Coherence and optical electron spin rotation in a quantum dot

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Outline

Part I

Background: QC with quantum dots, Λ system

Spontaneously generated coherence: theory

Experimental results

Part II

Background: Rabi oscillations, hyperbolic secant pulses

Single-qubit rotations

Quantum computing

$|\Psi\rangle = \cos(\theta/2)|0\rangle + \sin(\theta/2)\, e^{i\varphi}\, |1\rangle$

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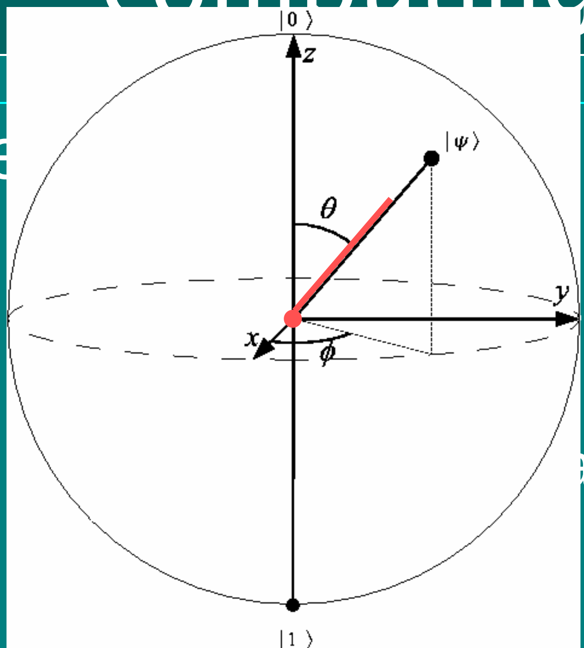


– Readout

– Qubit-specific measurement

– Long coherence times

$\rho = \alpha' |0'\rangle\langle 0'| + \beta' |1'\rangle\langle 1'|$

$\alpha' = \beta' = ½$

Completely mixed

(Unpolarized)

Two-level system

Qubit candidates

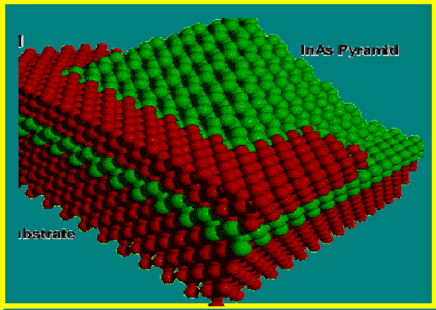
- Electron spins in QDs
- Nuclear spins
- Atomic levels
- Superconducting qubits
- …

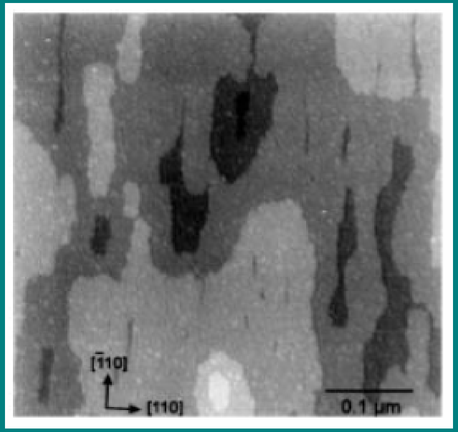
Bloch vector

Two-level QM systems can be represented by a vector on/in a unit-radius sphere

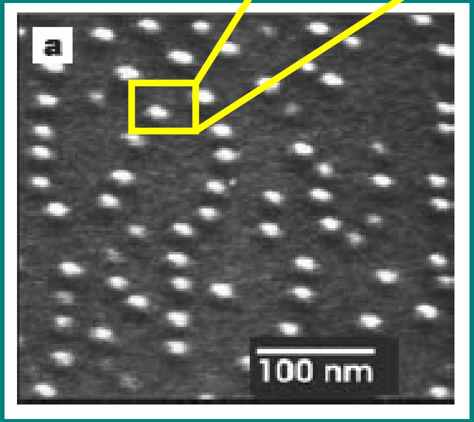
Quantum dots

- Semiconductor nanostructures with 3D nanometer confinement for electrons/holes
- Atomic-like energy levels
- Fluctuation dots, SADs, gated dots
- Growth axis ≡ z

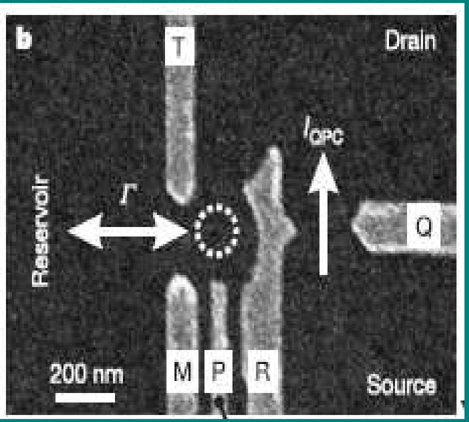




D. Gammon et al., PRL 76, 305 (1996)



J. P. Reithmaier et al., Nature 432, 197 (2004)



J. M. Elzerman et al., Nature 430, 431 (2004)

QIP with optically controlled electron spins trapped in QDs

- Quantum dot with single excess electron
- e spin carries quantum information

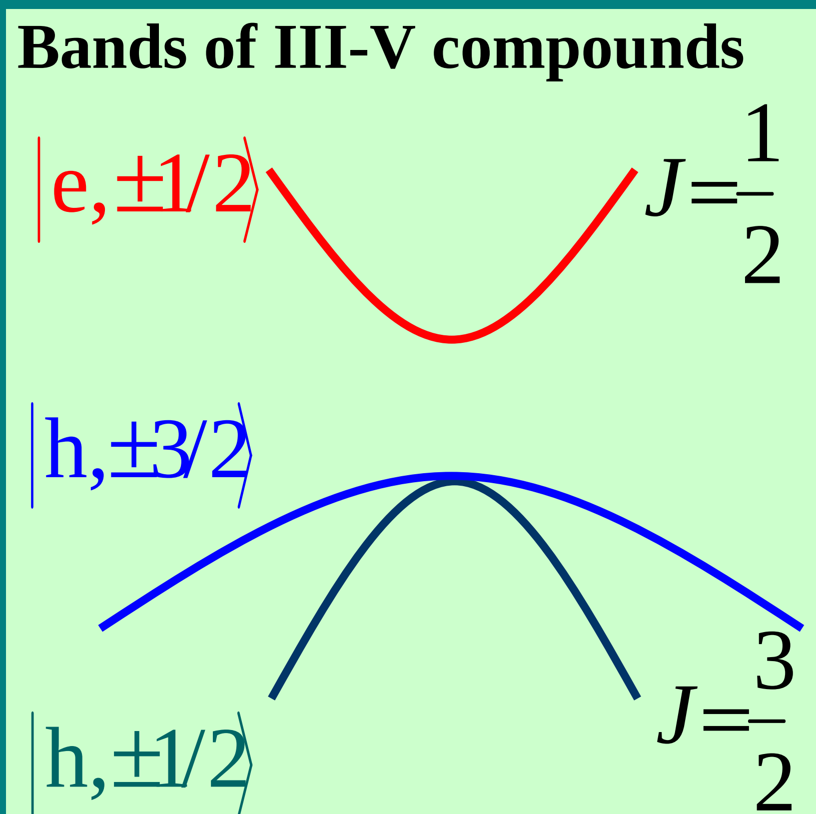
- Operations: optically by Raman transitions via trion

