Quantum optics in mesoscopic systems

Lecture II

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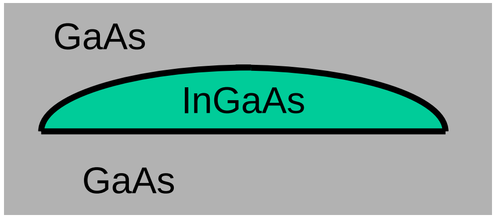
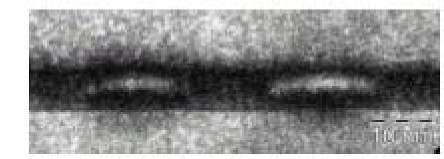
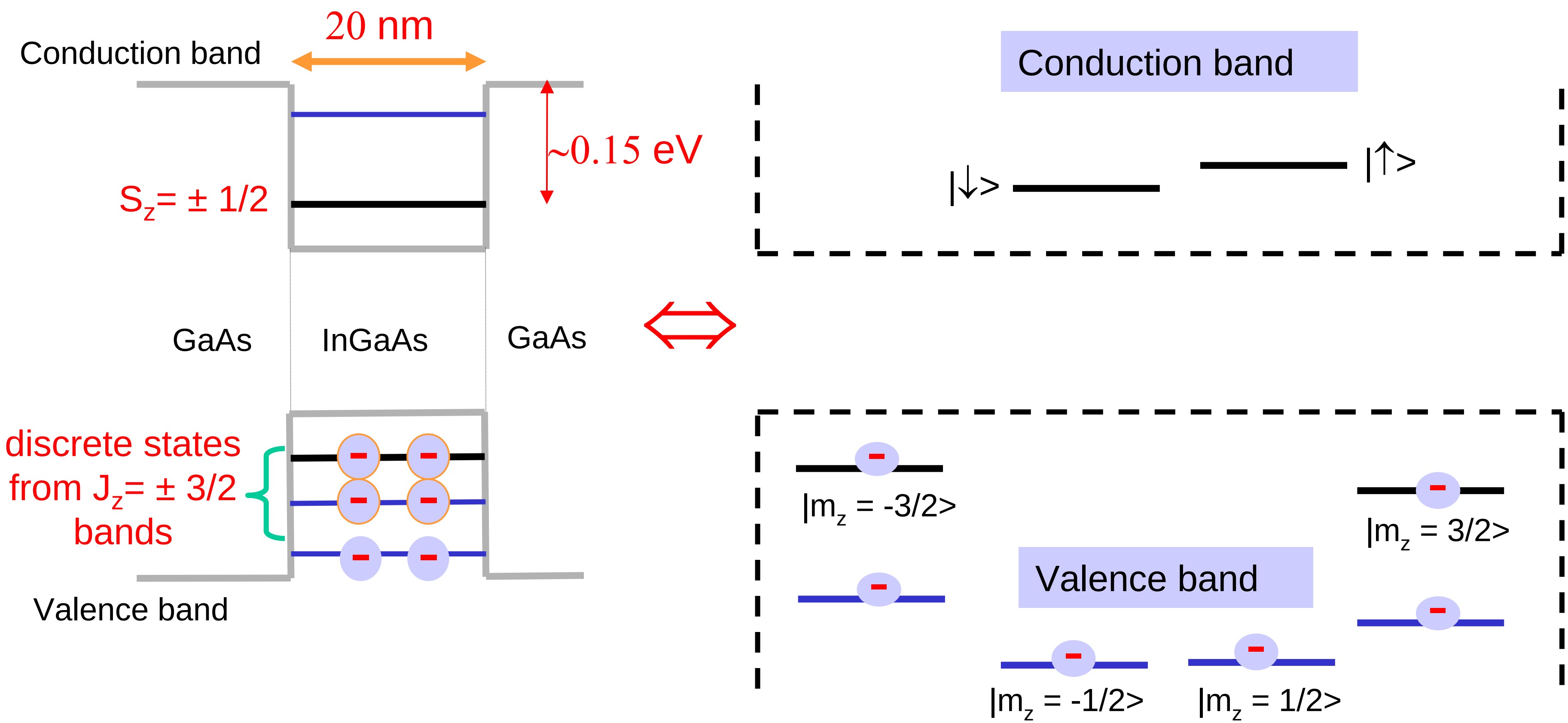
Outline

1) Optical pumping of a single-electron spin
2) Faraday rotation from a single confined spin
3) How strongly can a quantum dot absorb light?
4) A new solid-state system for quantum optics



Quantum dots (QD)





- Spin is a “good” quantum number for conduction band electrons
- Highest energy discrete valence-band states are “heavy-hole states”
- ~10^5 atoms (= nuclear spins) in each QD.

