KITP Spintronics Program Seminar April 25, 2006

Optical control of the electron spins
Single Spin Optoelectronics

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Three key questions

1. Does an electron spin in a quantum dot qualify as a TLQS?
2. Can we make a team of the spins dance prettily?
3. Can one make money from it (by investing or taxing)?

Research funded by ARO/LPS, NSF DMR, DARPA/QuIST/AFOSR

Optical control of electron spins in semicondutor nanodots

UCSD
Theory
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Carlo Piermarocchi
Yseulte Dale
Sophia Economou
Wang Yao
Renbao Liu
Michael Leuenberger
Clive Granger
Semion Saikin

Nanocavity
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Shaya Fainman
Yaoming Shen
CalTech
Axel Scherer
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Gang Chen
Todd Stievater
Xiaoqin Li
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Jun Cheng
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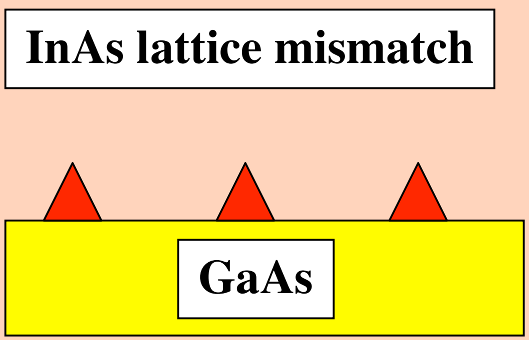
Naval Res Lab
Fabrication & Characterization
Dan Gammon
D.S. Katzer
D. Park
J.G. Tischler
A.S. Bracker

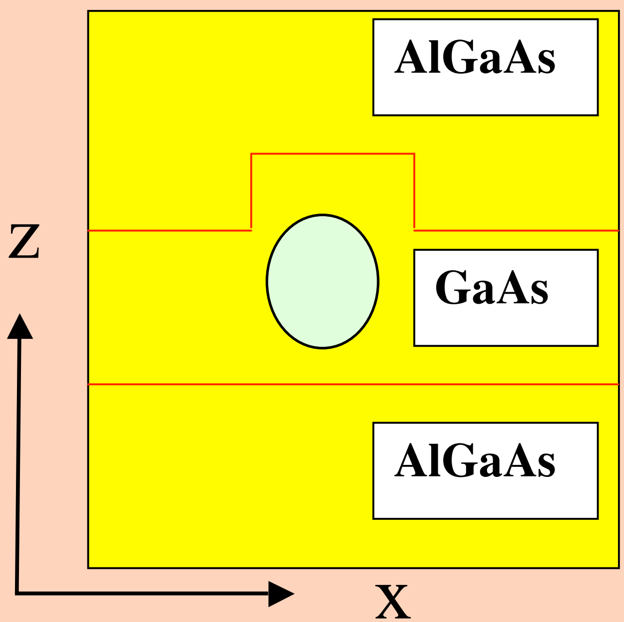
Three Kinds of Semiconductor Quantum Dots

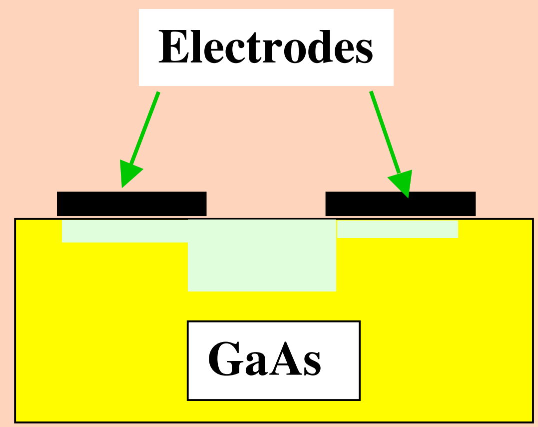
Self-assembled quantum dots
(3-10 nm)
$\Delta E \sim 100$ meV

Interface fluctuation quantum dots
($30 \times 40 \times 3$ nm^3)
$\Delta E \sim 10$ meV

Gated quantum dots
(100 nm)
$\Delta E \sim 1$ meV

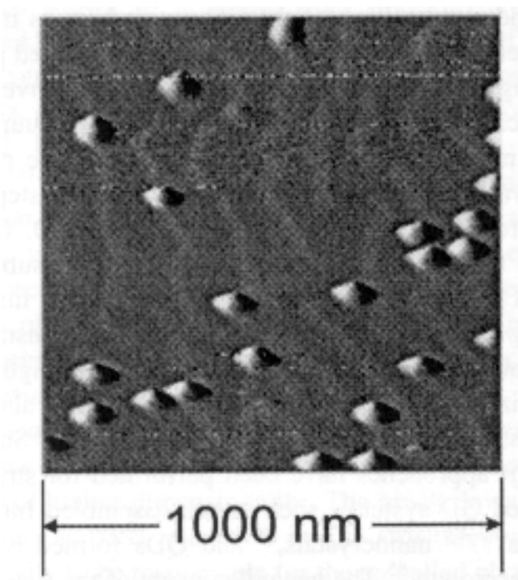






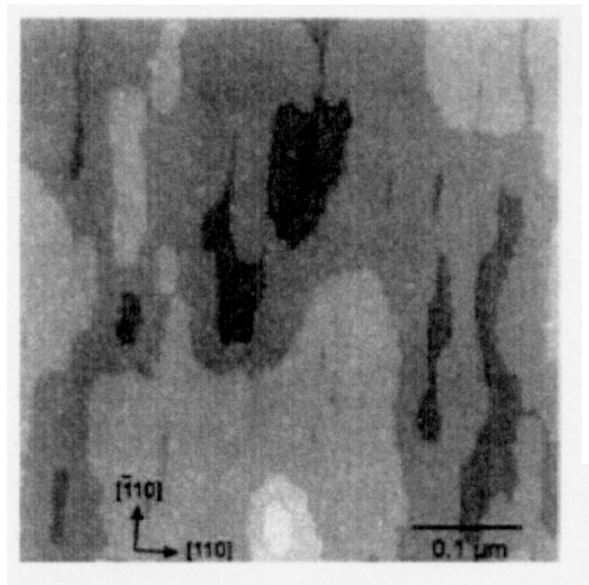
Experimentalists' view of Quantum Dots

Self-assembled quantum dot



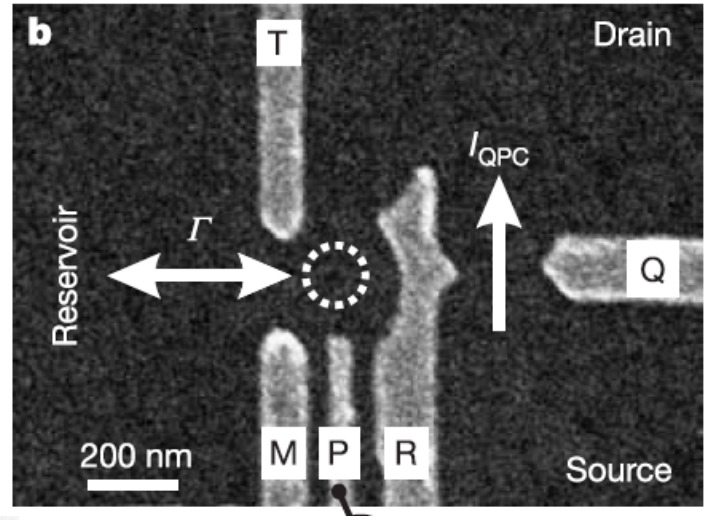
A. Zrenner, et al. J.Chem.Phys. **112**, 7790 (2000).

Interface fluctuation quantum dot



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

Gated quantum dot

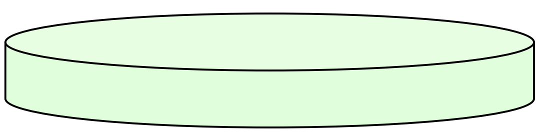


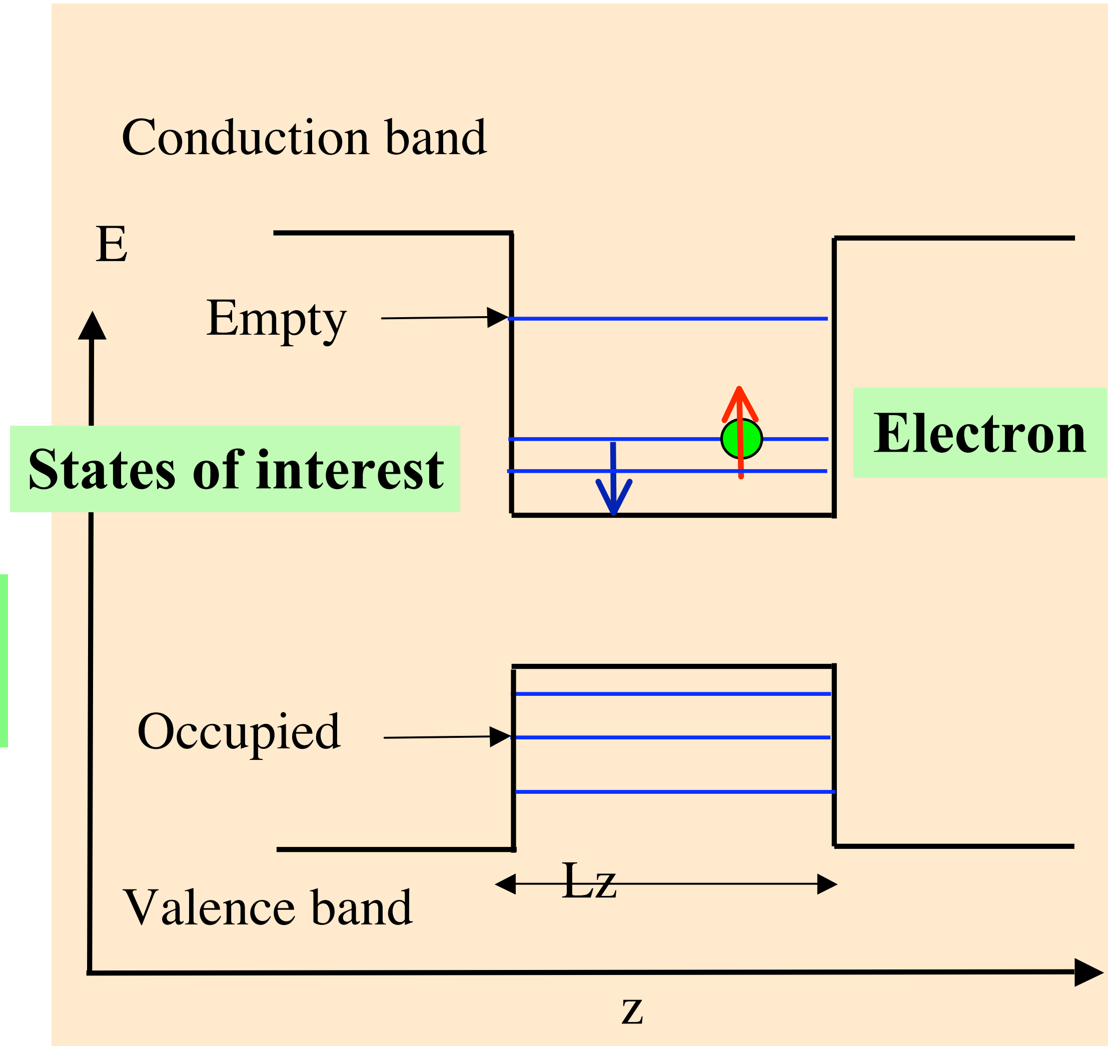
Elzerman et al. Nature **430**, 431 (2004)

Theorists' view of quantum dots

Square-well quantum dots

Lateral harmonic well qauntum dots





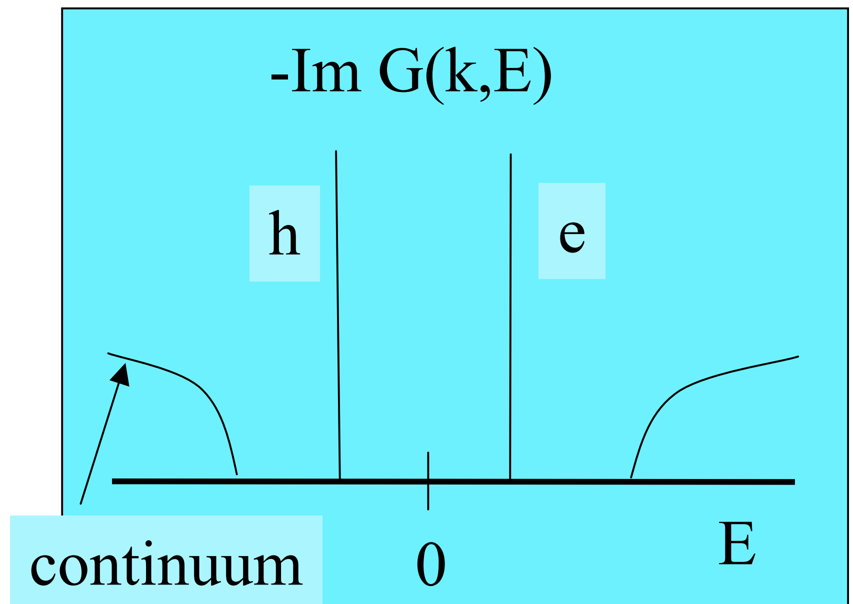
Is an electron in a dot isolated?