- Trion: bound state of electron and exciton

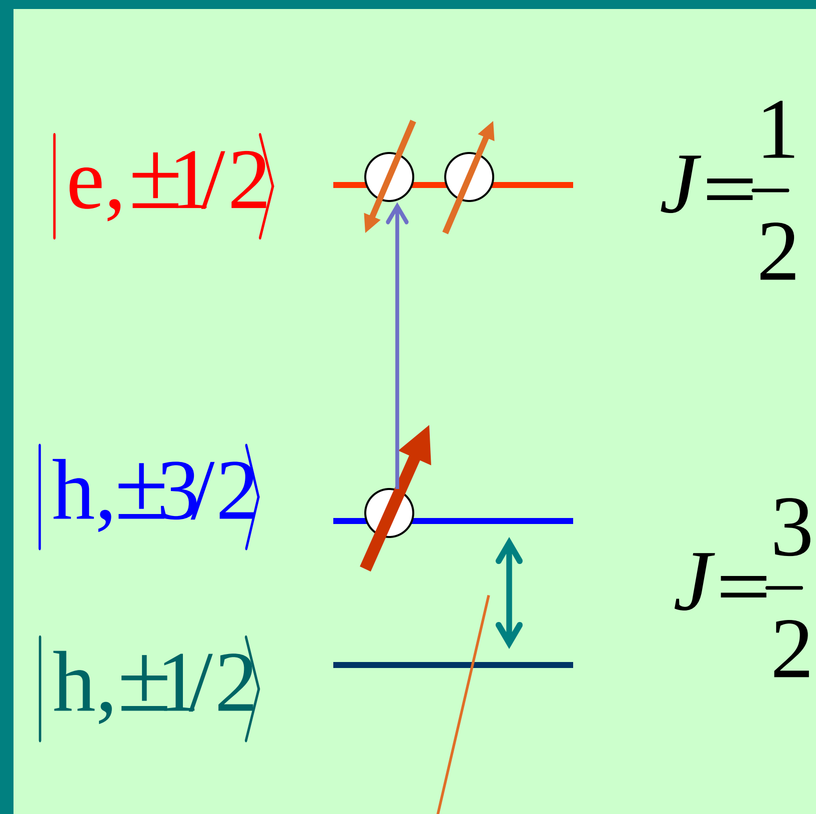
- Inter-dot coupling:
  - With common cavity mode (Imamoglu et al. PRL ’99)
  - Optical RKKY (C. Piermarocchi et al. PRL ’02)

Energy levels & HH-LH splitting

Bulk



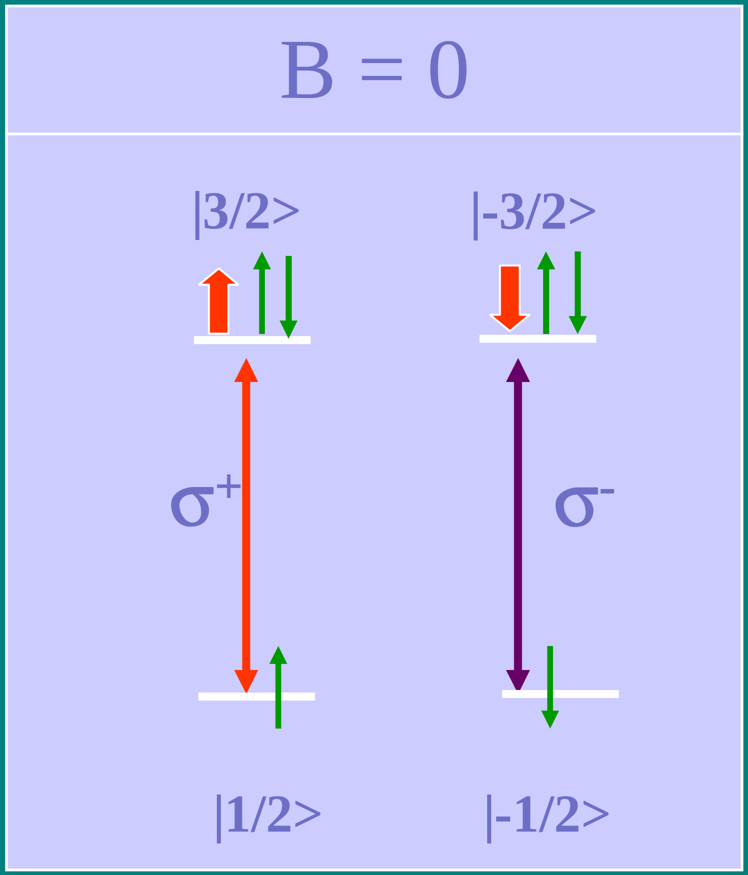
Quantum dot



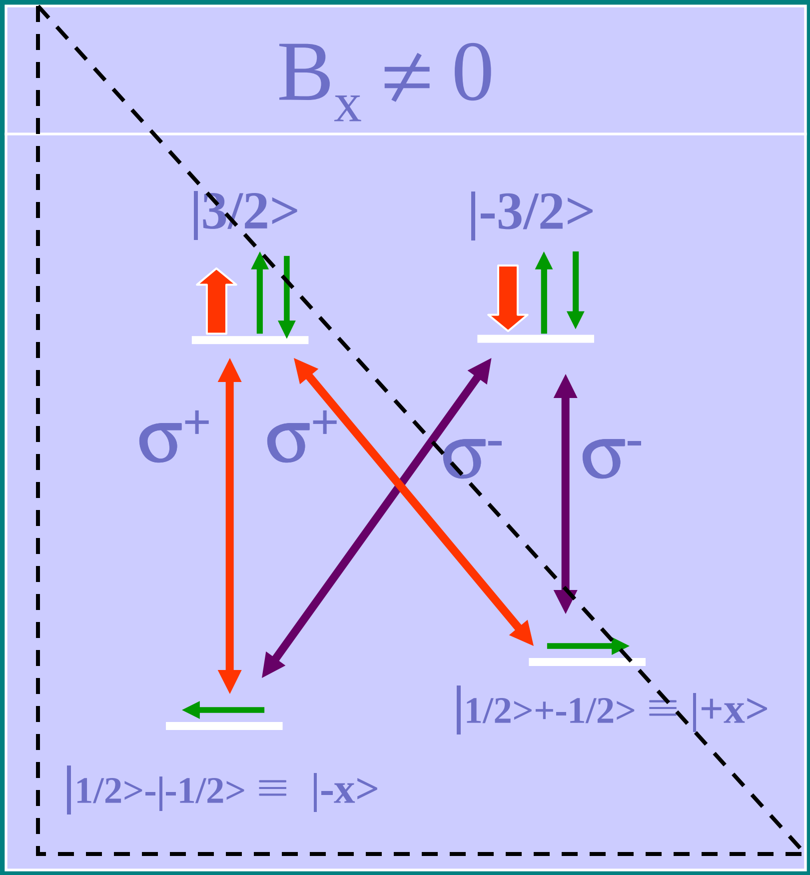
Confinement- induced
H-L hole splitting

Lambda system in QD

Without B field, no Raman transitions possible: cannot implement qubit operations:



Perpendicular B field mixes spin states, enables Raman transitions



Choosing eg σ^+ light yields a Lambda system

Decay & decoherence

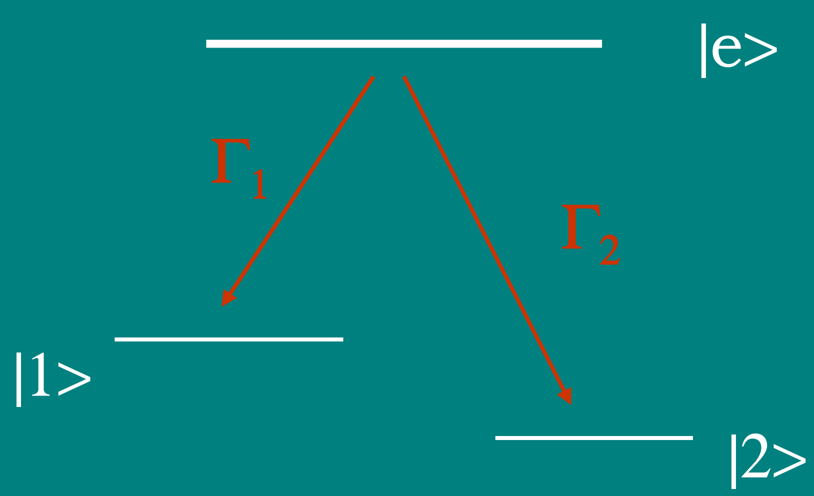
- Decay equations of *generic* Λ system known from atomic physics