Artificial alkali-like atom?

- Is it possible to realize a quantum dot system with 2 or more low energy states with a long coherence time?

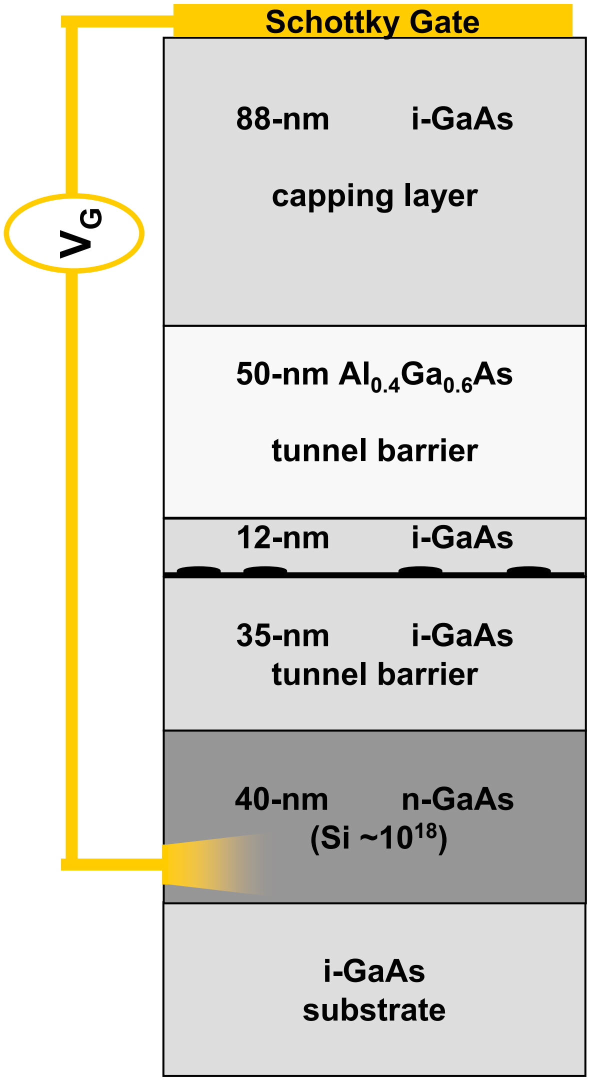
⇒ Spin states of an excess conduction-band electron:

A system with long coherence times (> 10μs) + fast optical manipulation

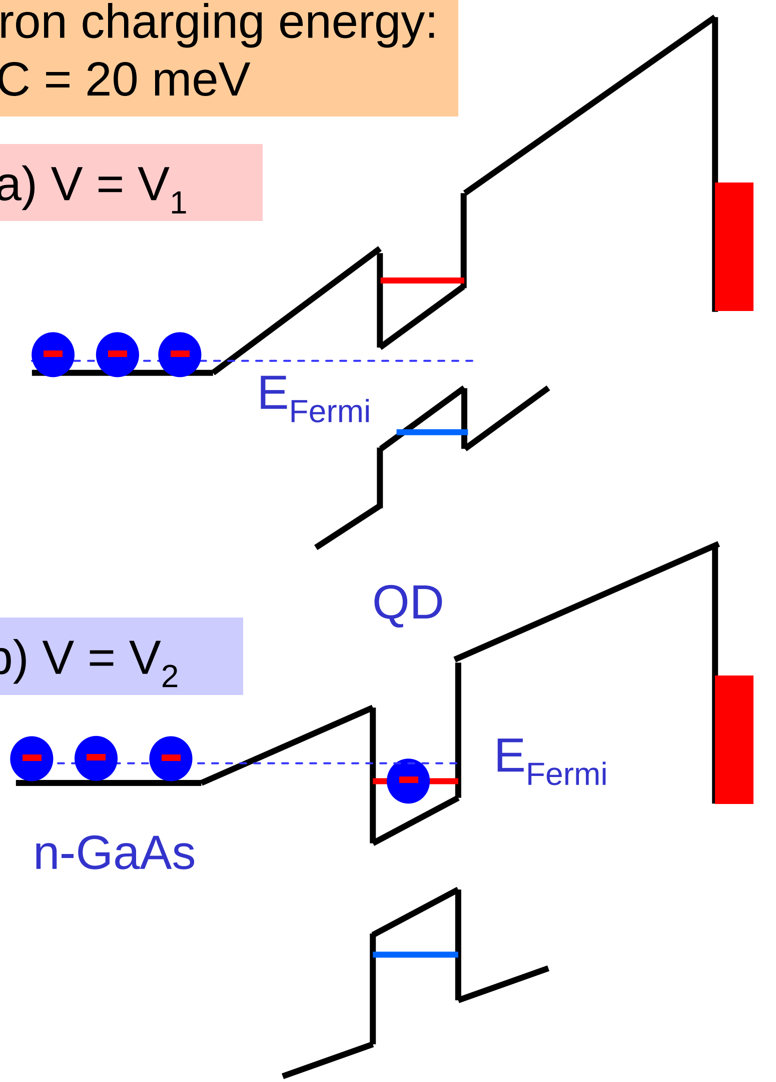
Controlled charging of a single QD: principle