- **Assumption: periodic lattice with no vibrations (low temperature).**
- **Consideration of e-e interaction, lattice symmetry and semiconductor band gap leads to the spectrum shown for an electron added to the ground state or removed from it.**
- **Without radiative interaction, the exciton is an exact excited state.**
- **Confinement of an electron in a quantum dot.**

N+1 electron problem

Kohn PR (1960)
Sham, PR (1966).
Sham and Rice, PR (1966).

Electron spectral density



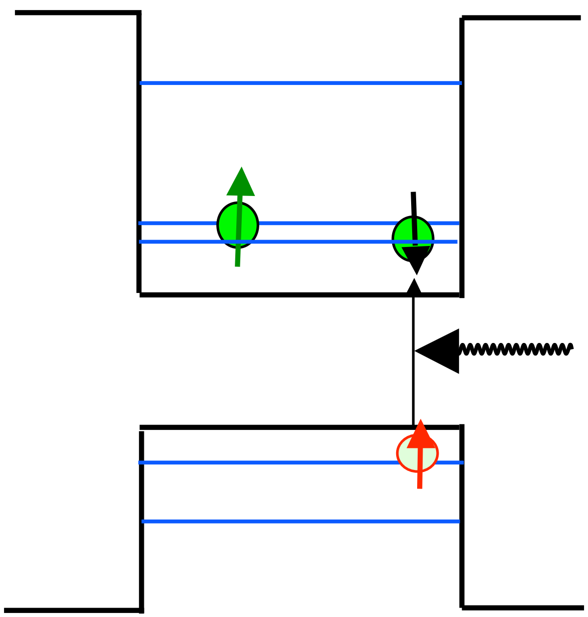
Interaction of the dot spin with outside

- Preparation of initial state (initialization)
- Quantum operations by optical control
- Measurement of single spin state
- Decoherence and recovery - KITP Spintronics Program seminar 4/11/06