- Can be derived from a Master equation. Basic idea:
  - ➢Start with total system dynamics, ignore (trace out) the bath
  - ➢End up with non unitary evolution for system Wavefunction → Density matrix

Decay & decoherence come from ignoring a part ('bath') of the total system

Example: Spontaneous emission of generic Λ system initially excited

$|\Psi\rangle = |e\rangle$



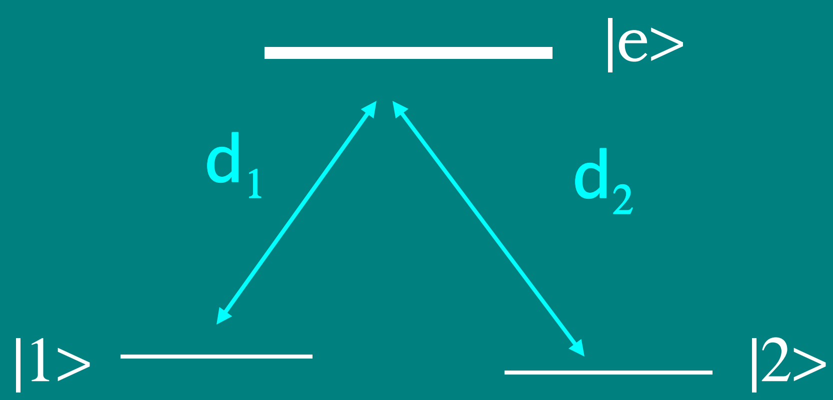
Finally: $\rho = 0.5\,|1\rangle\langle 1| + 0.5\,|2\rangle\langle 2|$

Common 'wisdom': spontaneous emission always produces decoherence.

Spontaneously generated coherence (SGC)

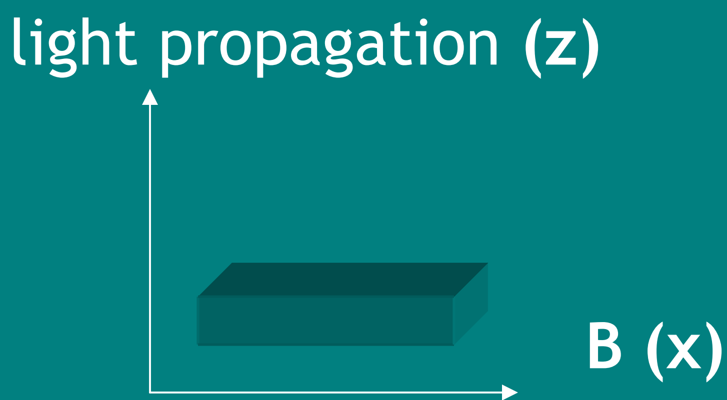
- Theoretically predicted in atoms: Spontaneous decay may result in superposition (coherence) of recipient states, i.e. a term $(\partial_t \rho_{12})_{sp} = \Gamma \rho_{ee}$
  (Javanainen'92)

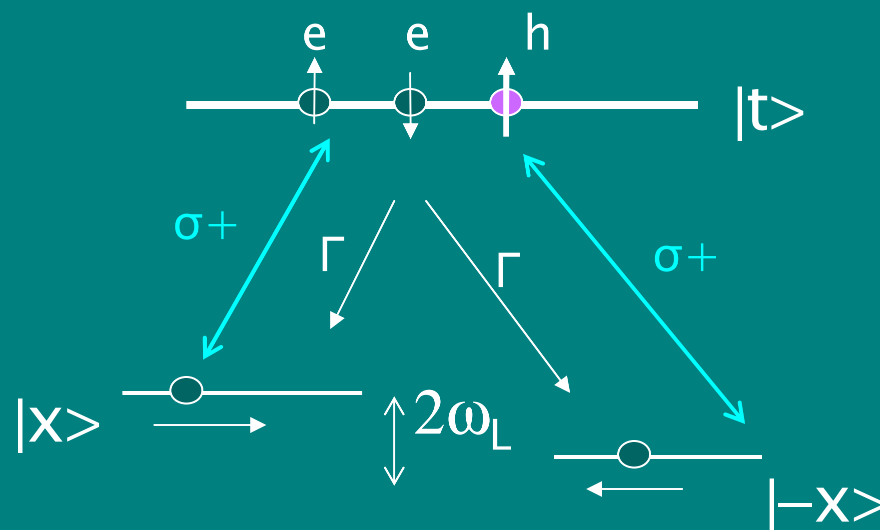
- Has *not* been observed in atoms



Conditions
- E_{12} small
- $d_1 \cdot d_2 \neq 0$

Features of the QD Λ−type system





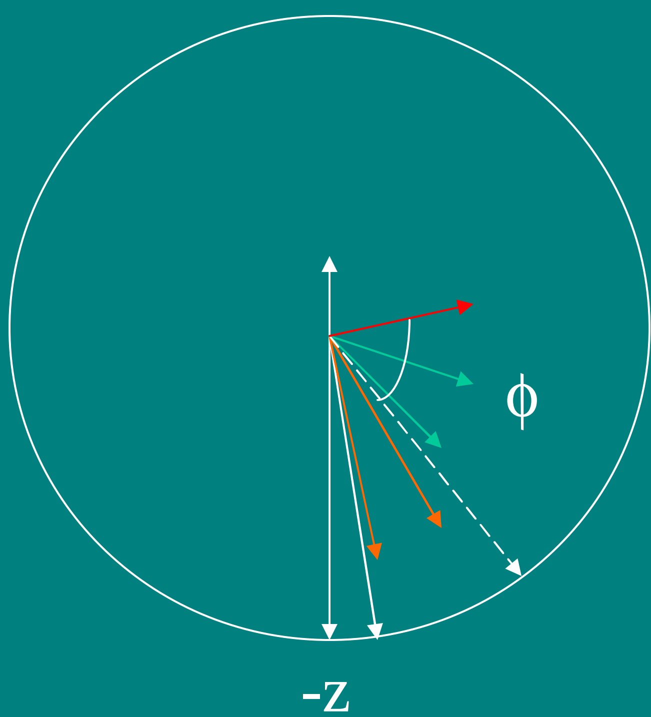
- Small Zeeman splitting
- 2 transitions have same polarization

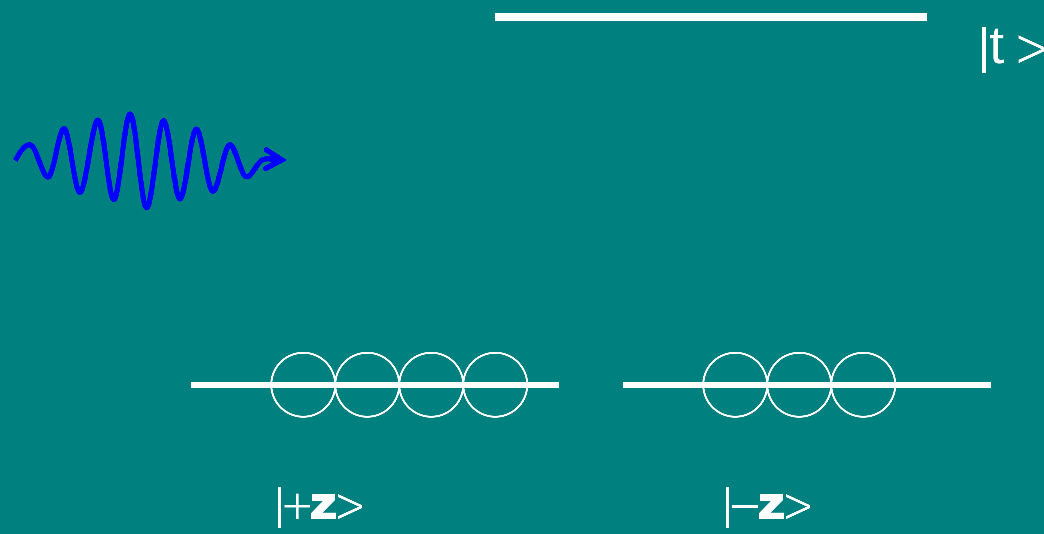
- Fluctuation QDs: HH trion splitting $\propto$ B^3 $\rightarrow g_{x,hh} \approx 0$ (J. G. Tischler et al.) $\rightarrow$ trion does not precess!
- SGC requirements are fulfilled