Quantum dot embedded between n-GaAs and a top gate.

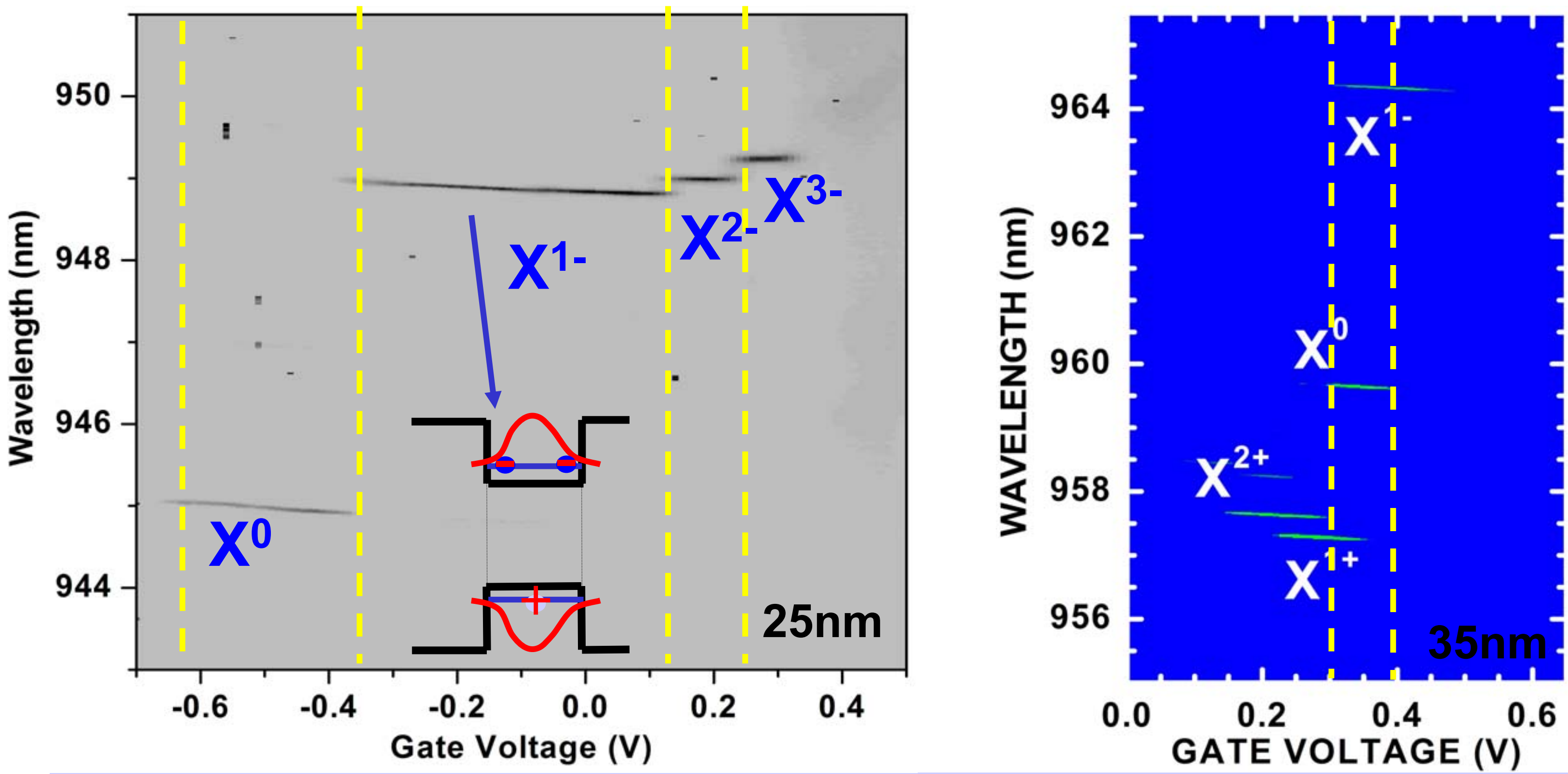
Coulomb blockade ensures that electrons are injected into the QD one at a time