Optical transitions in a charged dot

Single particle levels

Spin State to Trion



Multi-particle states

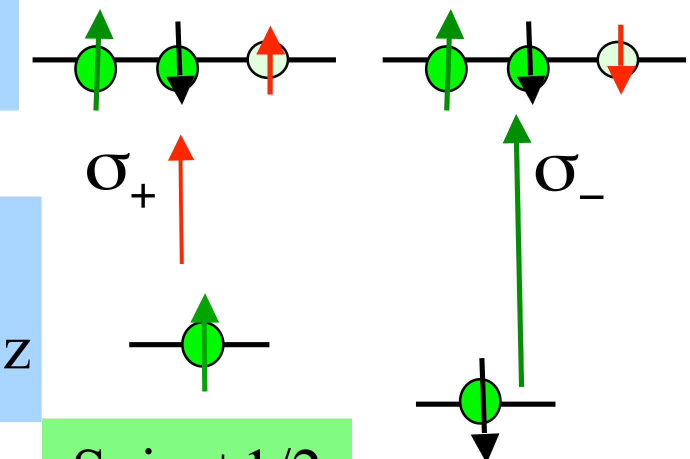
Selection rules

Spin +3/2

Spin −3/2

Trion

Magnetic field along z

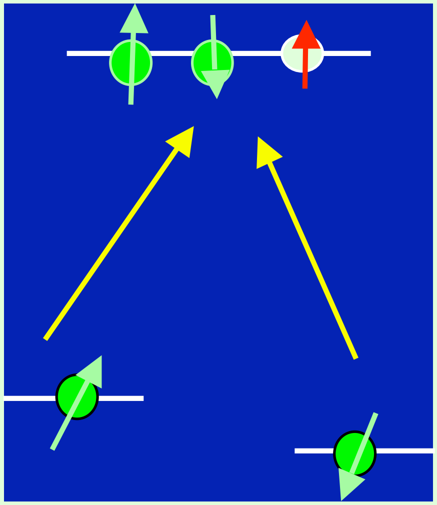


Spin +1/2

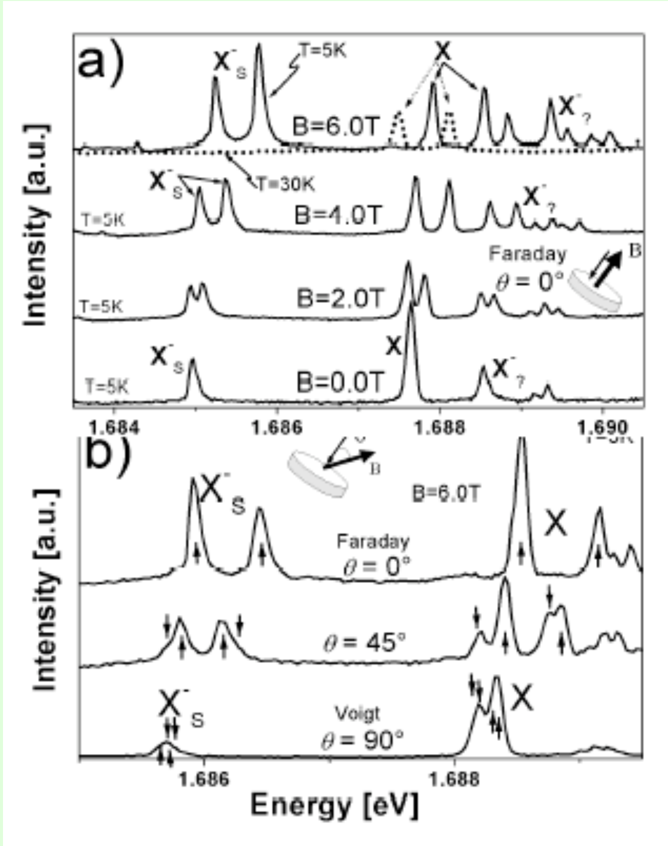
Spin −1/2

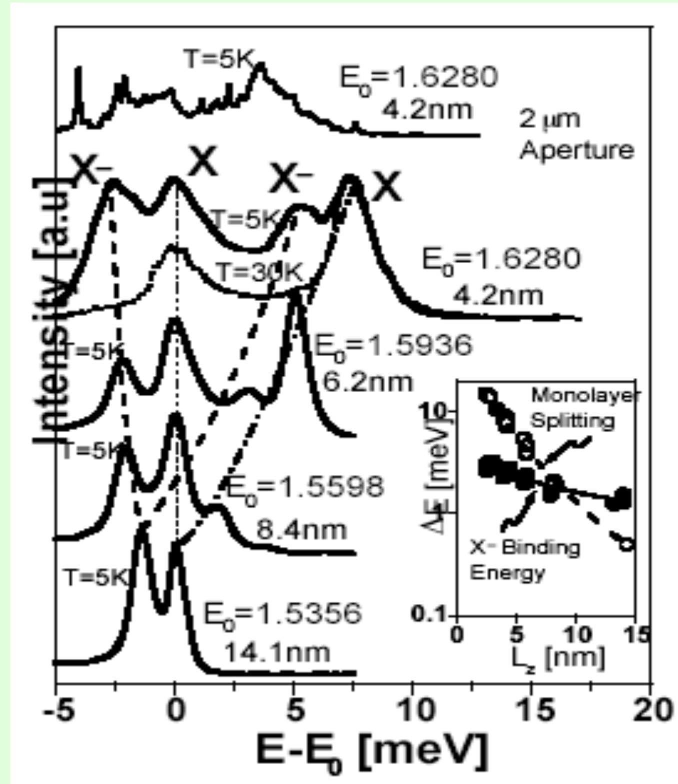
Trion states in a single dot

Ensemble Luminescence Spectra



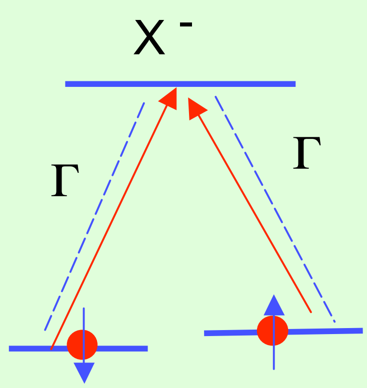
Magnetic field along x

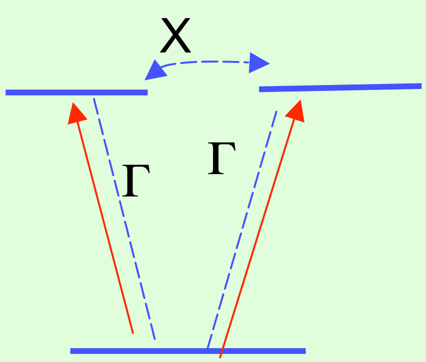


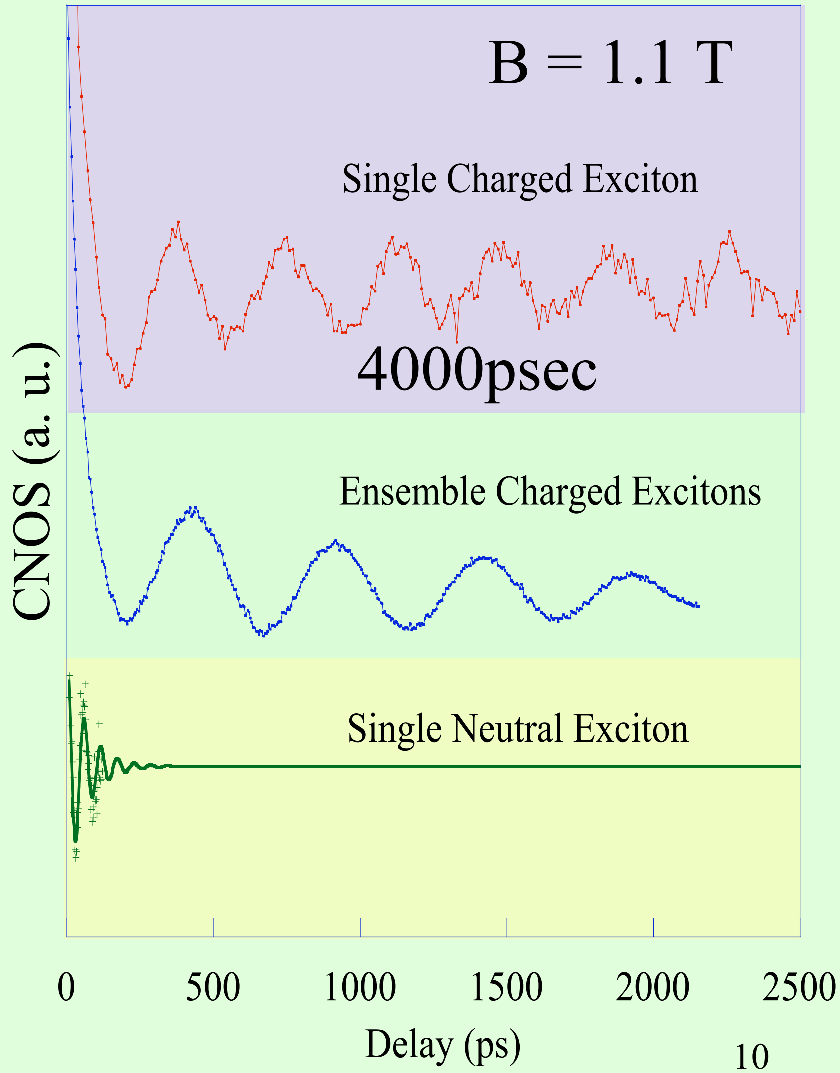


J.G. Tischler, D. Gammon and A.S. Bracker, NRL

Single Electron Spin Coherence





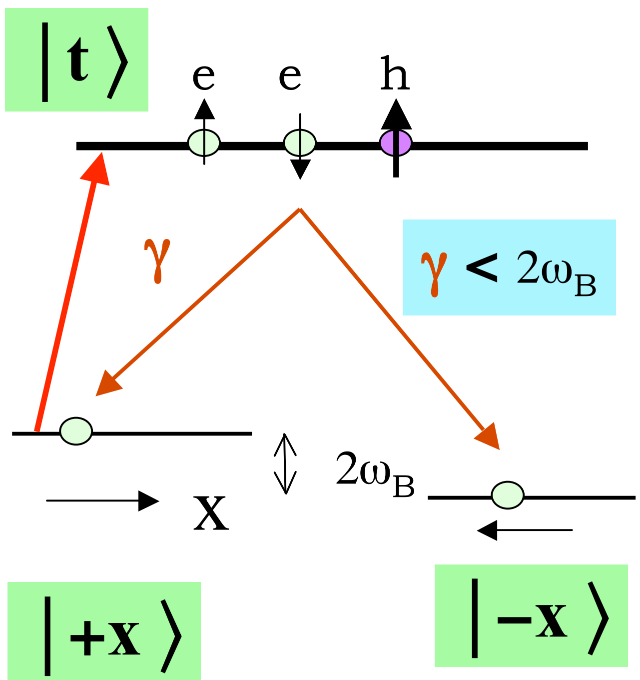


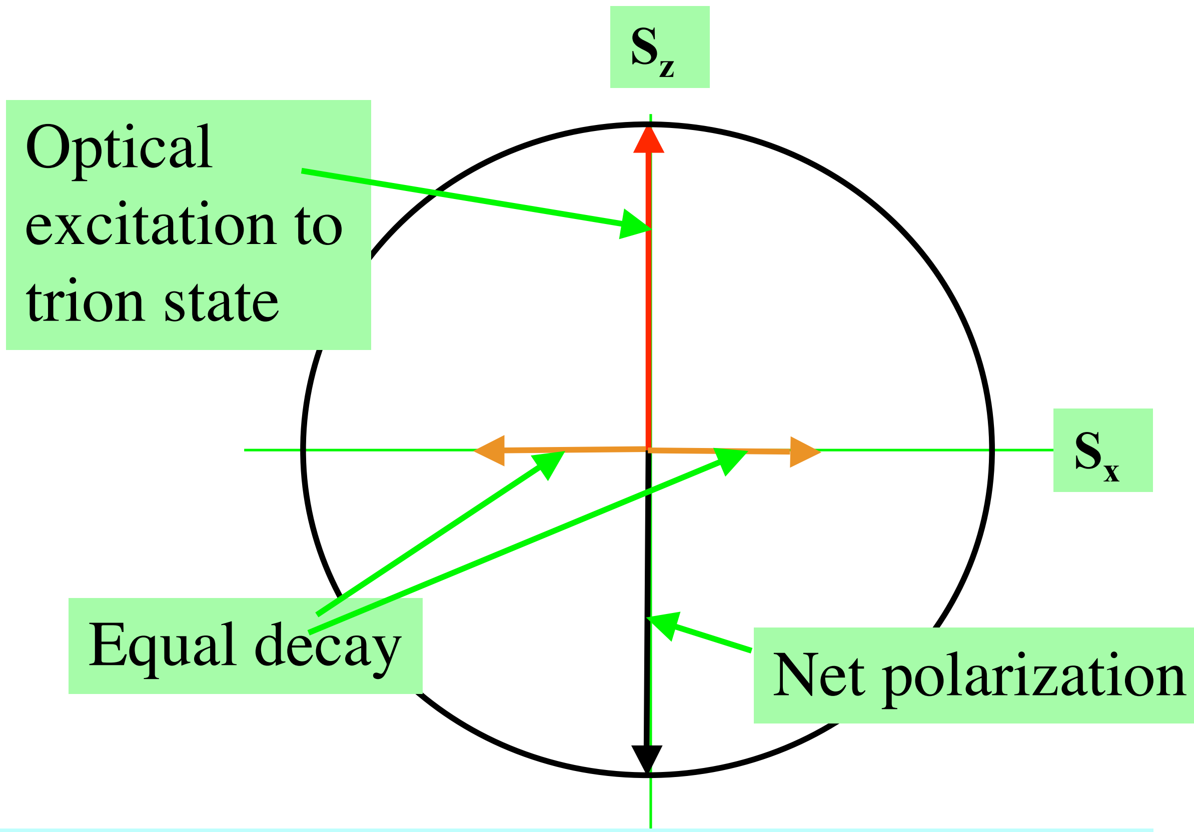
Where does the spin polarization come from?

Initially unpolarized system remains unpolarized.

$$\hat{\rho}_T = \begin{bmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{bmatrix}$$

$$\hat{\rho}_T(t) = e^{-iH/t}\hat{\rho}_T e^{iH/t} = \hat{\rho}_T$$

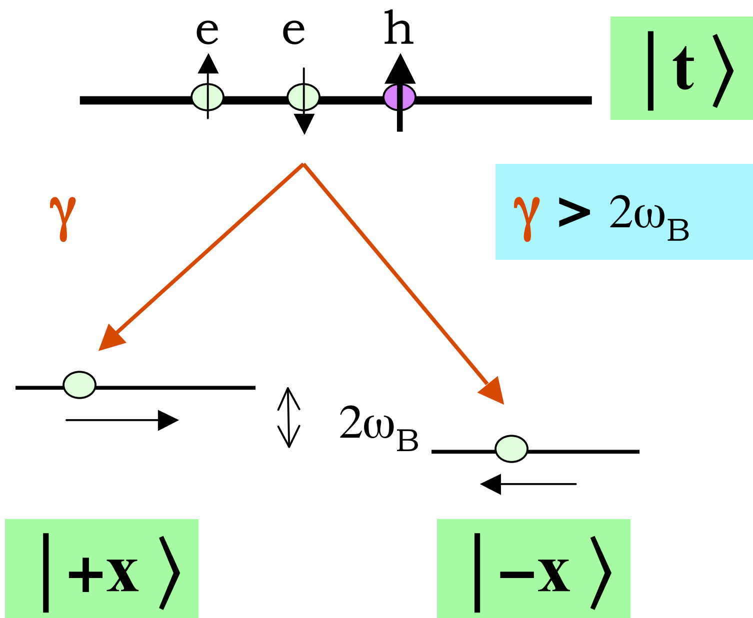


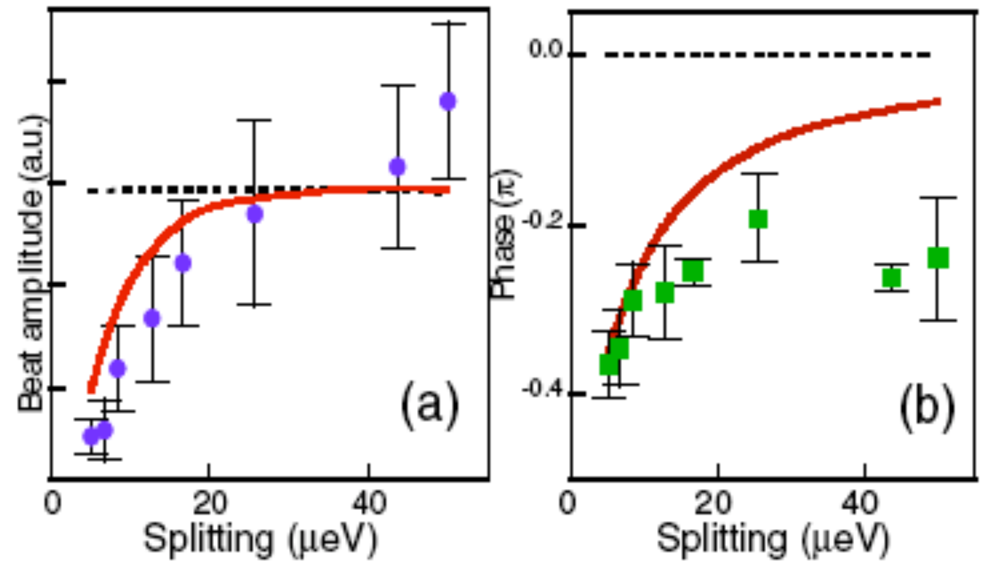


LJ Sham

One shot: 50% success rate, 10^3 cycles to improve to 0.999

Optical Decay of the Trion





Spontaneous emission creates spin coherence (SGC)

M. V. Gurudev Dutt, Jun Cheng, Bo Li, Xiaodong Xu, Xiaoqin Li, P. R. Berman, D. G. Steel, A. S. Bracker, D. Gammon, Sophia E. Economou, Ren-bao Liu, and L. J. Sham, Phy. Rev. Lett. **94**, 227403 (2005).

S.E. Economou, Renbao Liu and L.J. Sham, PRB **71**, 195327 (2005)

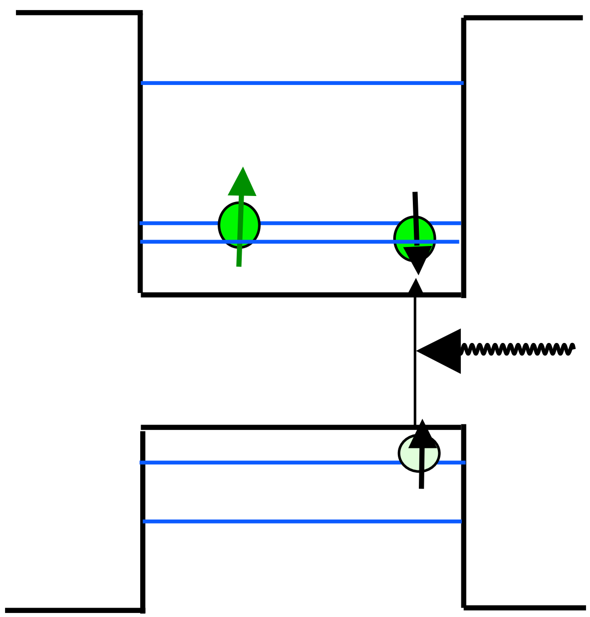
Rotation of single electron spin (single qubit gate)

Single particle levels

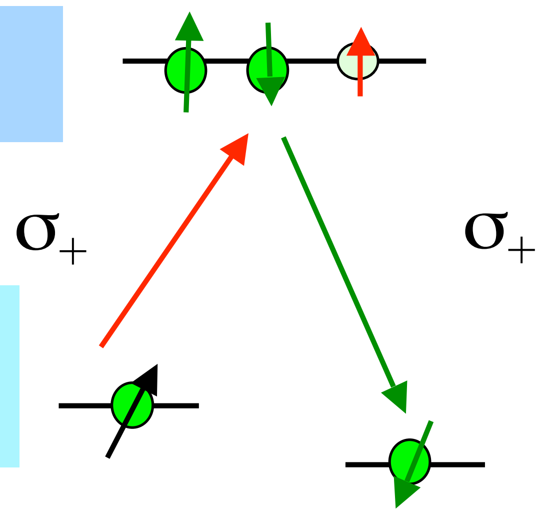
Multi-particle states

Spin State to Trion

Adiabatic NR Raman Spin-flip Process



Trion



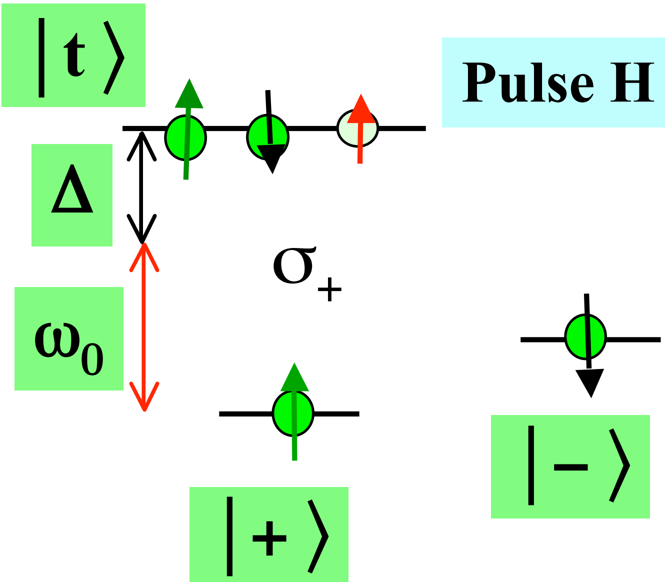
Magnetic field along x

Theo est. op time ~< 10 ps

Pochung Chen, C. Piermarocchi, L.J. Sham, D. Gammon, and D.G. Steel, PRB **69**, 075320 (2004).

