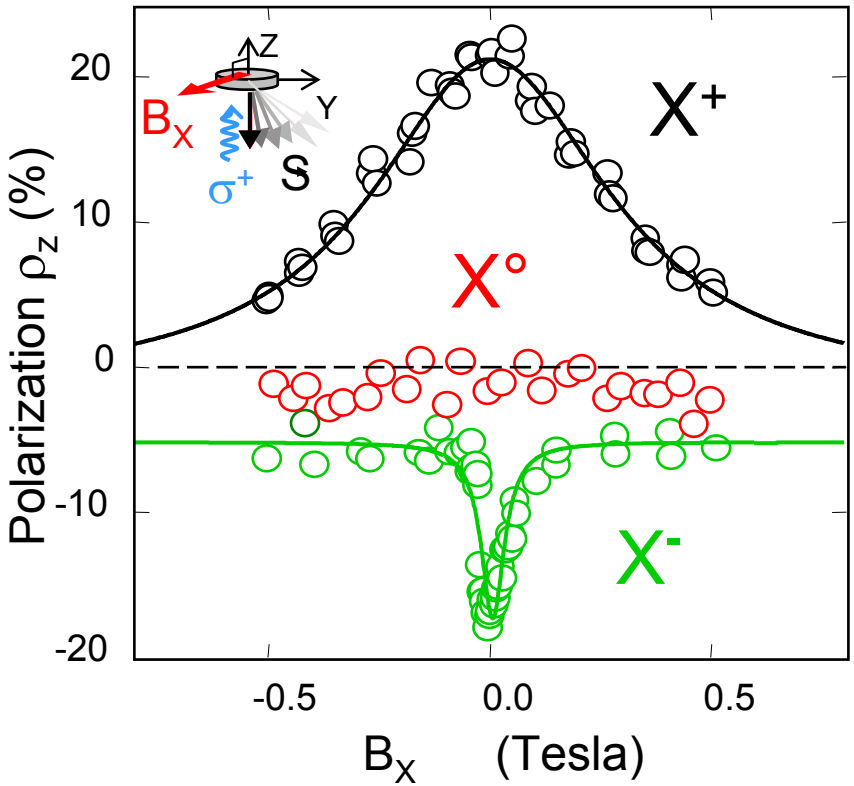


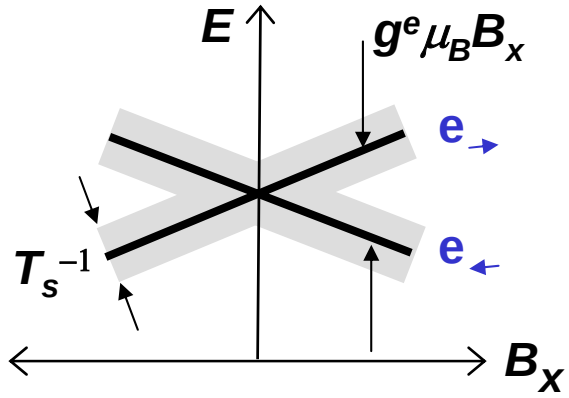
Previous work:

Dzhioev *et al.*, *Phys. Solid State*, **40** 1587 (1998)

Cortez *et al.*, PRL **89**, 207401 (2002)

The Hanle effect and electron spin lifetimes





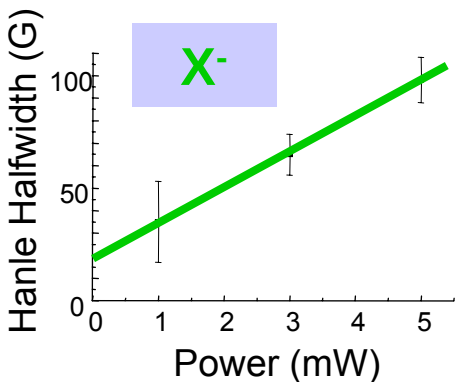
Polarization:

$$\rho_z(B) = \rho_z(0)\frac{1}{1+(B/B_{1/2})^2}$$

Halfwidth:

$$B_{1/2} = \left(\hbar/\mu_B g^e\right)T_s^{-1}$$

$g^e \sim 0.2$



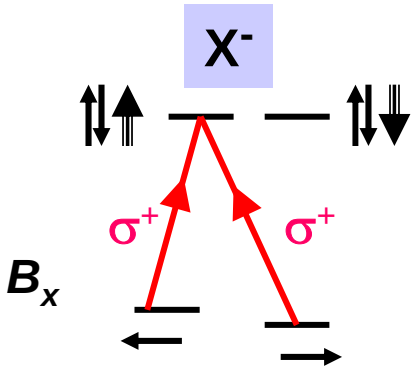
X° : *No polarization*

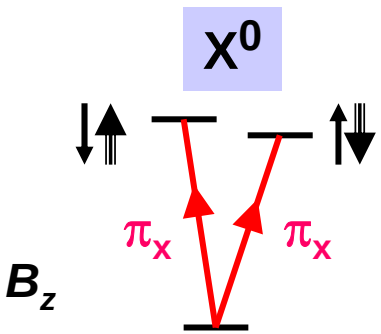
X+ : $B_{1/2}$ = 3.5kG $\Rightarrow$ $T_S \approx$ 160 psec

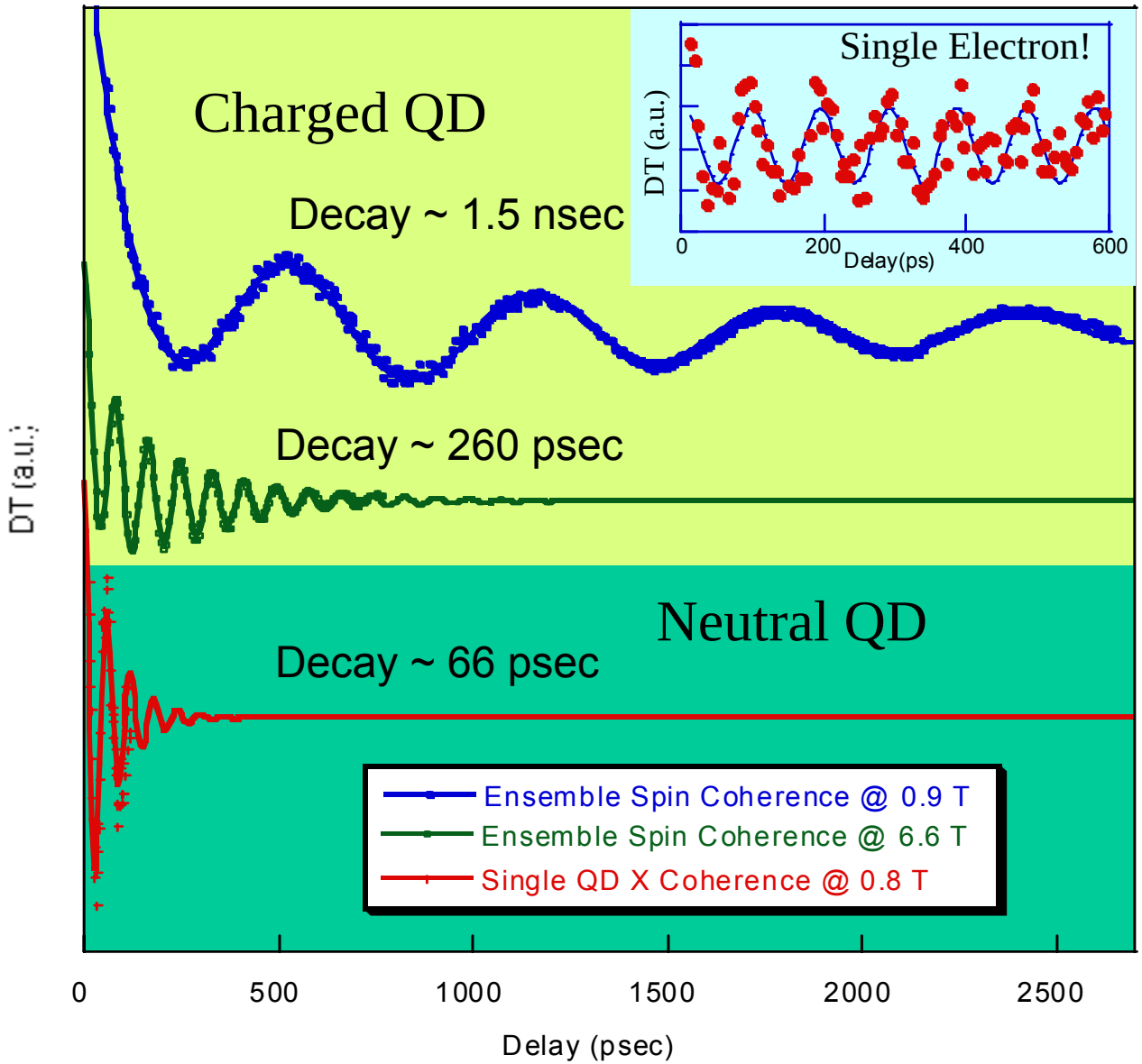
X- : $B_{1/2}$ = 20G $\Rightarrow$ $T_S \approx$ 30 nsec