Single electron charging energy:
e^2/C = 20 meV



Voltage-controlled photoluminescence (PL)

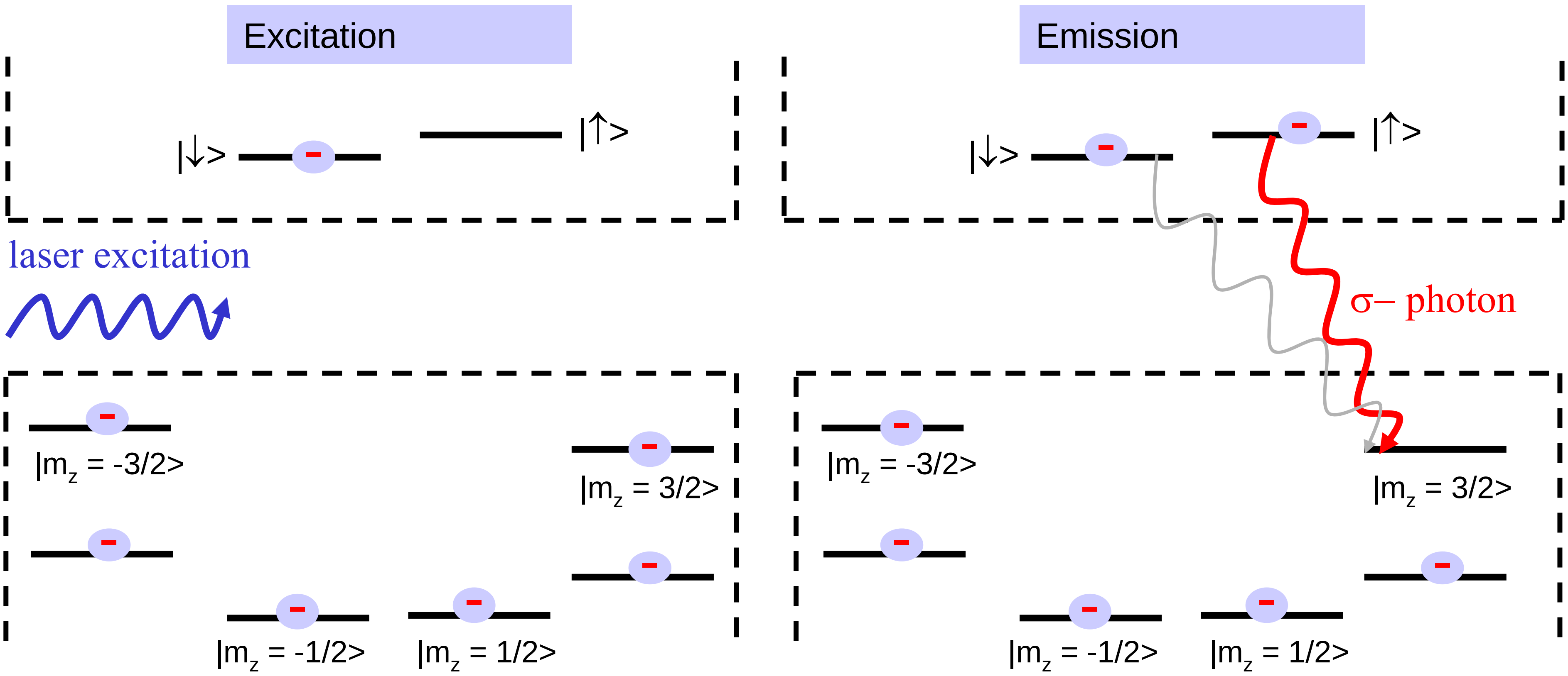


Quantum dot emission energy depends on the charge state due to Coulomb effects.