Rotation about the optical (growth or z) axis

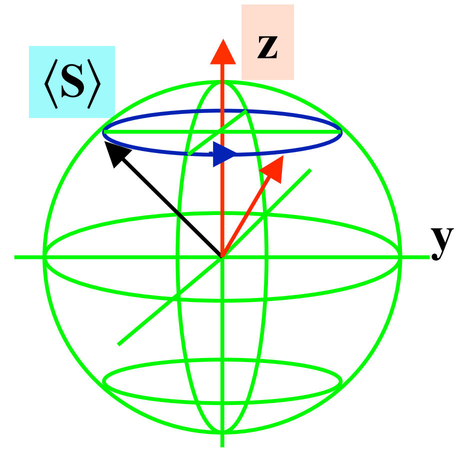
Initial spin state, $|\psi\rangle = \alpha|+\rangle + \beta|-\rangle$



Pulse H $\Omega\ \mathrm{sech}(\sigma\ t)\ e^{i\omega_o t}$

bandwidth

central frequency



2π Rabi rotation

Rosen & Zener, PR (1932)

Final state, $|\psi\rangle = \alpha\ e^{-i\phi}|+\rangle + \beta|-\rangle$

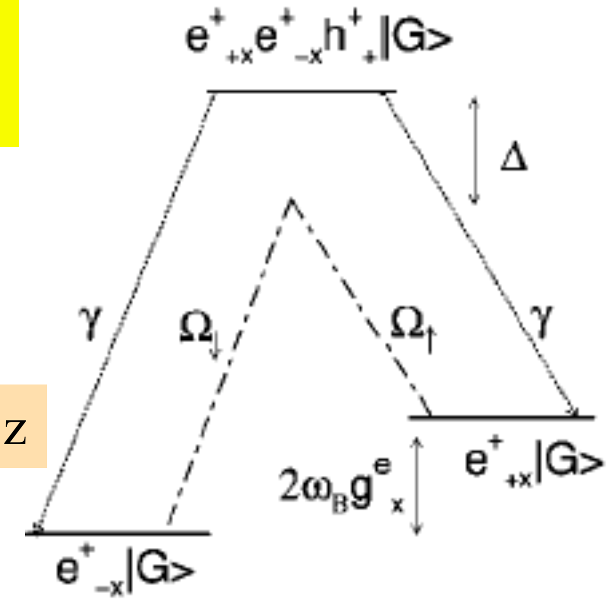
Δ - detuning

$$\tan\phi = \frac{2\sigma\Delta}{\Delta^2 - \sigma^2}$$

Sophia Economou and L. J. Sham, QELS (2006)

Optical control of general spin rotation

2 pulses, input: amplitudes $\Omega_\uparrow(t)/\Omega_\downarrow(t)=\cot\beta$, relative phase α, and detuning Δ.



$$\begin{aligned}\Omega_\uparrow &= \Xi\sin(2\phi)\cos\beta,\\ \Omega_\downarrow &= \Xi\sin(2\phi)\sin\beta,\\ \Delta &= 2\Xi\cos(2\phi).\end{aligned}$$

B along x, light along z

$$\Xi = \sqrt{\Omega_\uparrow^2+\Omega_\downarrow^2+\left(\frac{\Delta}{2}\right)^2}.$$

Rotation axis polar angles $(2\beta,\alpha)$, angle =

$$-2\int dt\;\Xi(t)\sin^2\phi(t)$$

Conditions:
Zeeman >> pulse duration
Adiabatic, $|\dot\phi(t)| \ll 2\Xi(t)$

Optical decoherence 60 ps; spin decoherence longer than 10 ns.
Gaussian pulses of Rabi energy 1 meV, duration 8.74 ps, detuning 5 meV: the fidelity for a π rotation is 0.991.

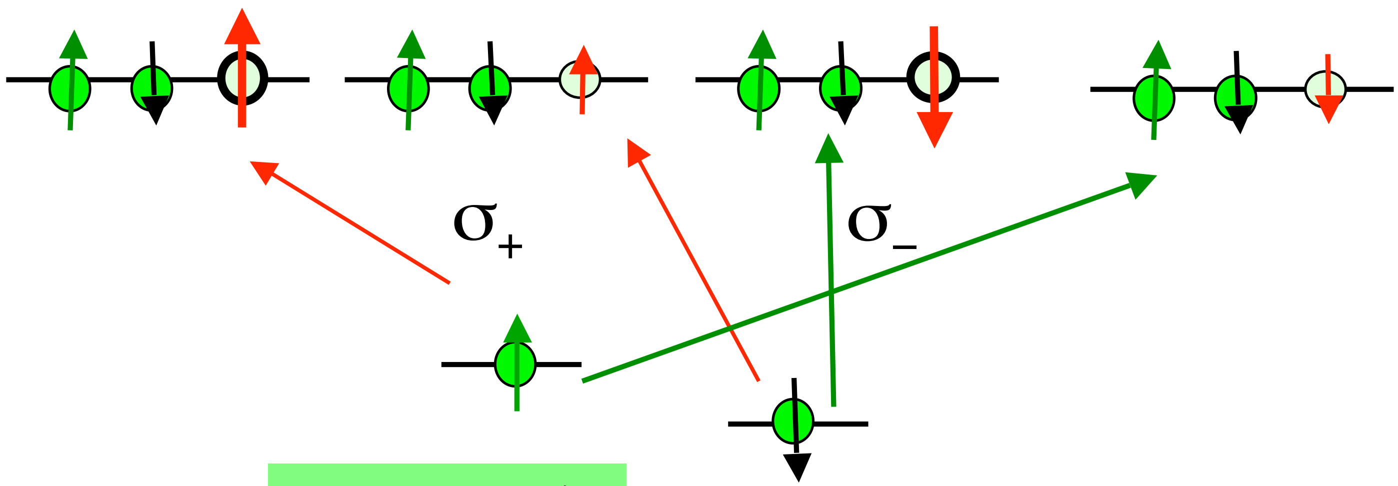
Imperfection of the selection rule

Heavy and light hole mixing, $J=3/2$, $m_J = \pm 3/2, \pm 1/2$

Hole state $|+3/2\rangle + \varepsilon|-1/2\rangle$

Spin $|-3/2\rangle$ - $\varepsilon'|+1/2\rangle$

Trions



Spin $|+1/2\rangle$

Spin $|-1/2\rangle$

Optical axis is tilted away from the z axis - deterministic.

Spin state preparation by optical pumping

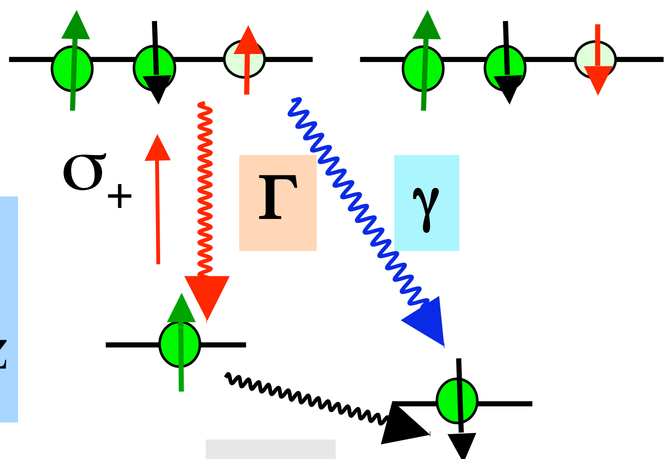
Multi-particle states

A. Kastler (1952)

allowed $\Gamma > \gamma$ forbidden

Trion

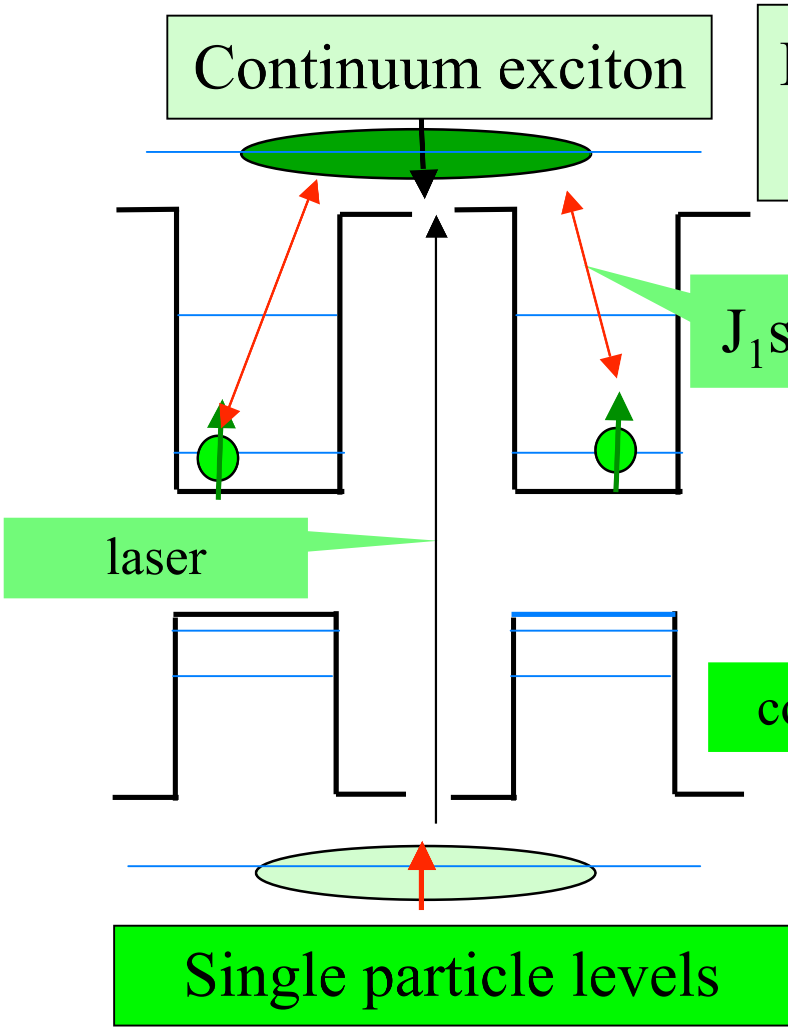
Magnetic field along z



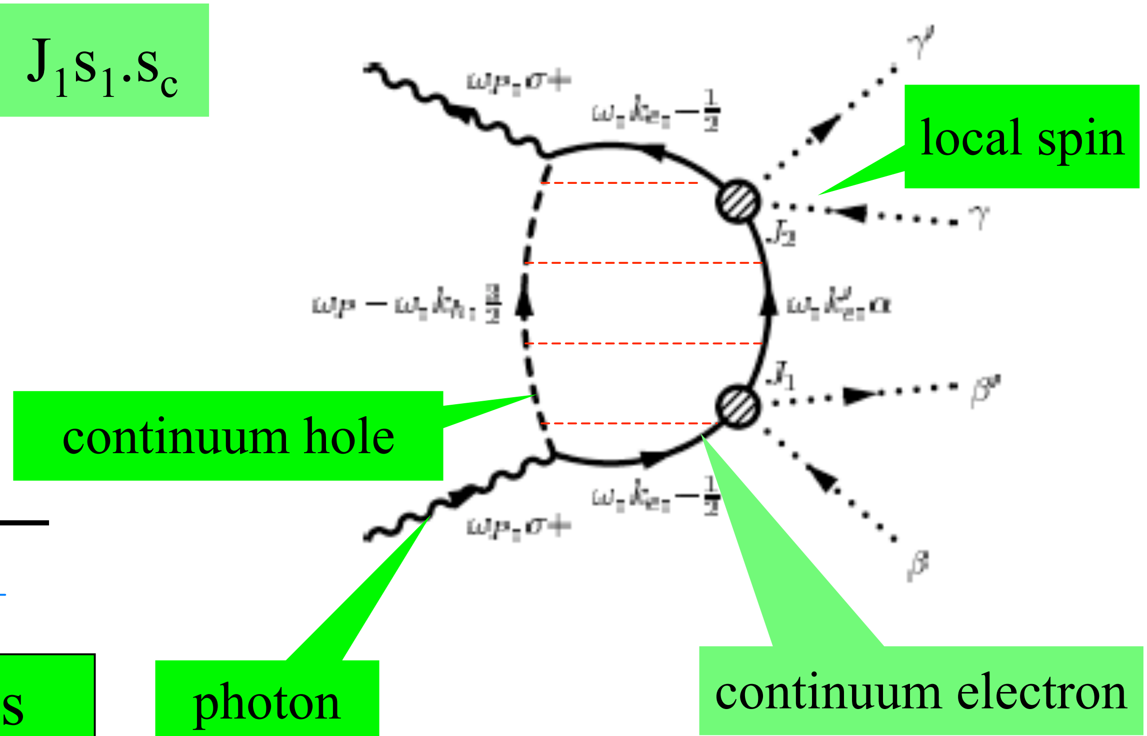
- Expt of SAQD InAs in GaAs
- Resonant laser excitation for a time (~300 ms) >> 1/ γ (1 μs) but less than T_1 due to tunneling
- Fidelity 0.998 at 3T (or spin T~20 mK for Zeeman~ 4K) - at op temp of 4K, B~62T, it would takes forever at rate $1/T_1$

Atatüre, Dreiser, Badolato, Högele, Karrai, Imamoğlu, Science Express, 4/6/06

Controlling spin interaction between two electrons in two quantum dots (ORKKY or Bloombergen-Roland)



Effective Heisenberg exchange between the electrons in two dots $Js_1.s_2$



Pochung Chen, C. Piermarocchi, L.J. Sham, and D.G. Steel, Phys. Rev. Lett. **89**, 167402 (2002).