Bracker et al., cond-mat/0408466

Quantum Beats

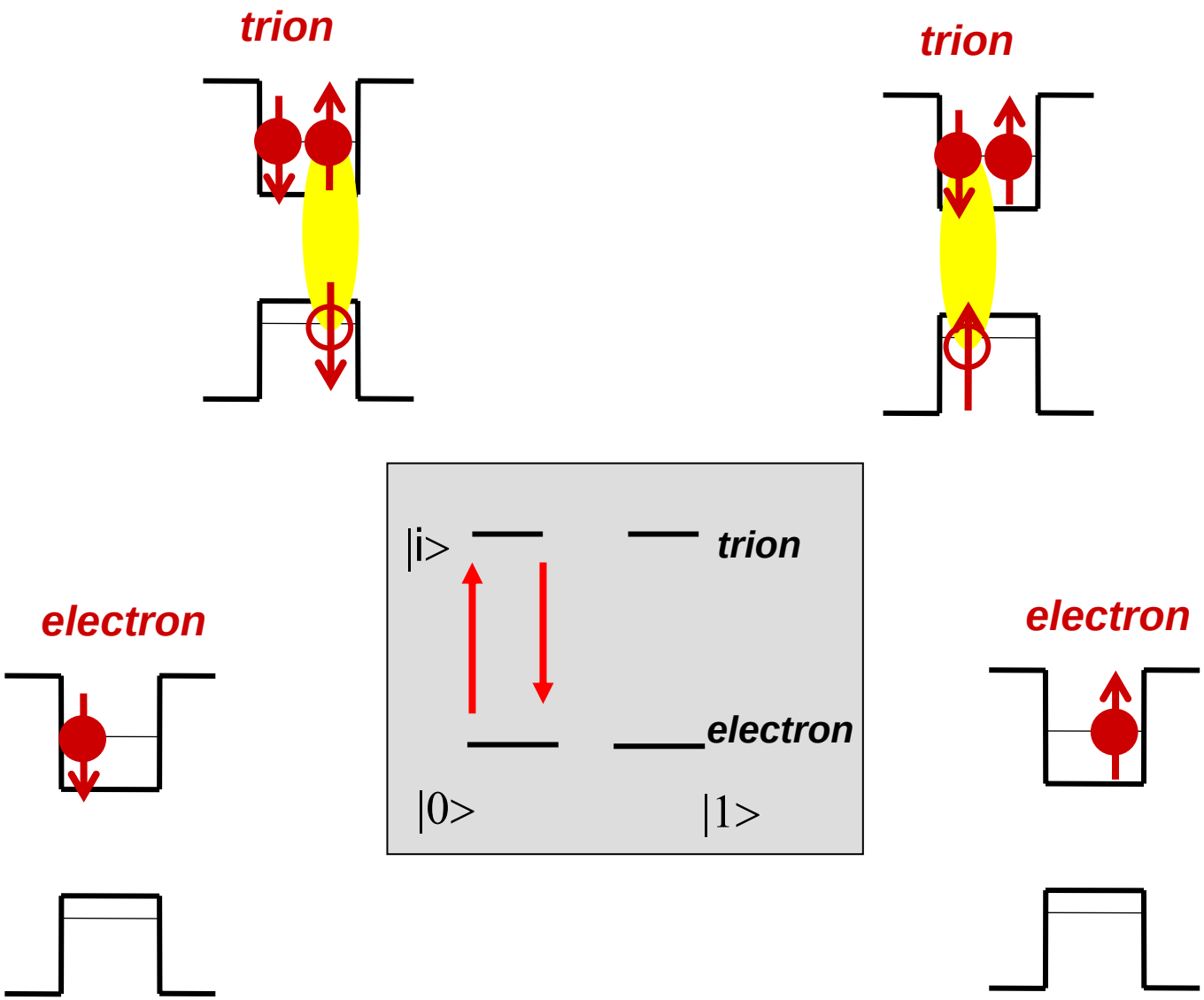






Gurudev Dutt et al. subm.