X^0 and X^{1-} lines shift with applied voltage due to DC-Stark effect.

The length of the tunnel barrier (25 vs 35 nm) strongly affects the PL.

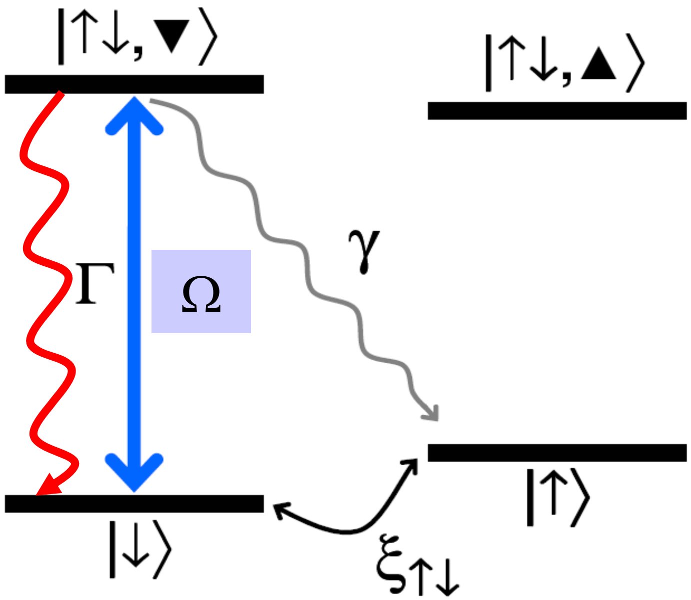
Charged QD X^{1-} (trion) absorption/emission