Effective interaction between two electrons in separate dots under optical excitation (RPA)

$2k_f R$ for above gap excitation

$$H = -2J(R)\sigma_1 \cdot \sigma_2.$$

3D $$J \sim \left(\frac{\Omega}{\Lambda}\right)^2 Ry^* \frac{e^{-2R/\kappa}}{R/\kappa},$$

2D $$J \sim \left(\frac{\Omega^2}{\Lambda\delta}\right) Ry^* e^{-2R/\kappa},$$

1D $$J \sim \left(\frac{\Omega}{\delta}\right)^2 Ry^* \left(1 + \frac{R}{\kappa}\right) e^{-2R/\kappa}.$$

Ω = Rabi energy

Λ = energy in dot

R = interdot distance

δ = detuning

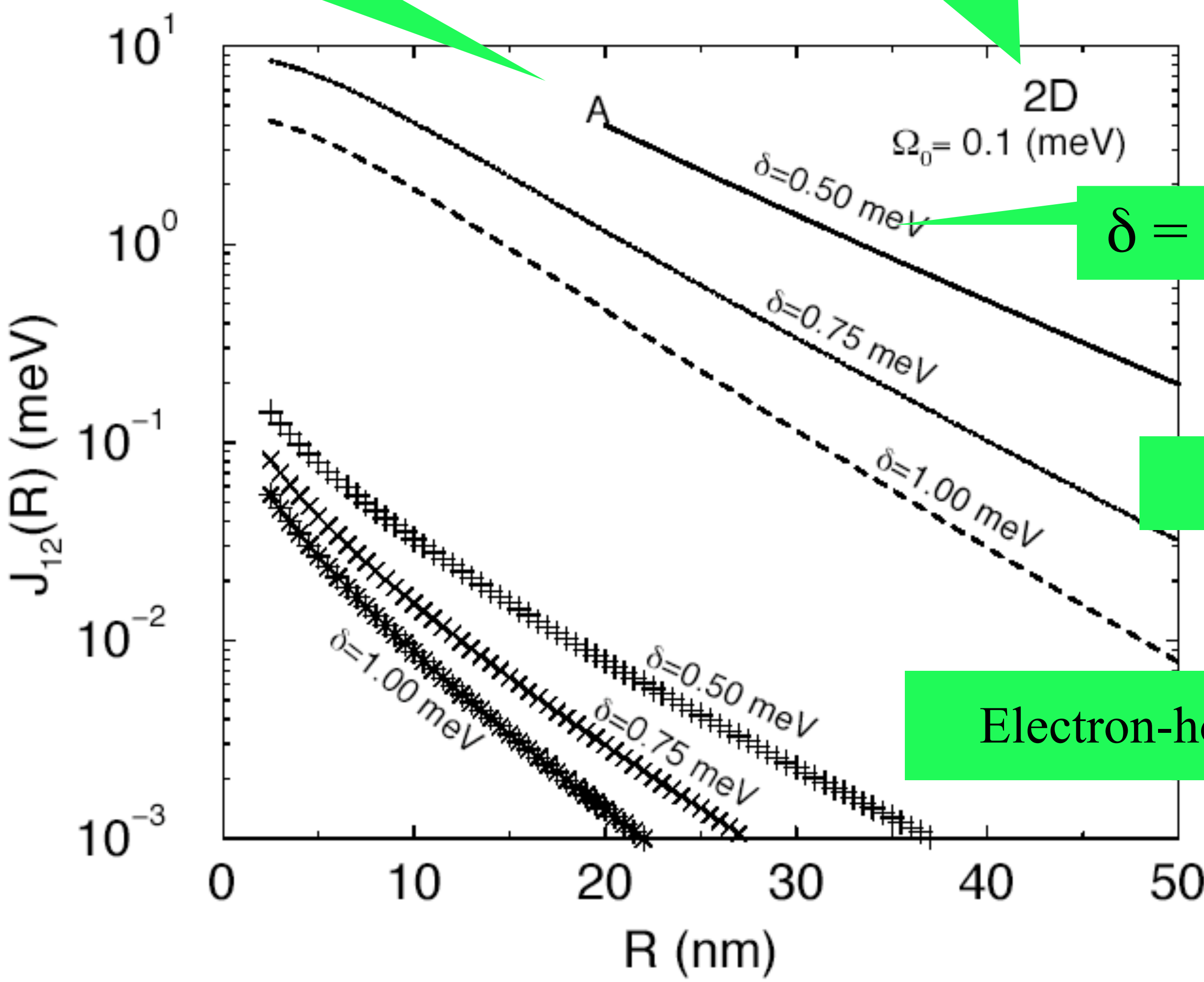
$$\kappa = \sqrt{\frac{\hbar^2}{2m\delta}}$$

Adiabaticity condition: pulse width in time $\gg \frac{\Omega}{\delta^2}$

Effective exchange interaction vs dot separation R

Adiabatic limit

Host excitons in 2D



δ = detuning

Excitons

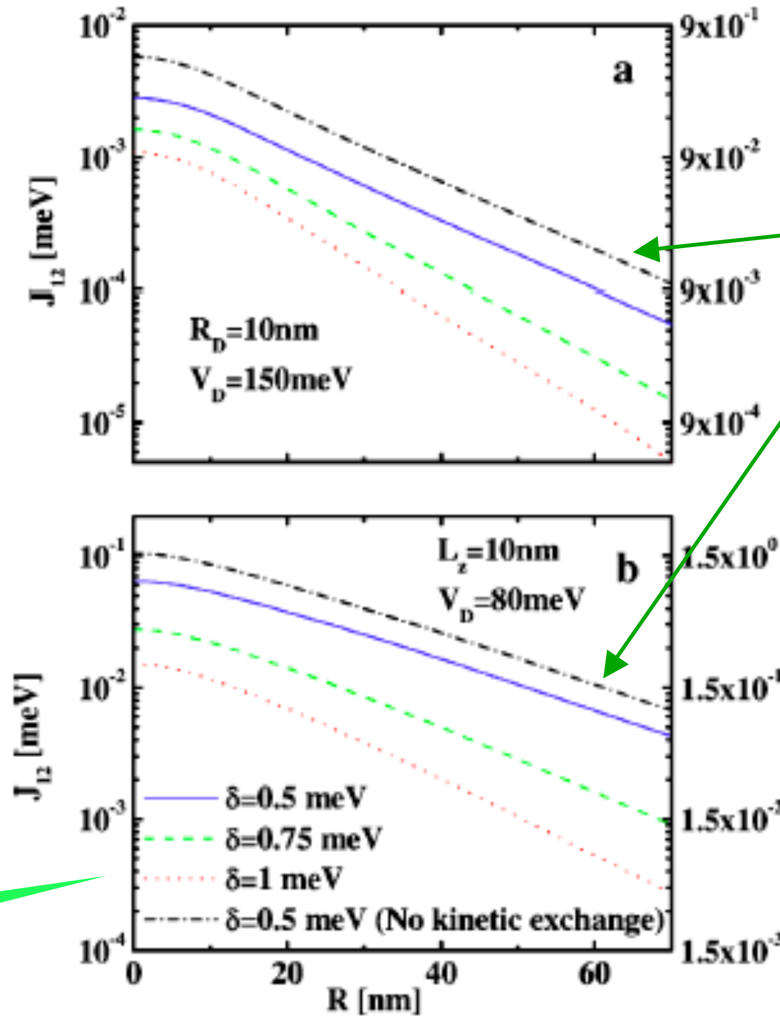
Electron-hole pairs

Effective exchange interaction vs dot separation R

Additional exchange & correlation between local and itinerant spins

Electron-hole pairs

δ = detuning



2D Host

No kinetic exchange

Excitons

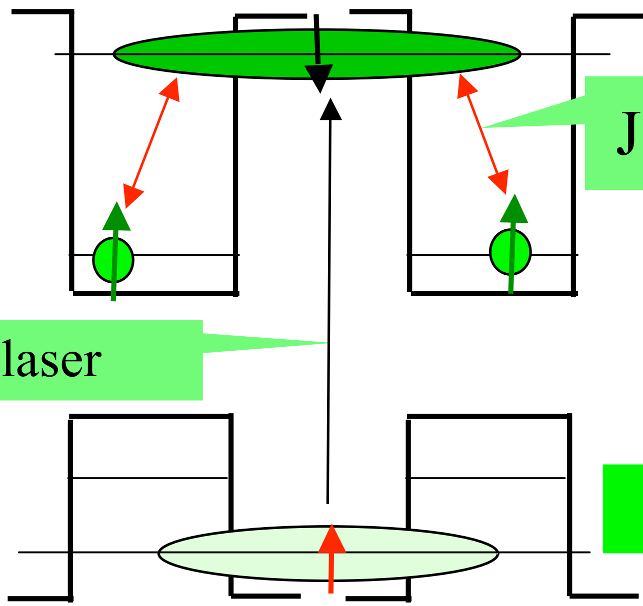
1D Host

Ramon, Lyanda-Geller, Reinecke, Sham, PRB **71**, 121305R (2005)

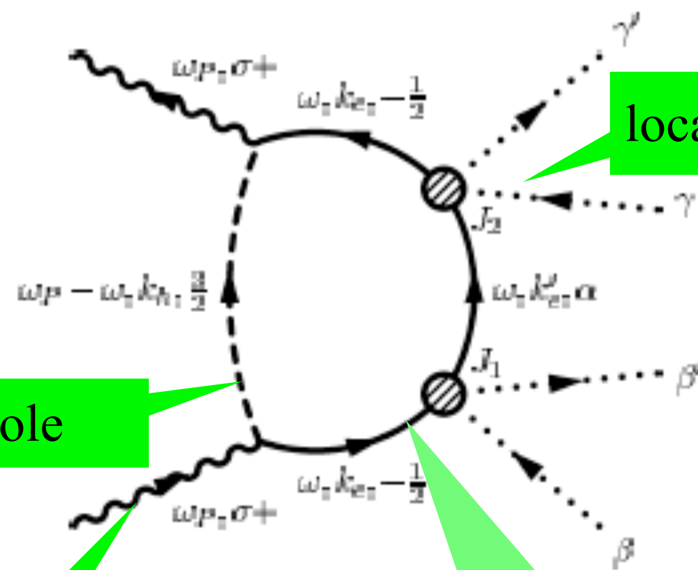
Modified ORKKY for two spin qubits in two quantum dots

Exciton over 2 dots

Effective Heisenberg exchange between the electrons in two dots $Js_1.s_2$

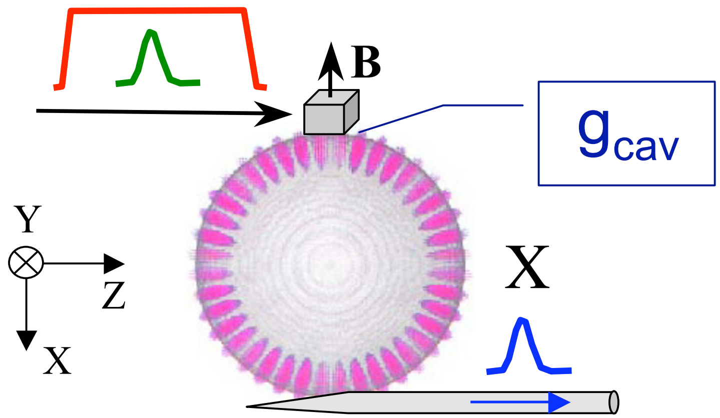


Single particle levels



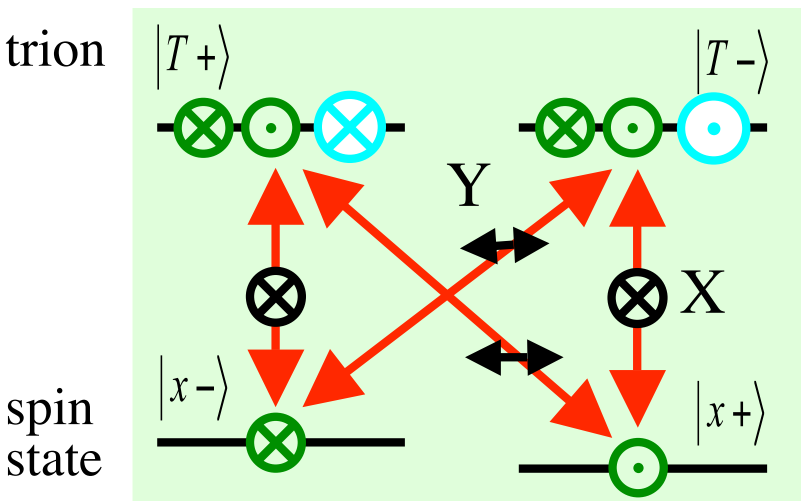
Pochung Chen, C. Piermarocchi, L.J. Sham, and D.G. Steel, Phys. Rev. Lett. **89**, 167402 (2002).