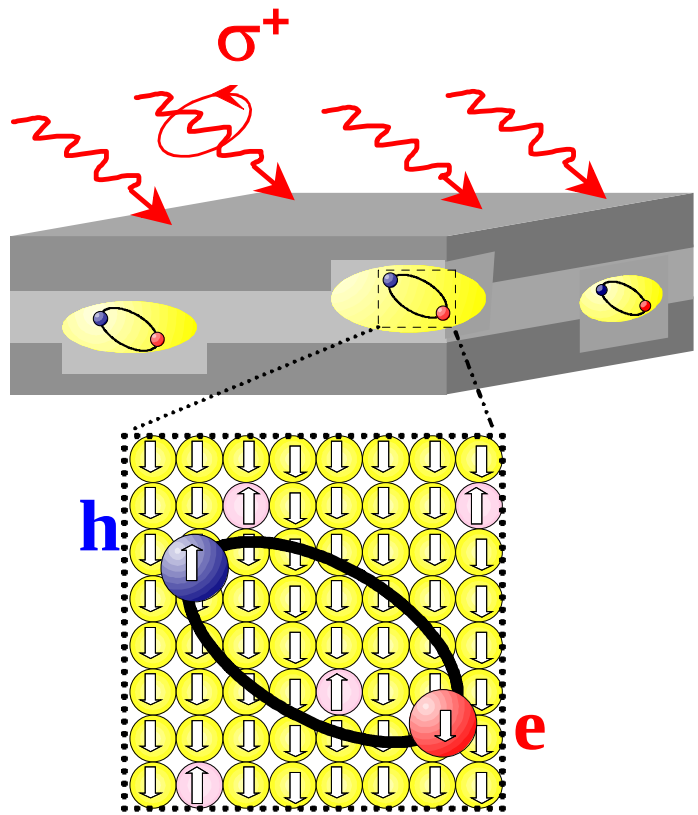
Measurement



Contents

- *Exciton as qubit*
- *Spin as qubit (from the optical point of view)*
- *Hyperfine interactions and nuclear spin*

Nuclear spin



Nuclear spin => effective magnetic field

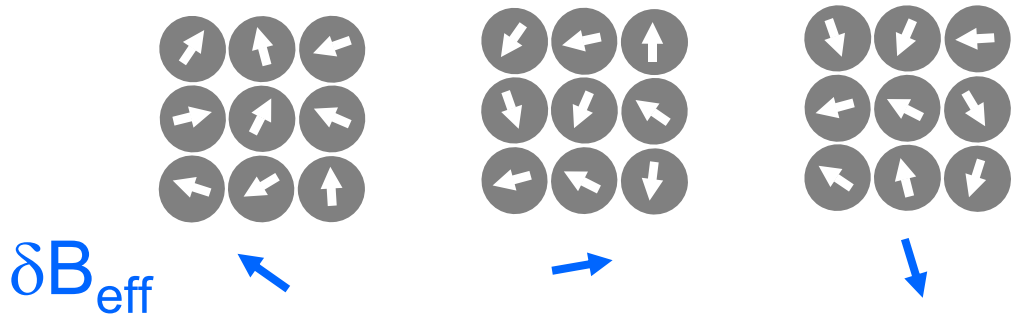
- *Average => Overhauser shifts*
- *Fluctuations => spin dephasing*

•*Brown et al. PRB* **54**, R17339 (1996)
•*Gammon et al., Science* **277**, 85 (1997)
•*Gammon et al., PRL* **86**, 5176 (2001)
•For a review see; *Gammon et al.,* Coherence in Semiconductor Q.Wires and QDs, ed. T. Takagahara (Gordon and Breach 2003) Chap. 8.
•*Bracker et al.,* cond-mat/0408466

Nuclear spin fluctuations

Electrons dephase in the effective magnetic field
produced by a net fluctuation of the nuclear spin

Merkulov et al., PRB **66** 153409 (2002)
Khaetskii et al., PRL **88**, 186802 (2002)
Dzhioev et al., PRB **65** 205309 (2002)



Inhomogeneous dot-to-dot variation OR
Long-time variation in a single dot
(spectral diffusion)