Origin of SGC: Intuitive Picture

Instead of energy eigenstates |±x> consider the |±z> states
=>two-level system (|-z> decoupled by selection rules)

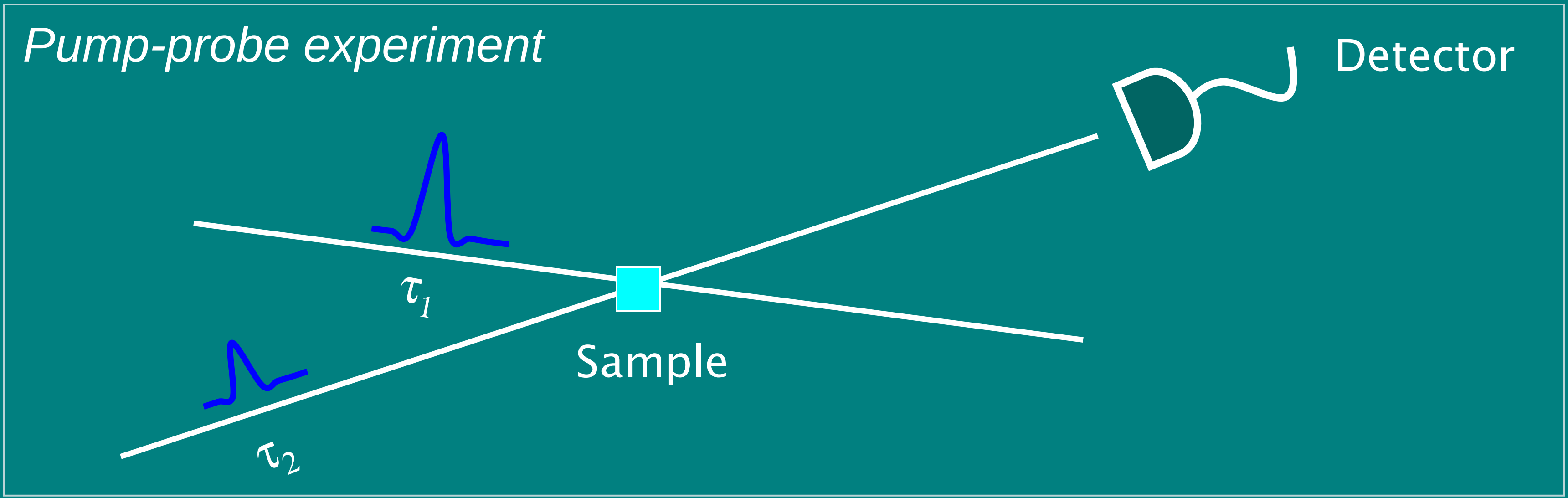
- **B(x)**



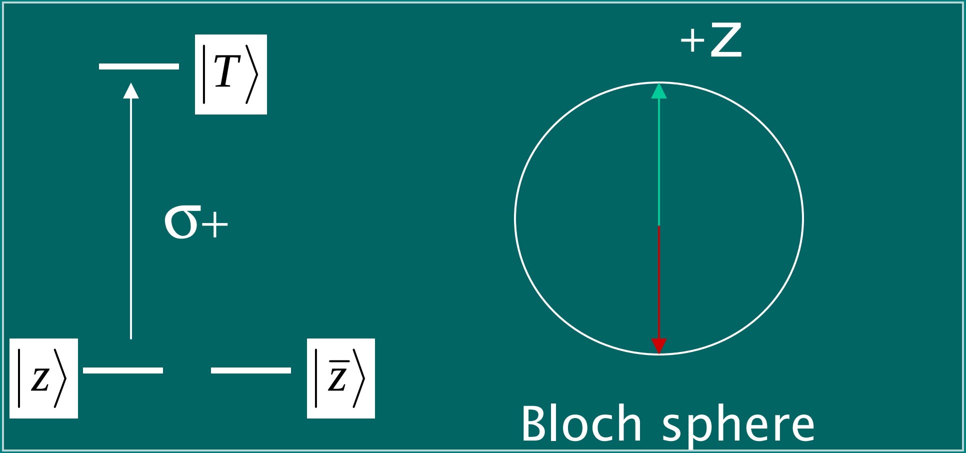


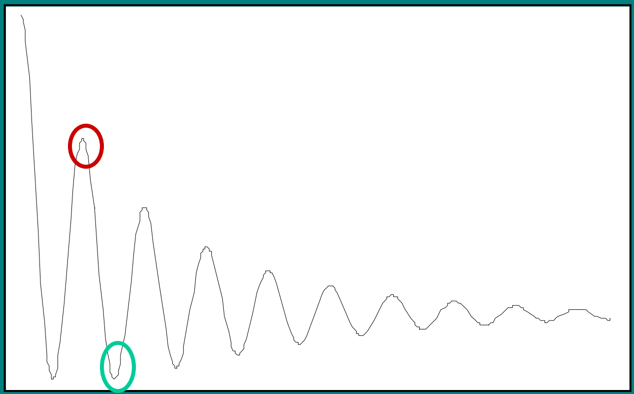
Limits

Experimental setup (theorist's view)