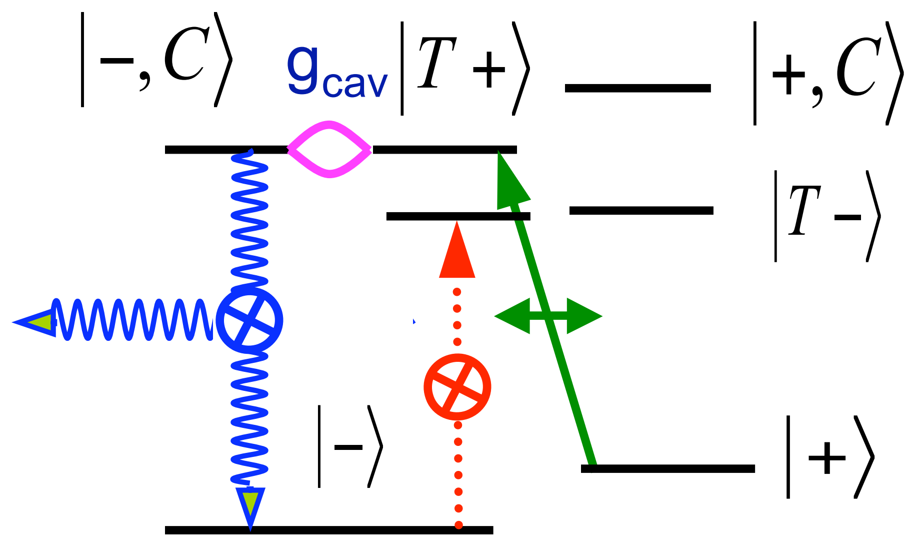
Cavity-dot-fiber for solid state CQED



- A single photon wave packet of any shape may be produced by a suitable control of pulse shape of laser light
- Thus, a single photon source
- Ultrafast spin cooling using the wave guide as an entropy dump (qubit initialization)

Selection rules

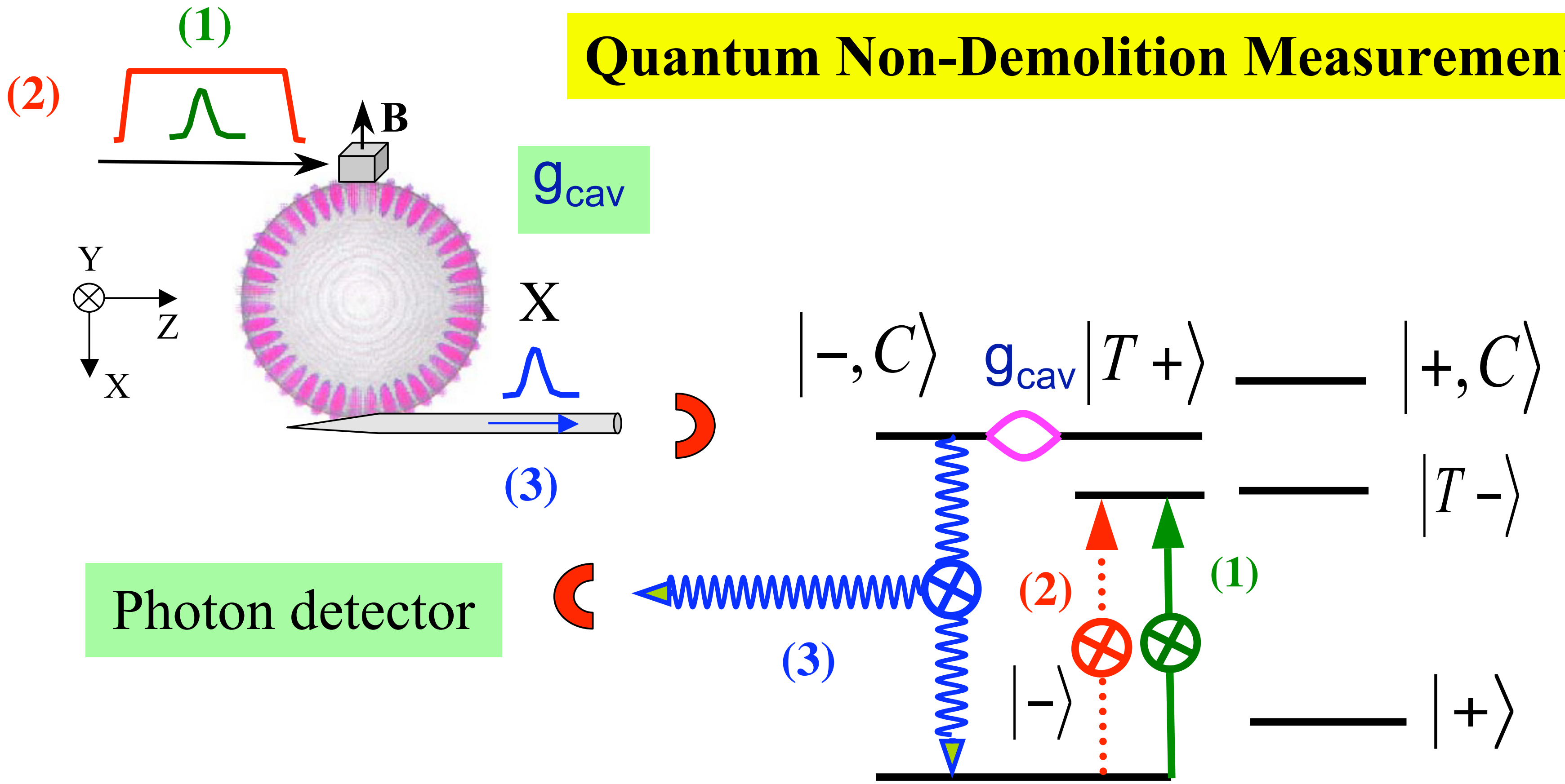




Yao, Liu and Sham, Phys. Rev. Lett. **95**, 030504 (2005)

Solid State CQED for Spin State Measurement

Quantum Non-Demolition Measurement



Photon detector

The three steps may be recycled

Renbao Liu, Wang Yao and L.J. Sham, Phys. Rev. B **72,** 081306 (R) (2005)

Quantum Non-Demolition Measurement

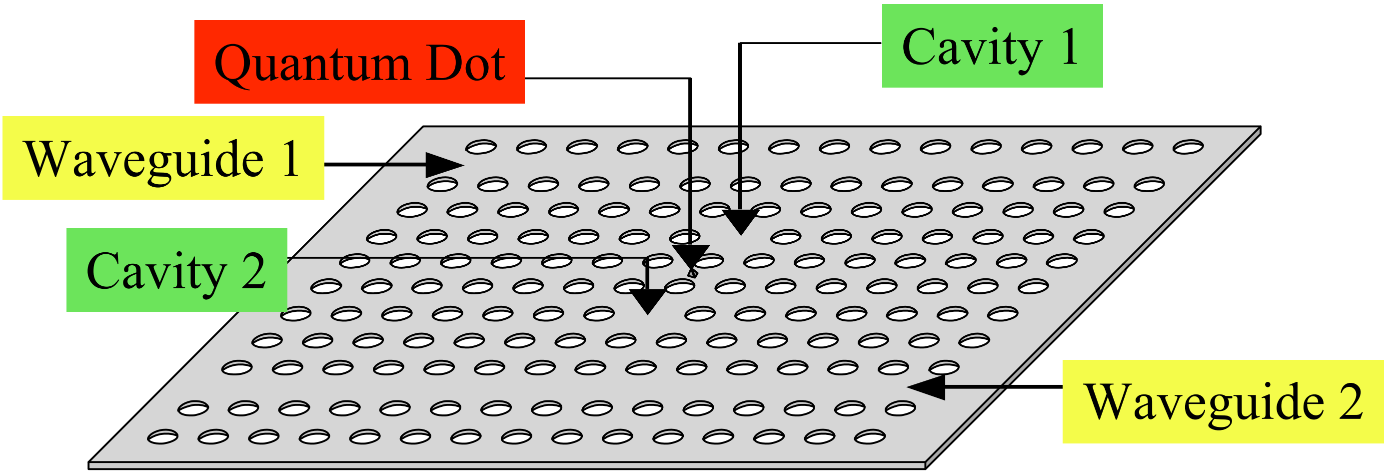
What is not a QND:

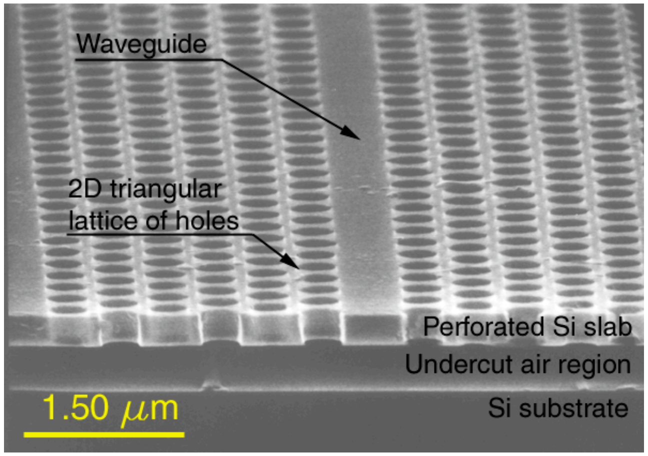
- Measure x of a free particle at time t=0
  - Uncertainty $\Delta x(0)$ leads to uncertainty $\Delta p(0) \sim h/\Delta x(0)$
- Then measure x again at time t
  - $x = tp/m$
  - $\Delta x(t) \sim t\, h/m\Delta x(0)$ -- back-action noise

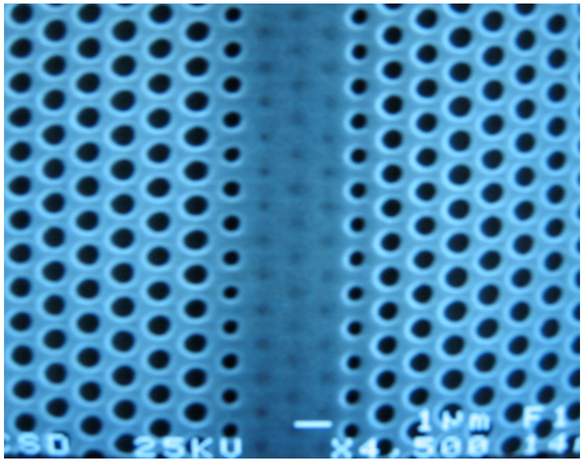
What is a QND:

- Measured observable A
  - A(0) commutes with A(t)