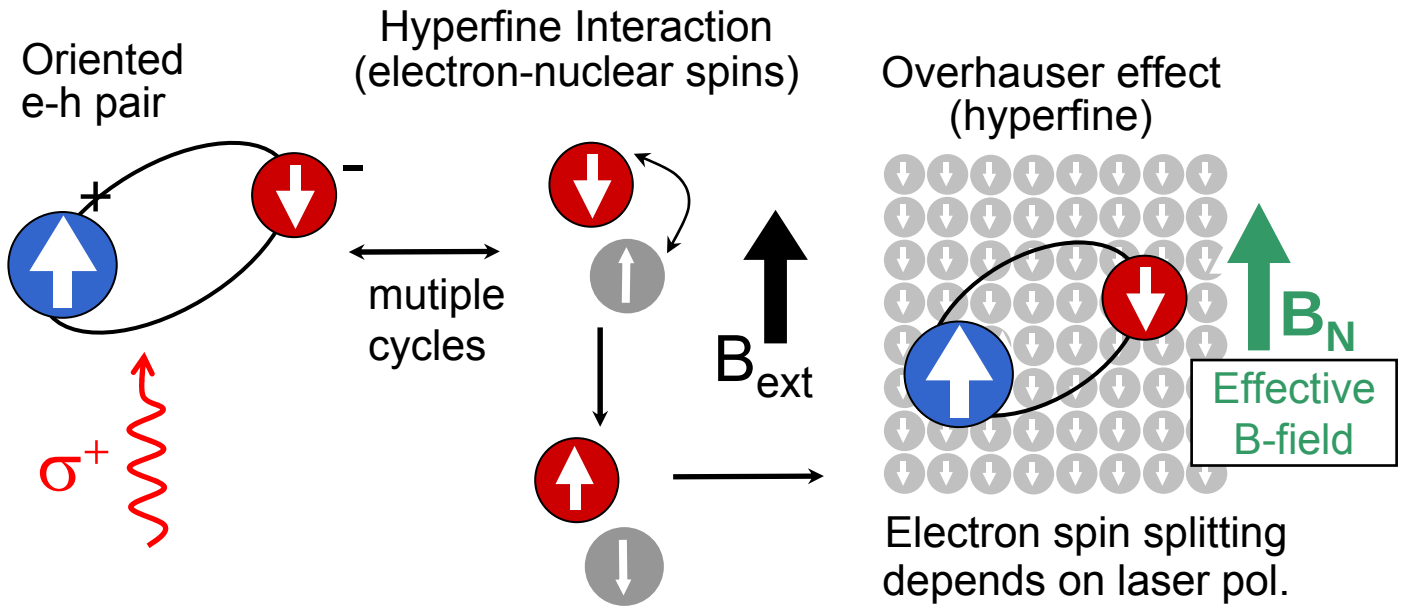
$$T_s \approx \hbar\sqrt{N} / A$$

N ≈ 10^5 atoms

A=90 μeV (hyperfine constant in GaAs)

expect: $T_s \approx 6$ ns
measure: 4-30 ns

Pumping of nuclei; Overhauser effect



Key Point:

B_N affects only electron spin

- *Not hole spin (p-like)!*
- *Not orbital (i.e. no diamagnetic shift)!*

Observed:

Max. Overhauser shift

$$\Delta E_N = (\Delta E_{\sigma+} - \Delta E_{\sigma-})/2 = 81\ \mu\text{eV}$$

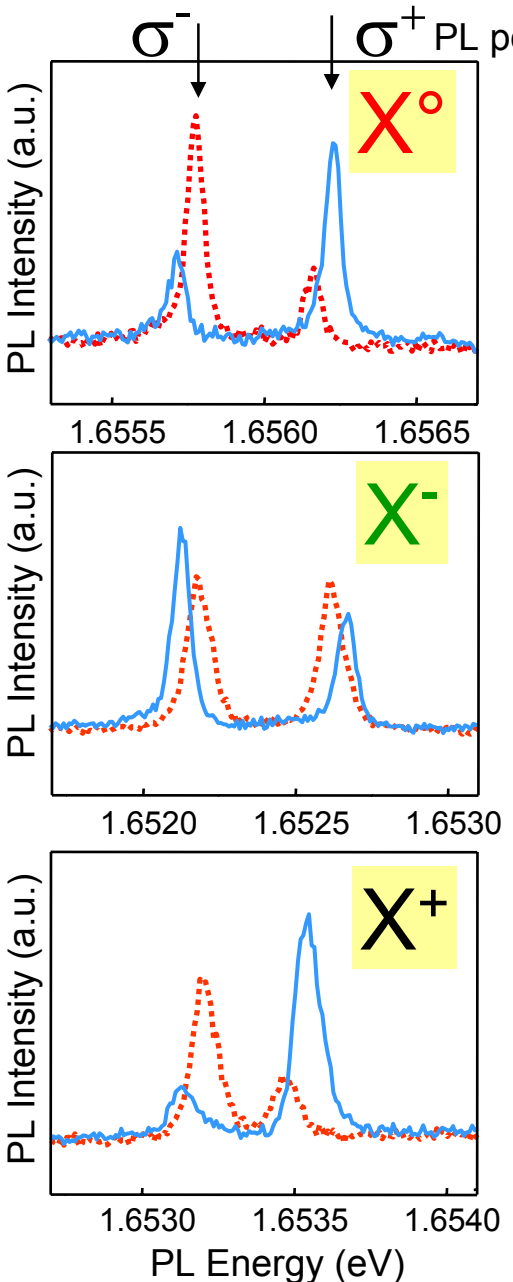
Nuclear Polarization

$$P_N = \Delta E_N / (3/2) * A_{hf} = 60\%$$

Effective B-Field

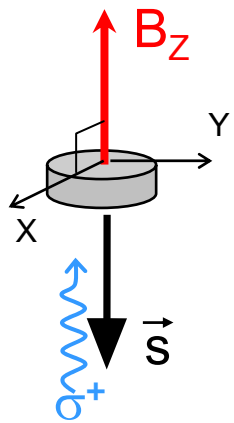
$$B_N = \Delta E_N / 2 g^e \mu_B = 14\ \text{Tesla}$$

X°, X+, X- in longitudinal magnetic field

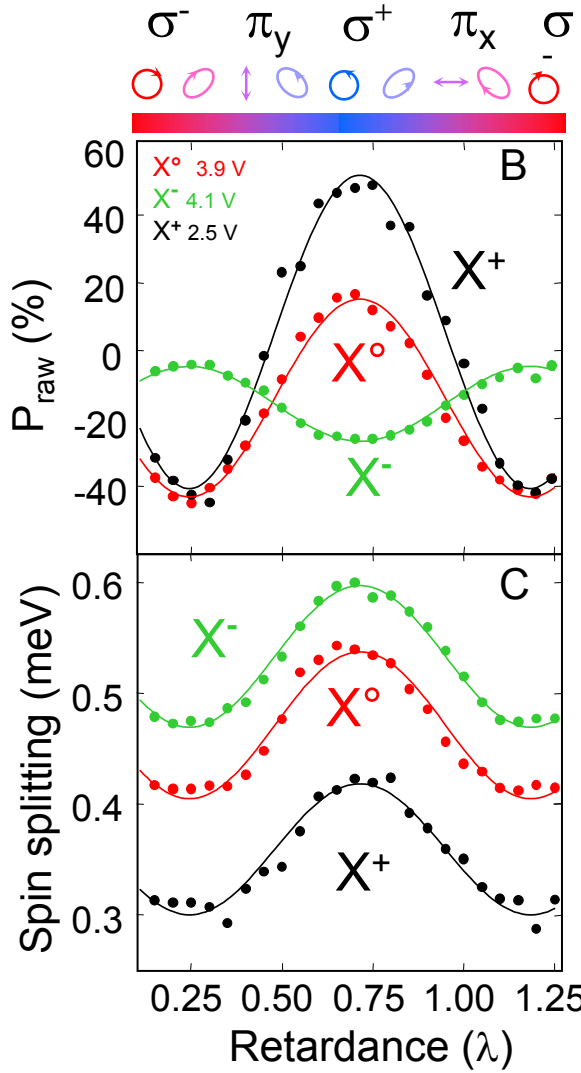


B_{ext} = 5T

Laser: σ^- σ^+



❖ Spin splittings vary with laser polarization:
→ signature of *optical pumping of nuclear spins*