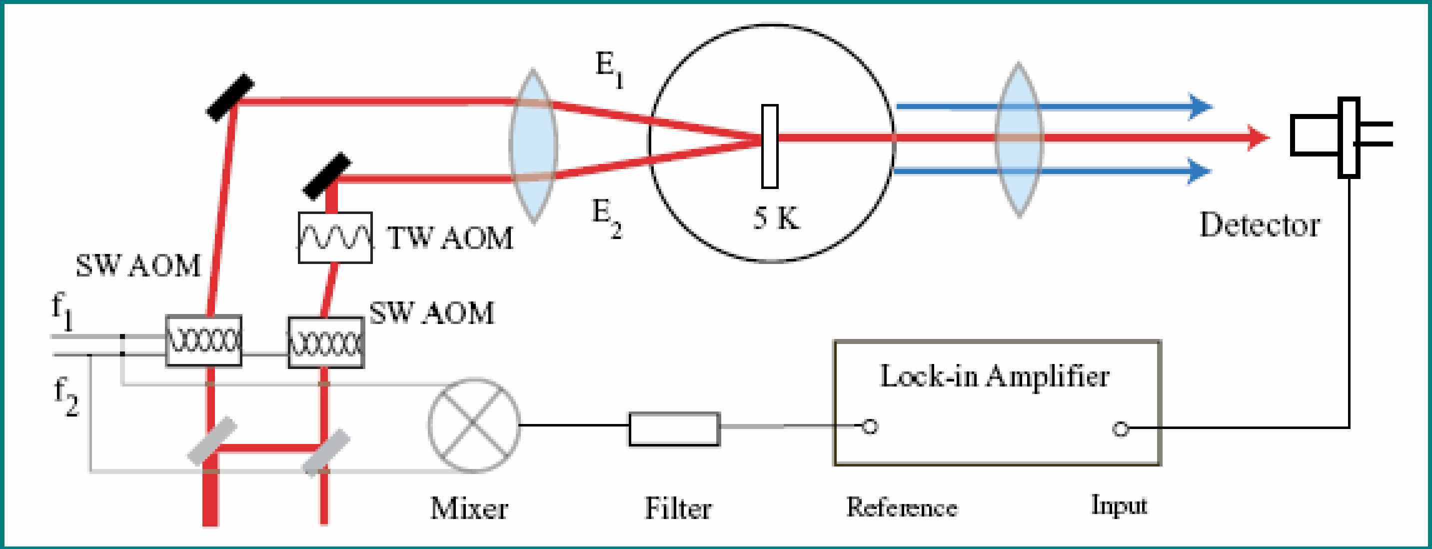


Differential transmission as fn of delay time $t_d = \tau_2 - \tau_1$

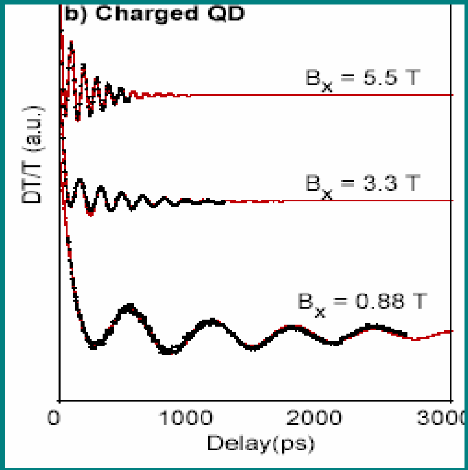




Experimental setup (experimentalist's view)



- Picks up nonlinear response (DTS)
- For low excitation power → 3rd order dominant
- DTS(σ−) – DTS(σ+) ~ S_z



Dutt et al., PRL **94,** 227403 (2005)

Analytical expressions

$$\Delta T \propto A\cos\left(2\omega_L t_d - \phi\right) e^{-\gamma_2 t_d} + B\, e^{-2\Gamma_2 t_d}$$

$$A \propto \sqrt{\frac{\gamma_2{}^2 + 4\,\omega_L{}^2}{\left(2\Gamma_c - \gamma_2\right)^2 + 4\,\omega_L{}^2}}$$

Amplitude

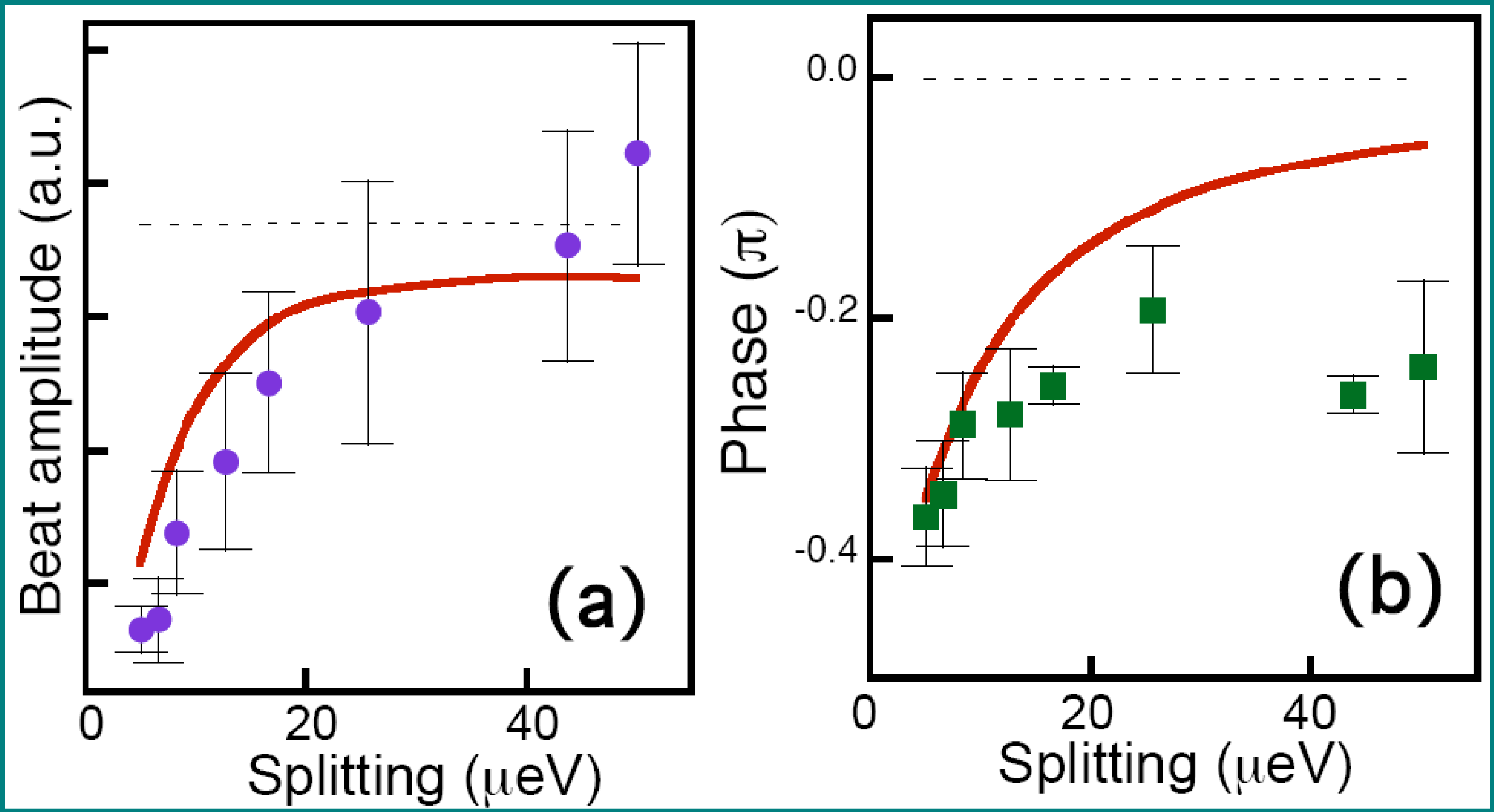
$$\phi = -\arctan\left(\frac{2\,\Gamma_c - \gamma_2}{2\omega_L}\right) - \arctan\left(\frac{\gamma_2}{2\omega_L}\right)$$

Phase

Economou, Liu, Sham and Steel, PRB 71, 195327 (2005)

Calculated & experimental results

Ensemble experiment



Dutt, Cheng, Li, Xu, Li, Berman, Steel, Bracker, Gammon, Economou, Liu, and Sham, PRL **94,** 227403 (2005)

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Background: Rabi oscillations, hyperbolic secant pulses

Single-qubit rotations

Review of proposals for optical spin rotations in QDs

- Chen,Piermarocchi,Sham,Steel (PRB '04):
  - No explicit frequency selectivity, but $\omega_L >> \Omega$ (weak pulses)
  - Adiabatically eliminate trion
  - *Implicitly* requires long pulses

Adiabaticity will slow down operations

- Kis & Renzoni (PRA '03):
  - Stimulated Raman adiabatic passage
  - Requires auxiliary lower level

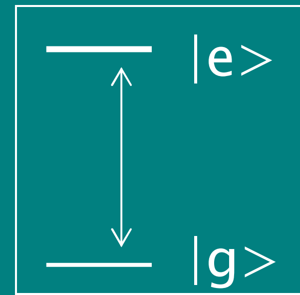
- Calarco,Datta,Fedichev,Pazy,Zoller (PRA '03):
  - π pulse to populate trion/wait/ π pulse to de-excite trion