Design with photonic lattice



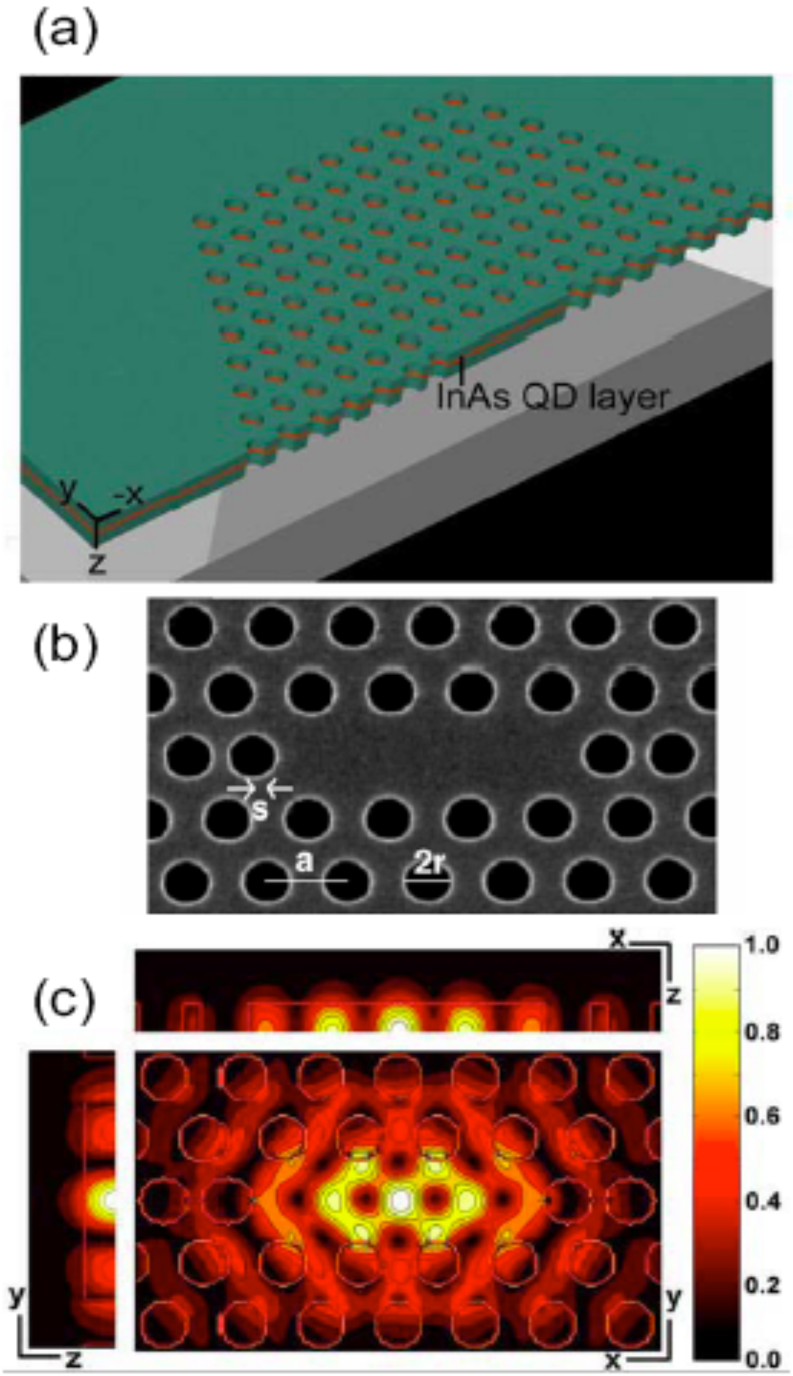


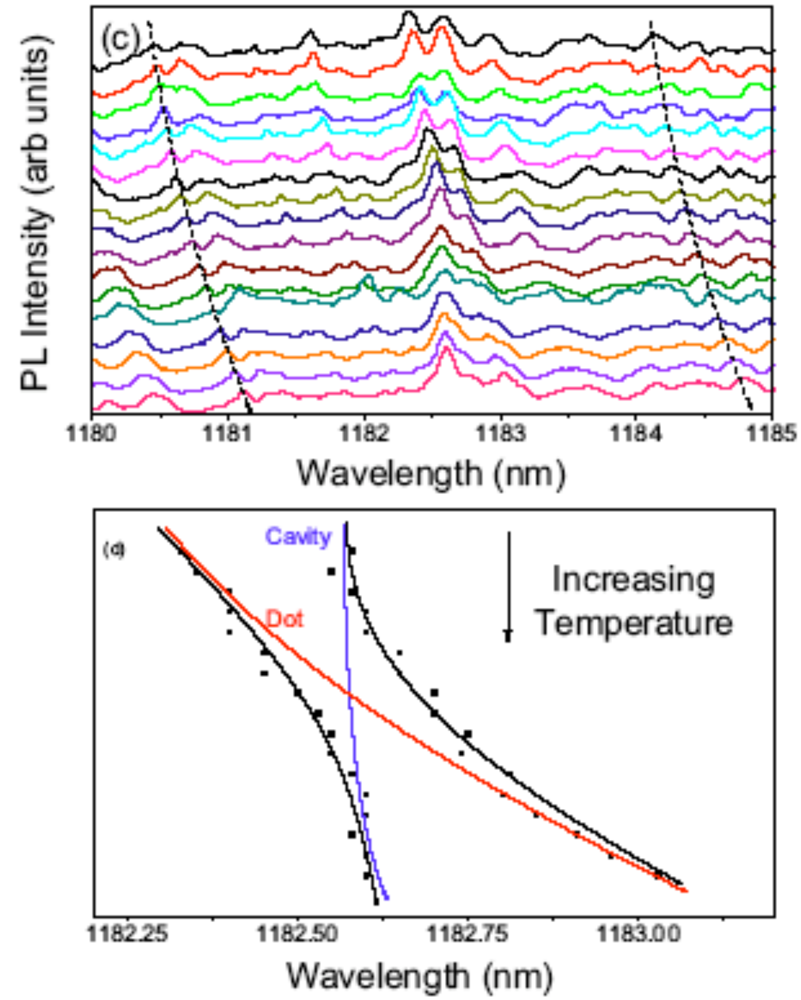


Based on current photonic lattice capabilities. See Scherer et al., IEEE Trans. NanoTech. **1**, 4 (2002).

Fainman et al., Applied Optics, **42**, 5450 (2003)

Evidence for Strong Coupling CQED





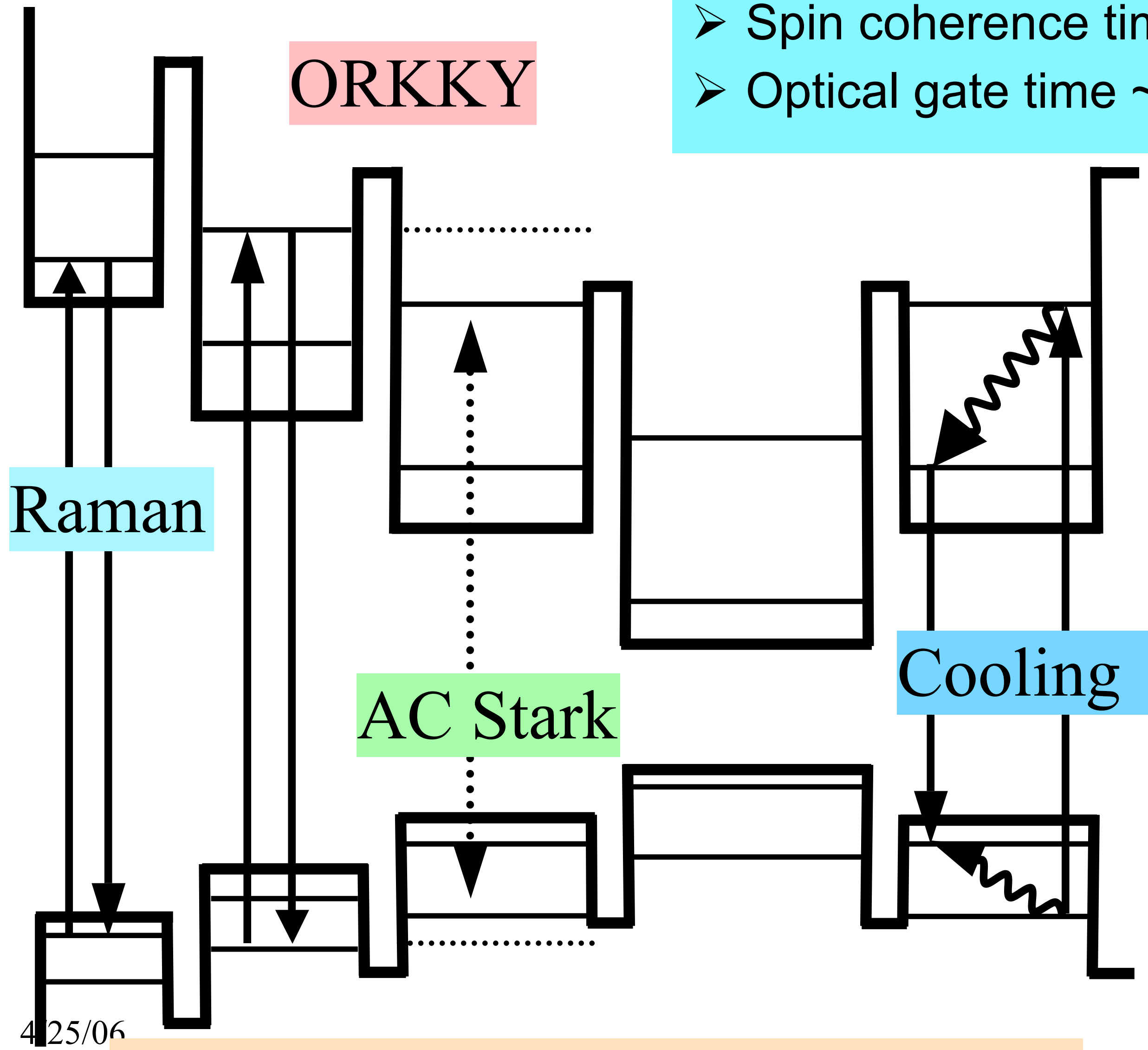
Yoshie, Schere, Hendrickson, Khitrova, Gibbs,Ruppe, Ell, Shchekin. Deppe , Nature

Proposed applications

- Optical control for a quantum processor and a scalable system of SAQDs for QC
- Distributed quantum computation with a quantum network of nodes of QD and microcavity connected by wave guides
- Using QD as strong nonlinear elements to provide photon-photon interaction for devices

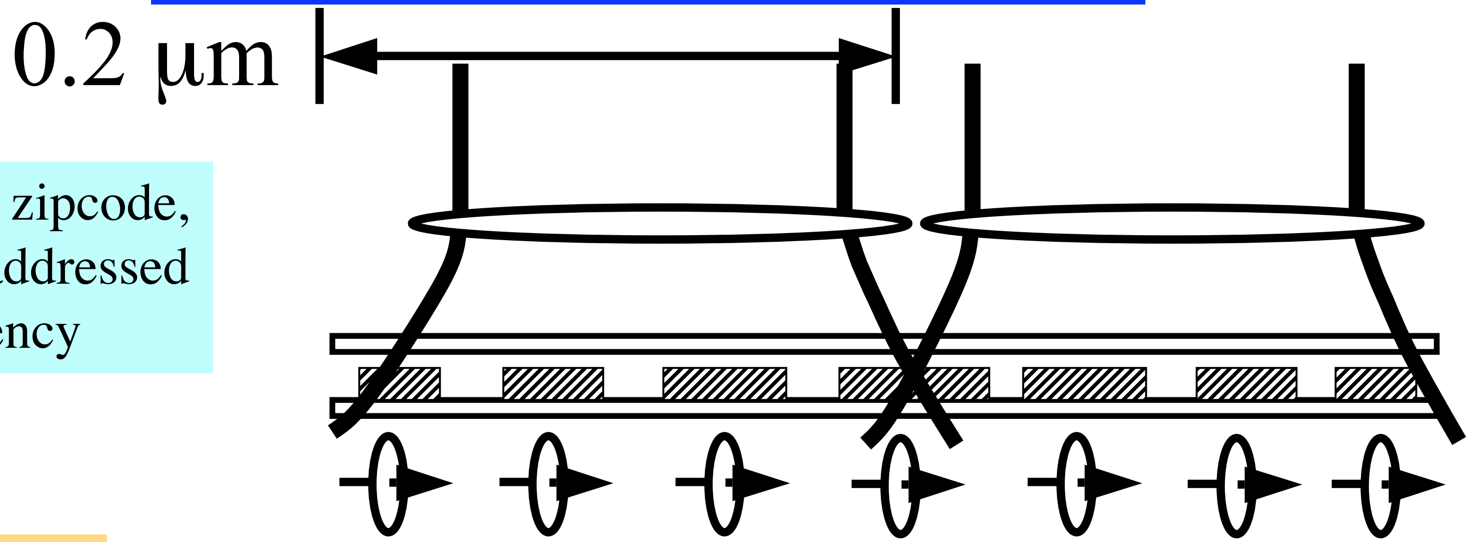
Energy Level Schematics for Optical Operations

- Spin coherence time ~ 10μs
- Optical gate time ~ 10 ps



Renbao Liu and L. J. Sham, unpublished.