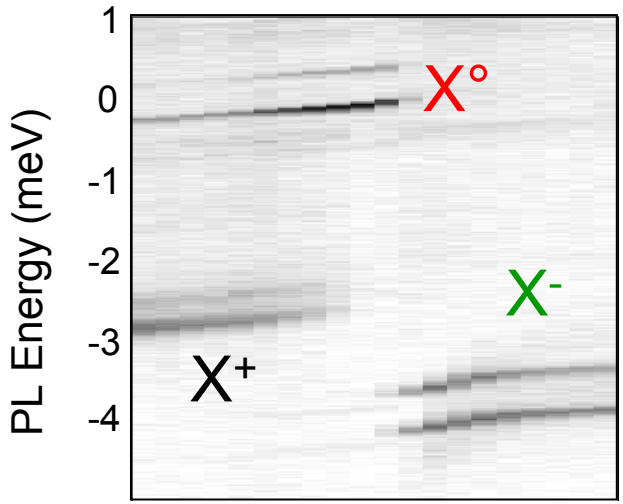
Amplitude: Polarization "memory"

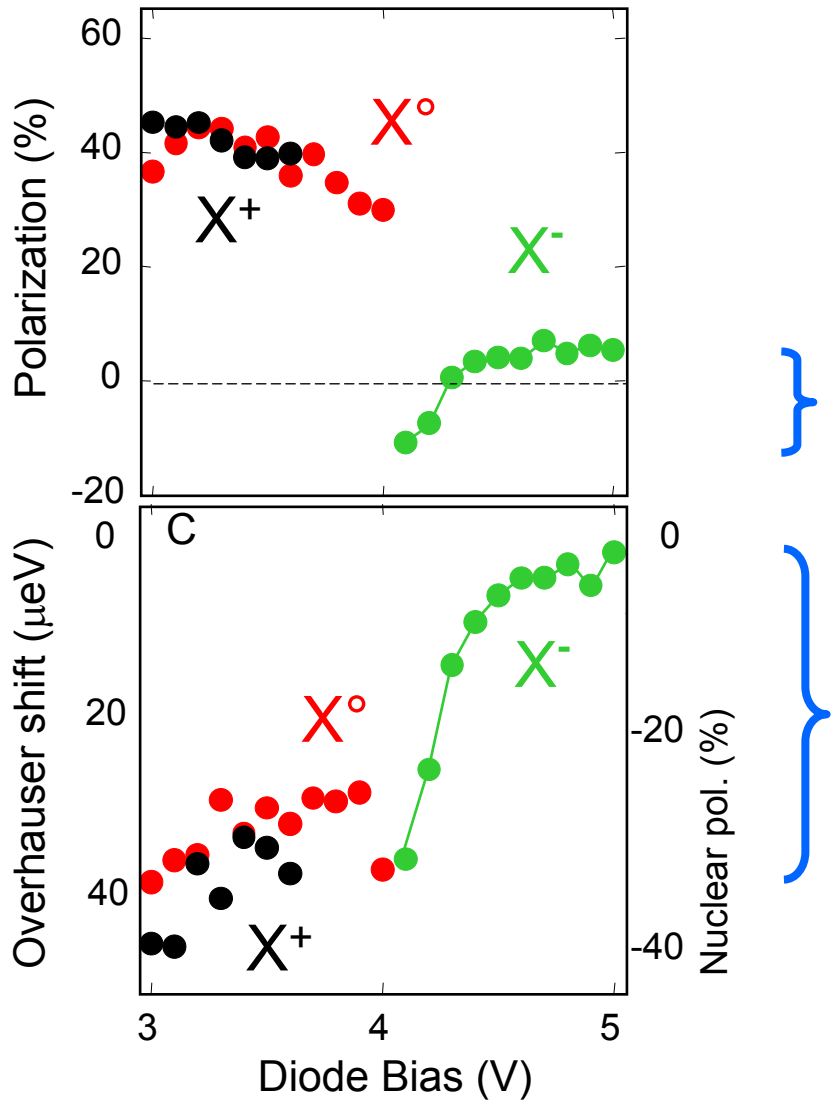
Offset: Thermal polarization

Amplitude: Overhauser shift

Offset: Intrinsic splitting

Bias dependence of polarization, B_z=5T





By increasing the bias and injecting unpol. *e*'s:

- X^- *polarization increases*
- *Nuclear polarization decreases*

Electron polarization is the link !

Allan Bracker et al., cond-mat/0408466

Future Directions

- ***Beyond the perturbative regime***
  - π pulses, etc.
- ***Ground state (spin) coherences***
  - Λ vs. V transitions
- ***Decoherence physics***
- ***QD molecules and more complex structures***
  - entanglement
- ***Quantum computing?***