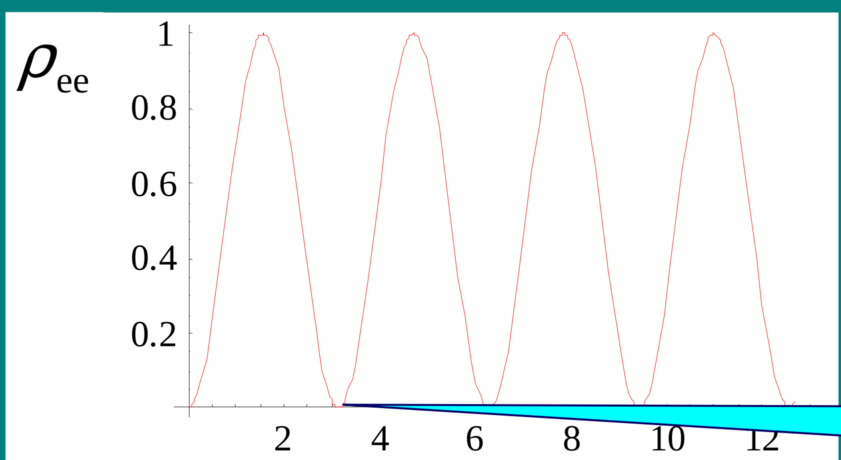
Suffers from trion decay rate

z rotations only

Rabi oscillations

- Two-level system with energy splitting ω_o
- Driven by laser with central frequency ω
- Define detuning $\Delta = \omega_o - \omega$
- Laser can be
  - CW → Rabi oscillations in time
  - Pulsed → Rabi oscillations as fn of *pulse area* $\mathcal{A} = 2\int dt\,\Omega_R(t)$



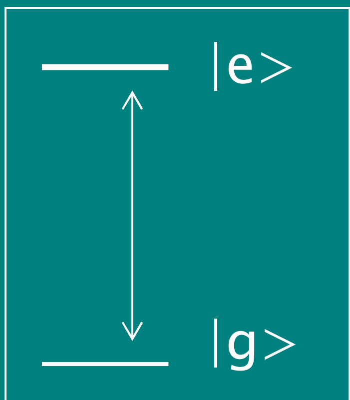


$$\Omega_R = d \cdot E_o$$

A two-level system can be mapped onto a spin (pseudospin).
SU(2) dynamics →

2π rotation: back to −|g>

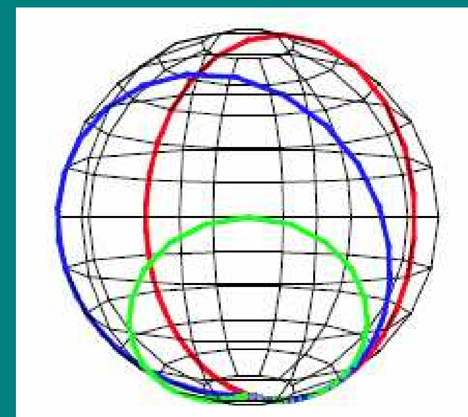
Review of sech pulses in 2-level systems



$V_{ge} = \Omega \, \text{sech}(\beta t) \, e^{i\Delta t}$

Δ = detuning

β = bandwidth



- Exact solution (Rosen & Zener Phys. Rev. '32)
- Pulse area can be defined for any Δ
- When $\Omega = \beta \rightarrow 2\pi$ pulse
- Population returns to |g> with an acquired phase:

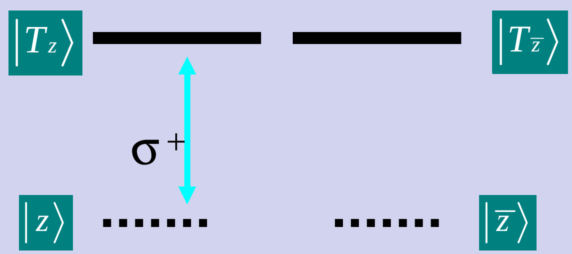
$$\phi = 2 \arctan\left(\frac{\beta}{\Delta}\right)$$

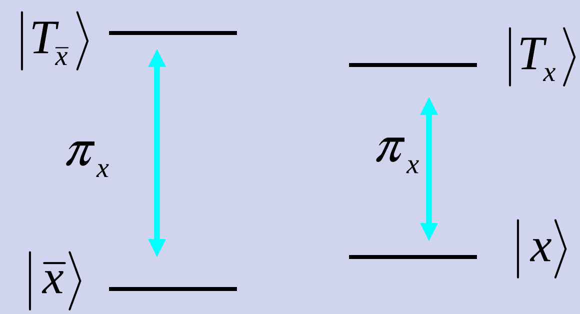
Global for 2lvl sys
Useful in presence of
A third level

Economou et al. PRB **74** (2006)

Use of 2π sech pulses for rotations: Strategy outline

- By choice of polarization, decouple different two level systems:





- Each time the ground state is a spin state along $\hat{n}$
- A phase is induced, which is a function of the detuning
- Phase φ on spin || $\hat{n}$ is a rotation about $\hat{n}$ by φ
- By changing $\hat{n}$ we can span the whole space

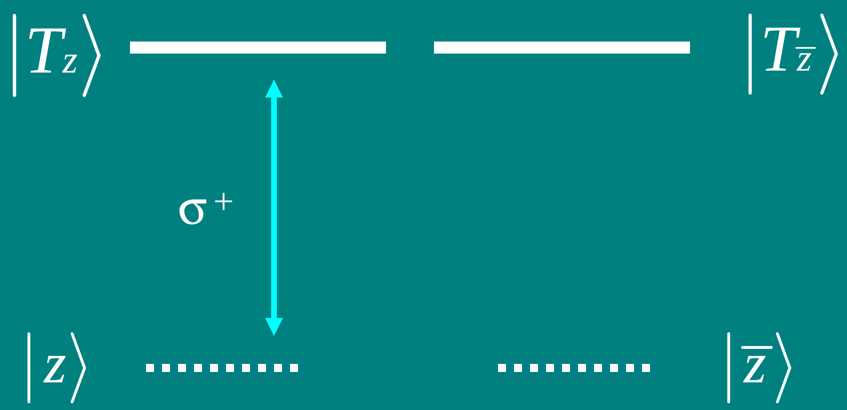
I. Small Zeeman splitting: z rotations

Broadband σ^+ pulse means $\beta >> \omega_e$

➔Spin precession ~ ‘frozen’ during pulse

➔2-level system + 2 uncoupled levels

$$U \simeq \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-i\phi} & 0 \\ 0 & 0 & e^{i\phi} \end{bmatrix}$$



$$U_{spin} \simeq \begin{bmatrix} 1 & 0 \\ 0 & e^{-i\phi} \end{bmatrix} = e^{-i\phi/2} \begin{bmatrix} e^{i\phi/2} & 0 \\ 0 & e^{-i\phi/2} \end{bmatrix}$$

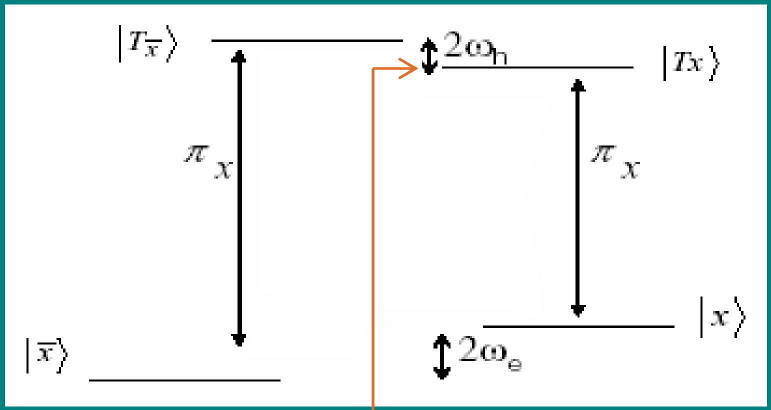
(in the z basis)

Ultra fast z rotations

Economou, Sham, Wu, Steel, PRB **74**, 205415 (2006)