Architecture of a 7 bit QC



Within each zipcode, each dot is addressed by its frequency

Resource estimate

TABLE I: Gates, pulses, and time-consumption required for factoring 15 with Shor's quantum algorithm

	# of one-bit gates[a]	# of swap gates	# of phase gates	# of pulses[b]	time-consumption[c]
a=4	4	1	3	48	0.8 ns
a=13 (Toffoli gate)	19	8	15	159	1.2 ns
a=13 (S- Toffoli gate)	12	6	7	102	1.0 ns

[a] All one-bit gates between two controlled gates are counted as one gate requiring 4 pulses which can be done within 10 ps
[b] including 21 pulses for initialization
[c] including the time for initialization, estimated as 100 ps per bit

Distributed QIP or QC Hardware & Operations

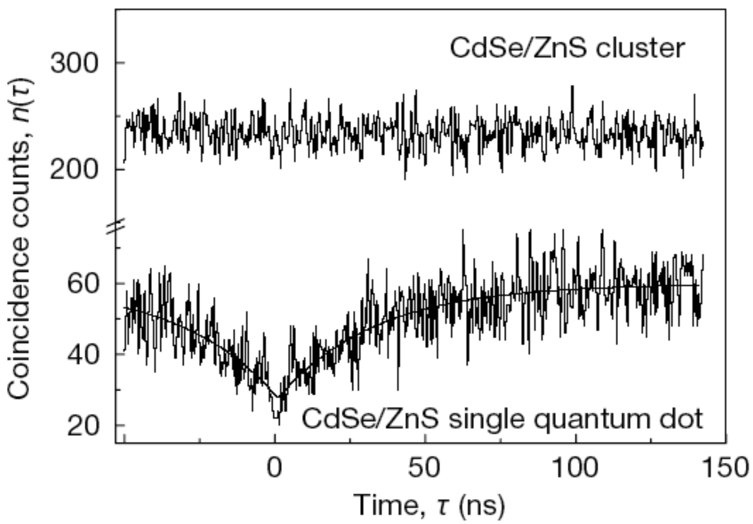
- Qubits
  - Stationary: spins in semiconductor nanodots or excitons
  - Flying: photons (number states or polarization states) in fiber
- Operations (clock speed 10 ps or 1 THz)
  - Optical control by lasers
  - Photon-electron interaction in vacuum and in cavity
- Write (initialization)
  - Optical pumping and decay
  - Control of cavity electrodynamics
- Readout
  - Aims for one shot measurement
  - Requires high efficiency single photon detector

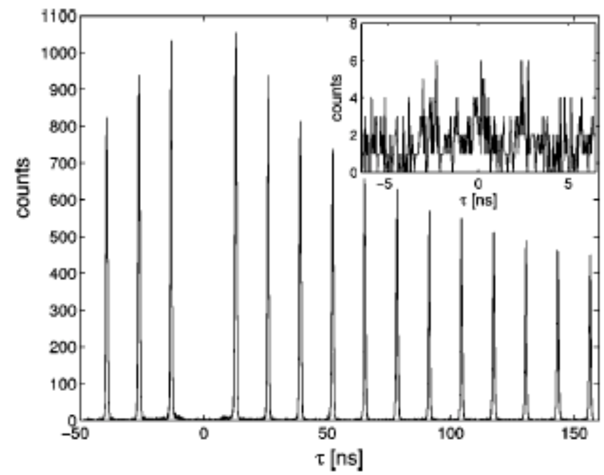
Yao, Liu, Sham, J. Opt. B: Quant. Semiclass. Opt. **7**, S318–S325 (2005)

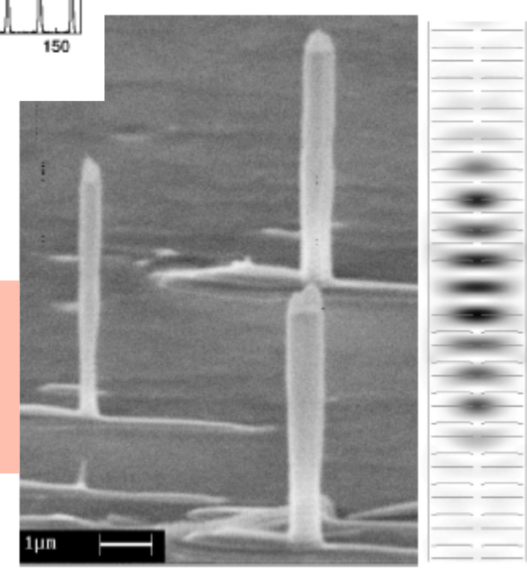
Single Photon Source from semiconductors

P. Michler, A. Imamoglu, M. D. Mason, P. J. Carson, G. F. Strouse & S. K. Buratto, Nature **406**, 968 (2000)

C. Santori, M. Pelton, G. Solomon, Y. Dale, and Y. Yamamoto, Phys. Rev. Lett. **86**, 1502 (2001).

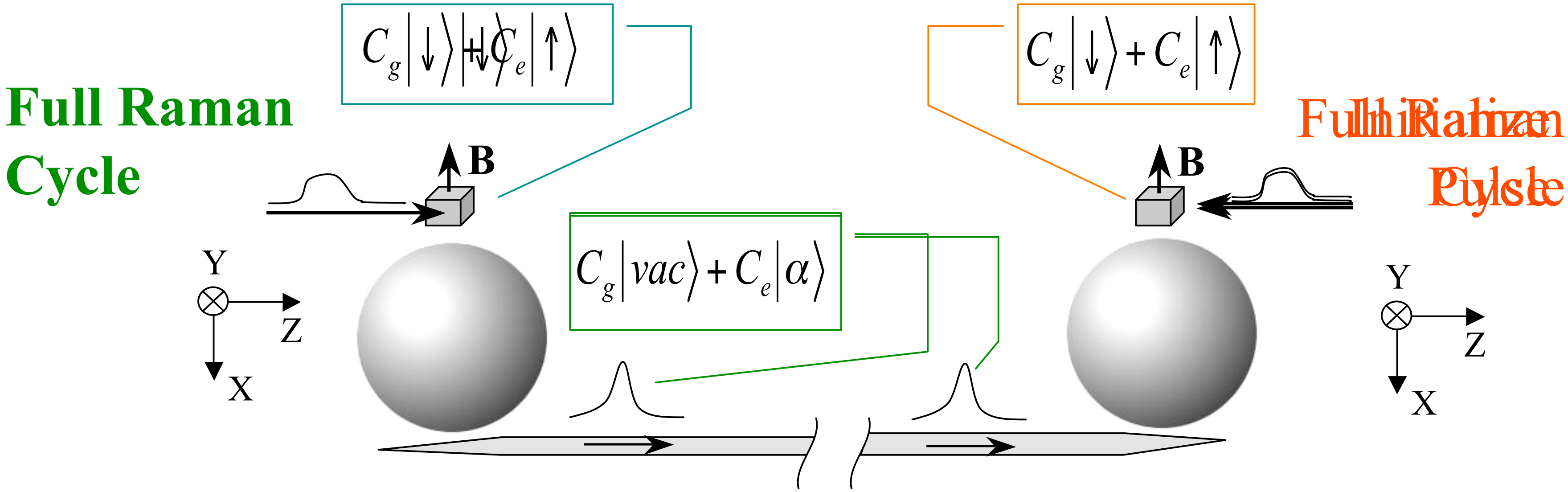






Jelena Vuckovic, David Fattal, Charles Santori, Glenn S. Solomon, and Yoshihisa Yamamoto, APL 82, 3596 (2003).

Quantum network with solid-state nodes



- **Initialize receiving node.**
- **Map spin qubit to photon qubit by a full Raman Cycle at the sending node.**
- **Photon qubit propagate in the quantum channel.**
- Map the photon qubit to the spin qubit at the receiving node by a full Raman Cycle.

Remote operations: swap & entanglement designed and simulated

Yao, Liu and Sham, Phys. Rev. Lett. **95**, 030504 (2005)

A proposal for a solid-state phase gate for two-photon entanglement

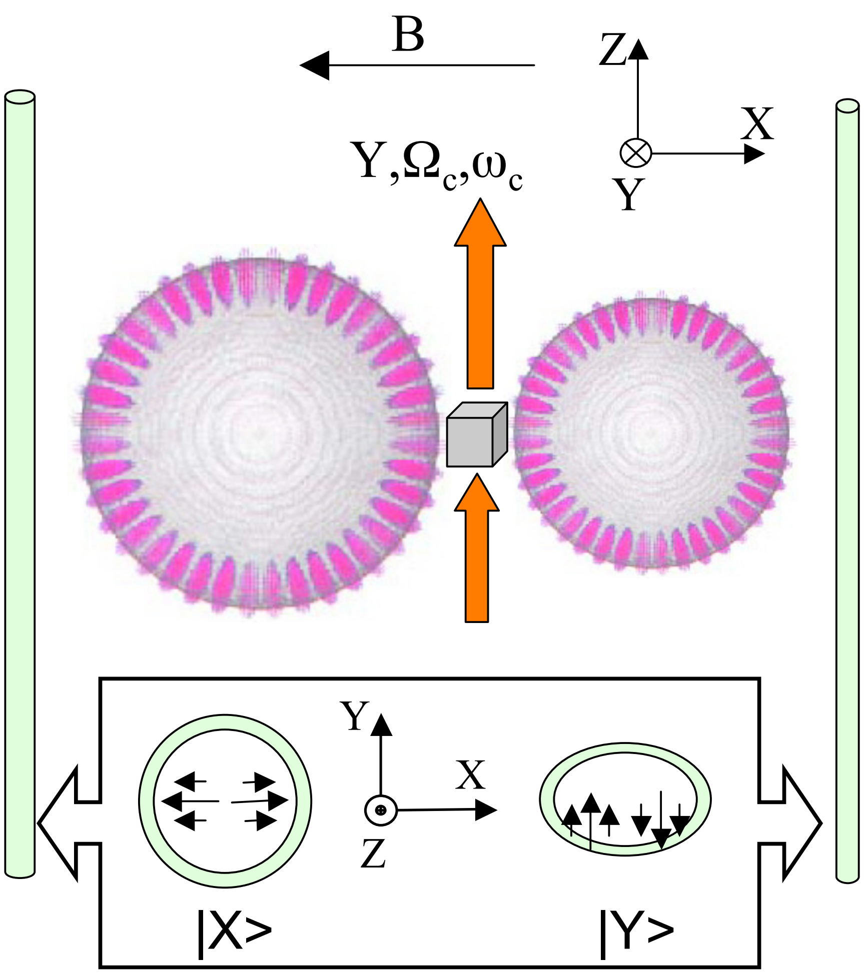
Aim

- Strong interaction between flying qubits for a logic gate
- Mediation by semiconductors
  - photon polarization qubit and electron spin in quantum dot or exciton qubit
  - connection via cavity photon

Possible strengths

- Stable structures which are easy to integrate with electronics and photonics
- Strong nonlinearity from microcavity-quantum dot coupled system
  - Small cavity volume
  - Large transition dipole matrix element of quantum dot

Structure of a proposed phase gate



Yao, Liu and Sham, PRL 92, 217402 (2004).

- **Qubit by polarization**

  |X>, |Y>

- **Cavity Modes**
- **Gate Transformation**

  |XX> → $e^{i\phi}$ |XX>

  |XY> → |XY>

  |YX> → |YX>

  |YY> → |YY>

- **Linear reflection?**

  Reduced by EIT which also yields laser cooling.

- **Nonlinearity?**

  Coupling to dot

Summary

- An electron spin in a quantum dot is a sufficiently robust quantum system.
- Optical control shows significant experimental progress and provides potentially a broad range of operations with favorable clock speed and versatility for QIP and QC.
- Possibility of applications by a combination quantum optics and semiconductor nano-system is limited only by our imagination.