⇒ σ+ resonant absorption is Pauli-blocked

⇒The polarization of emitted photons is determined by the hole spin

Trion transitions in a charged QD

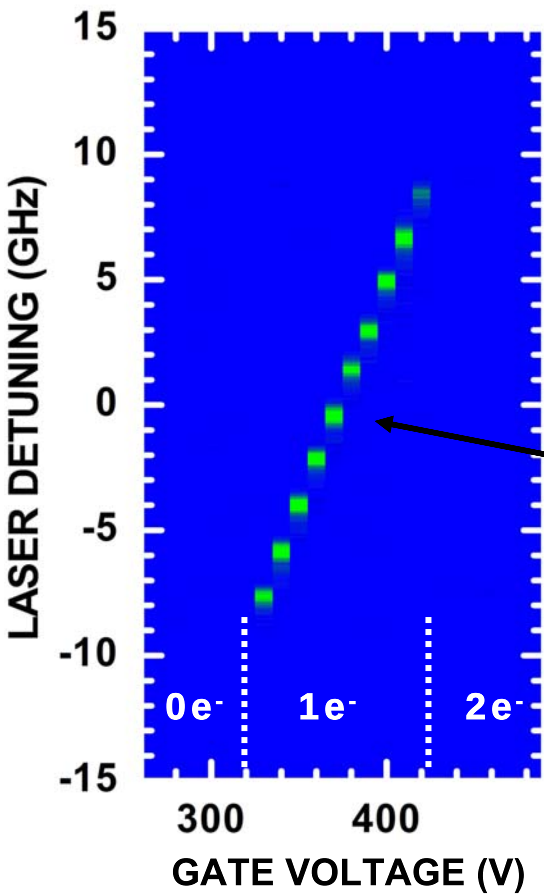


Γ: spontaneous emission rate Ω: laser coupling (Rabi) frequency

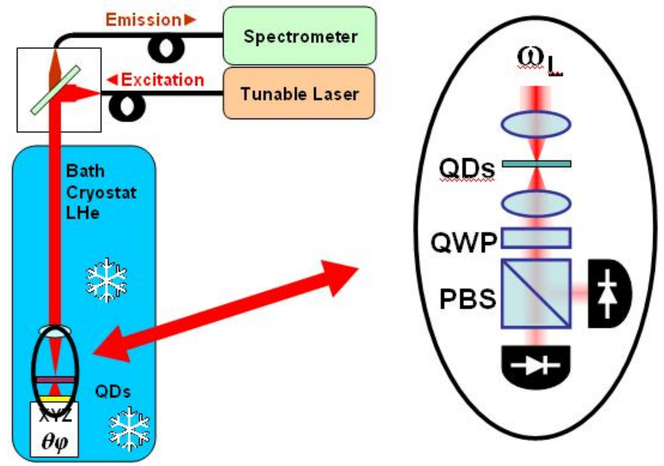
γ: spin-flip spontaneous emission rate due to electron or hole state mixing

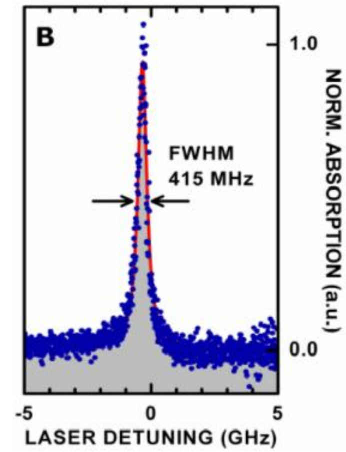
ξ: spin-flip rate due to hyperfine flip-flop or co-tunneling events

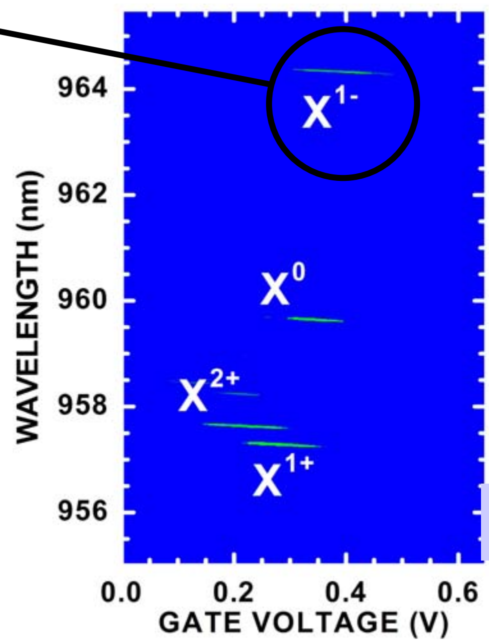
Absorption Plateau of a single-electron charged QD