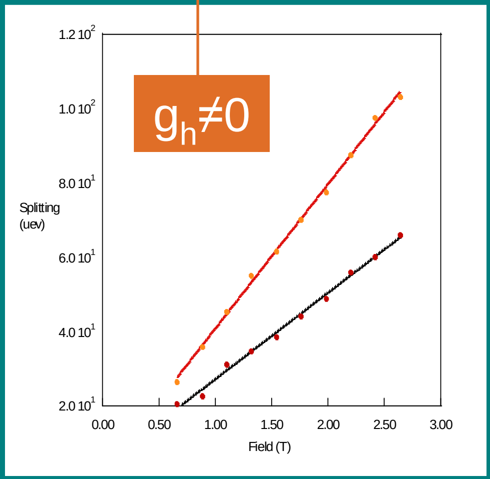
I. Small Zeeman splitting: x rotations

- Use of linearly polarized light decouples the 4-level system to two 2-level systems:
- Detunings for 2 transitions Δ_1, Δ_2
- Bandwidth β_x



2π sech pulse induces a *different* phase in $|x\rangle$ and $|\bar{x}\rangle$. The difference of phases is angl of rotation

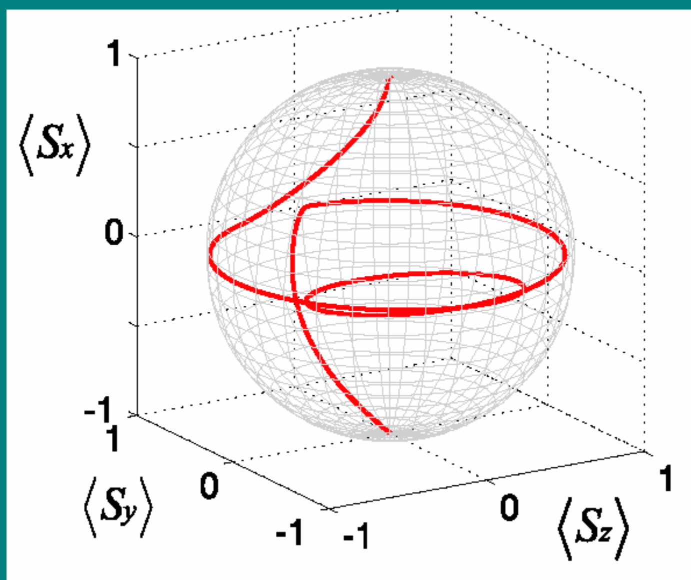
$$\phi_x = 2\arctan\frac{\beta_x(\Delta_1 - \Delta_2)}{\Delta_1\Delta_2 + \beta_x^2}$$

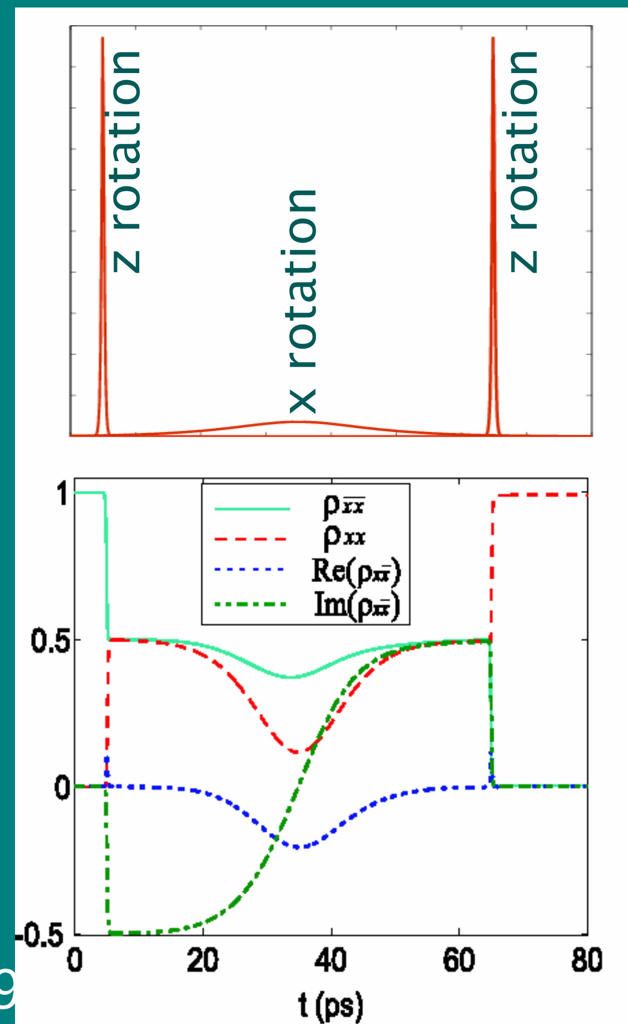


We have designed rotations about two axes, z and x
By combining them we can make any rotation!

Example: π rotation about y axis

Fidelity 99.28%



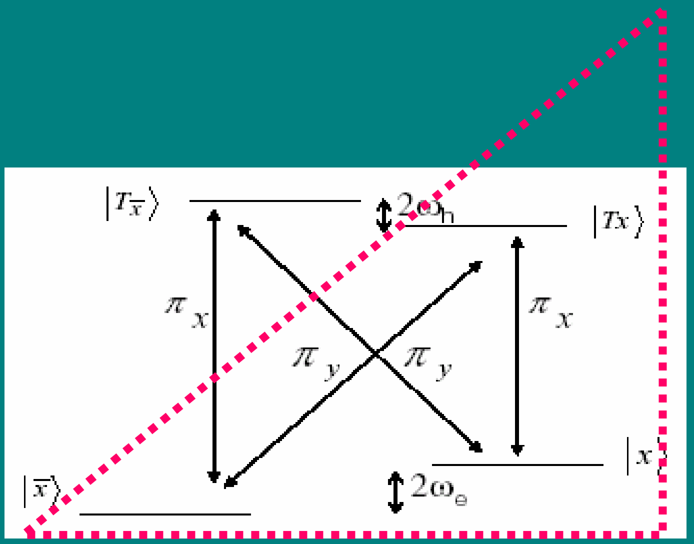


Parameters for InAs QDs used

Economou & Reinecke, cond-mat/070309

II. Large Zeeman splitting

- Above scheme requires large bandwidths for z rotations
- For QDs with large Zeeman splittings such lasers may not be available
- Modification of proposal



Use narrowband pulses to select a Λ system

Total laser field

$$\vec{E} = E_x\ f_x(t)\ e^{i\omega_x t}\hat{x} + e^{i\alpha}E_y\ f_y(t)\ e^{i\omega_y t}\hat{y} + c.c.$$

Choosing equal detuning and same f(t) creates a coherently trapped state

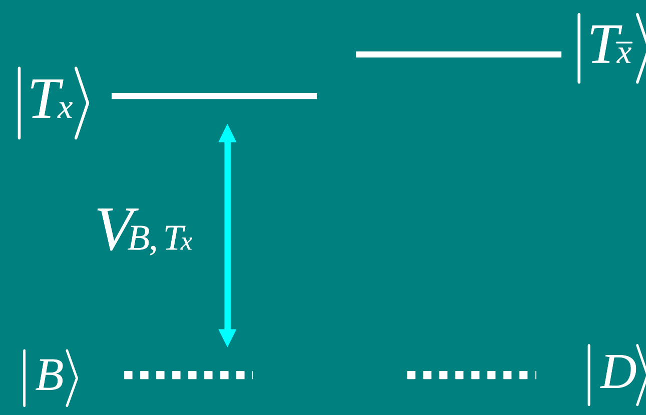
Bright/dark states determined by phase and relative strength of two lasers

Coherent population trapping + 2π sech pulses: analytic sln to Λ system

Energy eigenstates $|x\rangle$, $|\bar{x}\rangle$ are related to bright/dark $|B\rangle$, $|D\rangle$ by

$$\mathcal{T} = \begin{bmatrix} \cos\vartheta & -e^{i\alpha}\sin\vartheta \\ e^{-i\alpha}\sin\vartheta & \cos\vartheta \end{bmatrix}$$

where $\tan\vartheta = E_y/E_x$



Bright state coupling to trion is

$$V_{B,T_x} = \Omega_o\, f(t)\, e^{i\Delta t}$$

where $\Omega_o = \sqrt{\Omega_x^2 + \Omega_y^2}$

We want the total pulse acting on bright state to have area 2π : $\Omega_o = \beta$

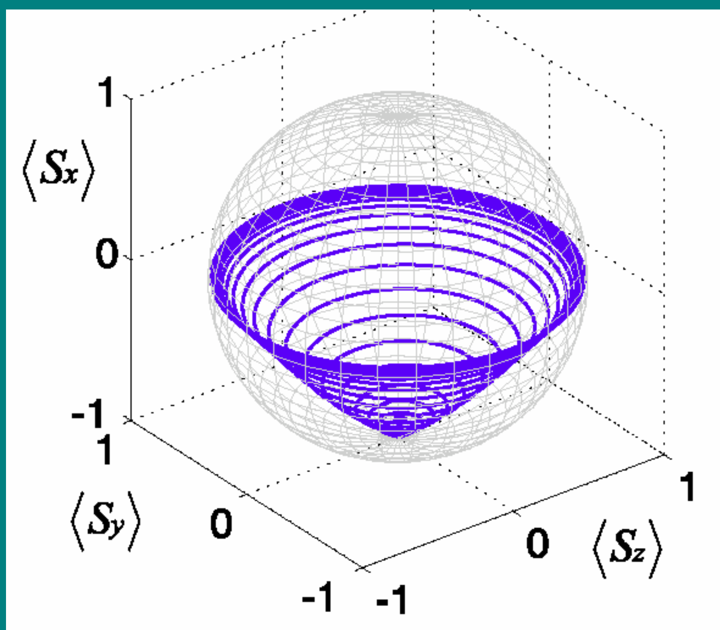
$$\phi = 2\arctan\left(\frac{\beta}{\Delta}\right)$$

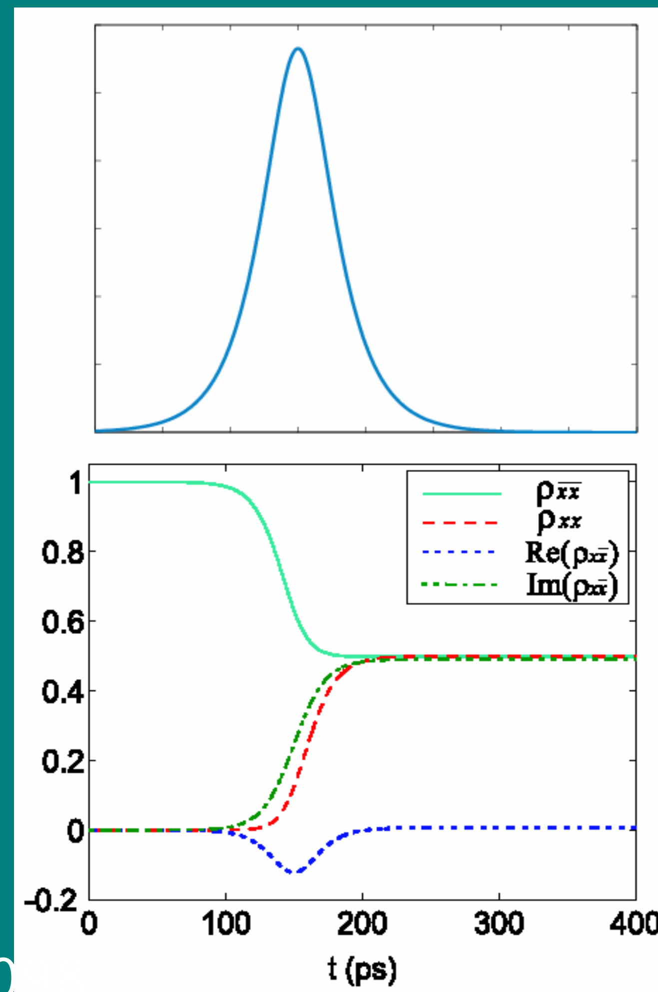
$$R_n(\phi) = e^{-i\phi\hat{n}\cdot\vec{\sigma}/2}$$

$$\hat{n} = (\cos\vartheta, \sin\vartheta\sin\alpha, \sin\vartheta\cos\alpha)$$

Example: π/2 rotation about z axis

Fidelity 98.84%



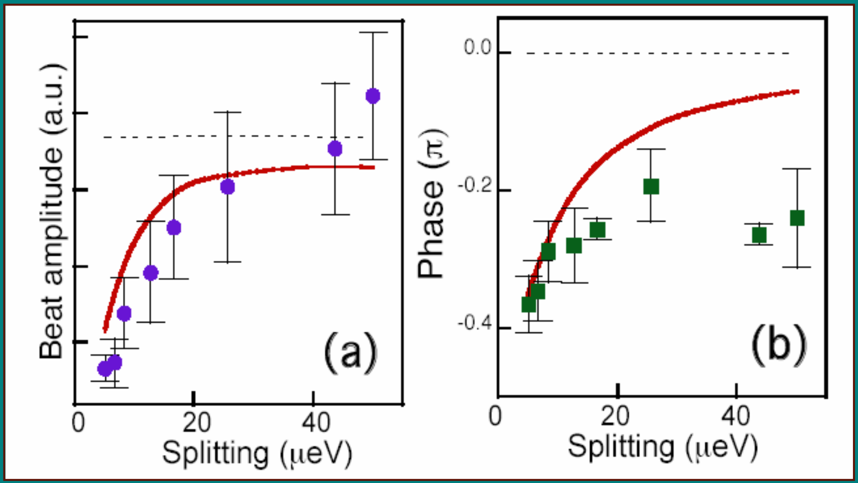


Parameters for CdSe QDs used

Economou & Reinecke, cond-mat/07030

Summary–I

- SGC has important effect on quantum beats in QDs
- First observation of SGC in QDs (not atoms)

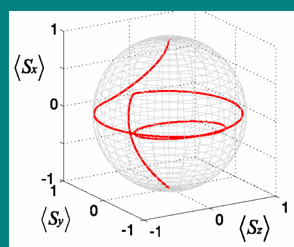


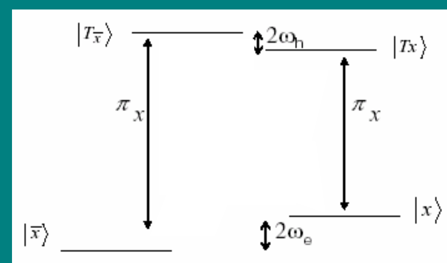
Summary–II

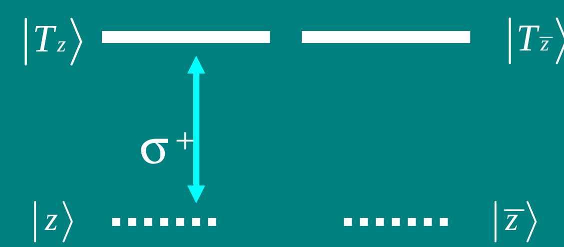
- 2π sech pulses to decouple 2 level systems

Phase $$\phi = 2\arctan\left(\frac{\beta}{\Delta}\right)$$

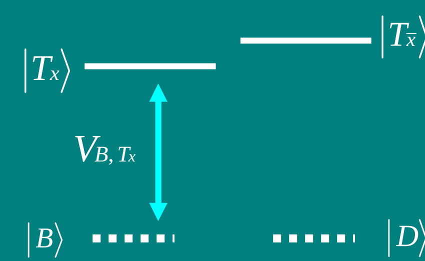
- Small Zeeman splitting







- Large Zeeman splitting: CPT scheme



- Simple for experimental demonstration