B = 0 Tesla

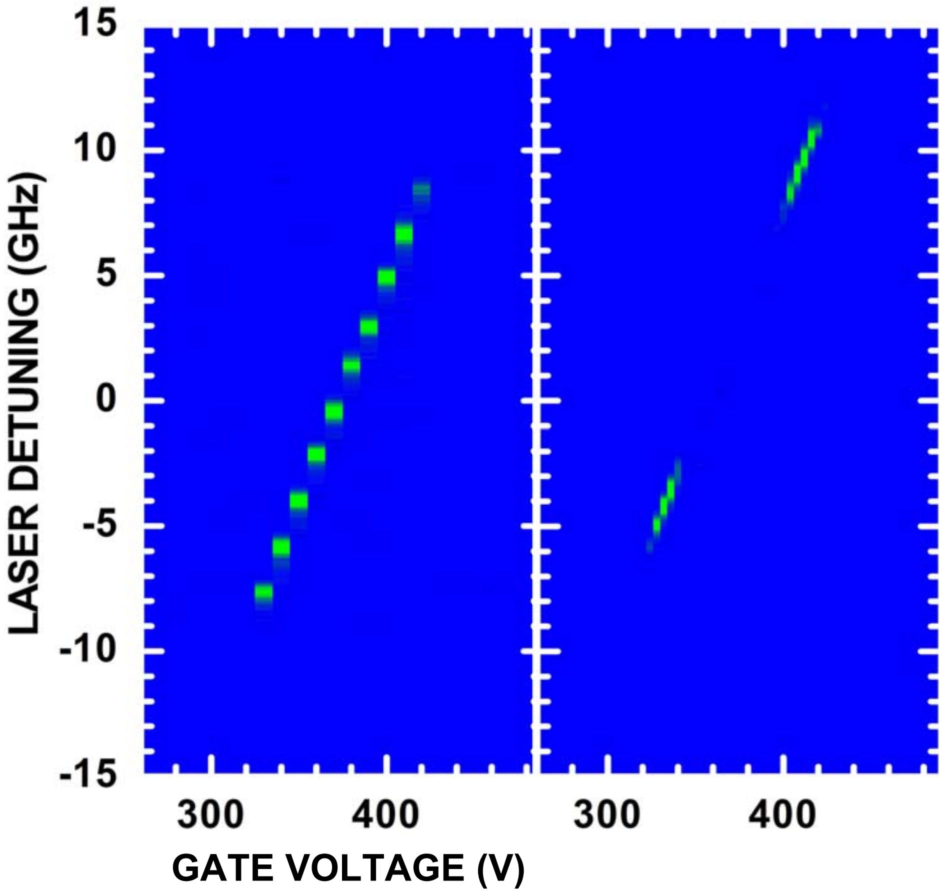






Photoluminescence

Absorption Plateau of a single-electron charged QD

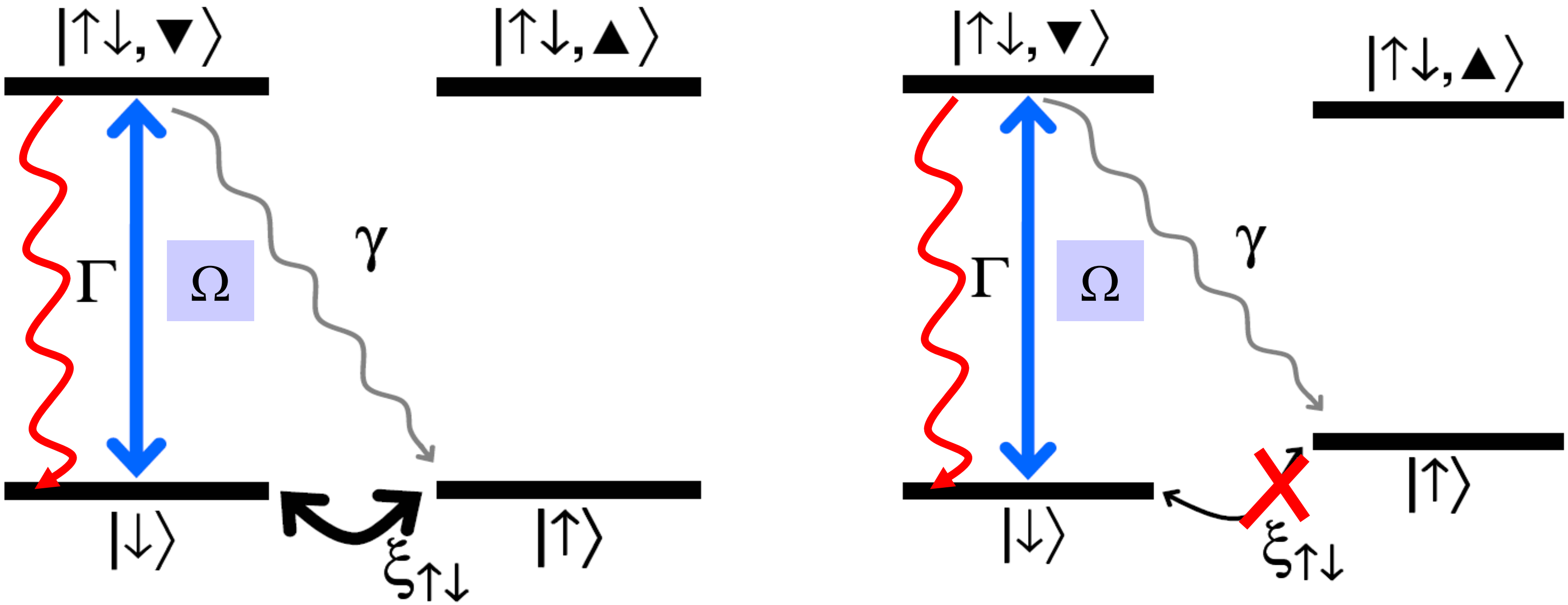


B = 0 Tesla   B = 0.2 Tesla

-An expected Zeeman shift of the absorption plateau to higher laser frequencies

-The dissapearance of absorption in the center of the plateau suggests <u>optical pumping</u>

Trion transitions in the center of the absorption plateau: Hyperfine mixing of spin-states

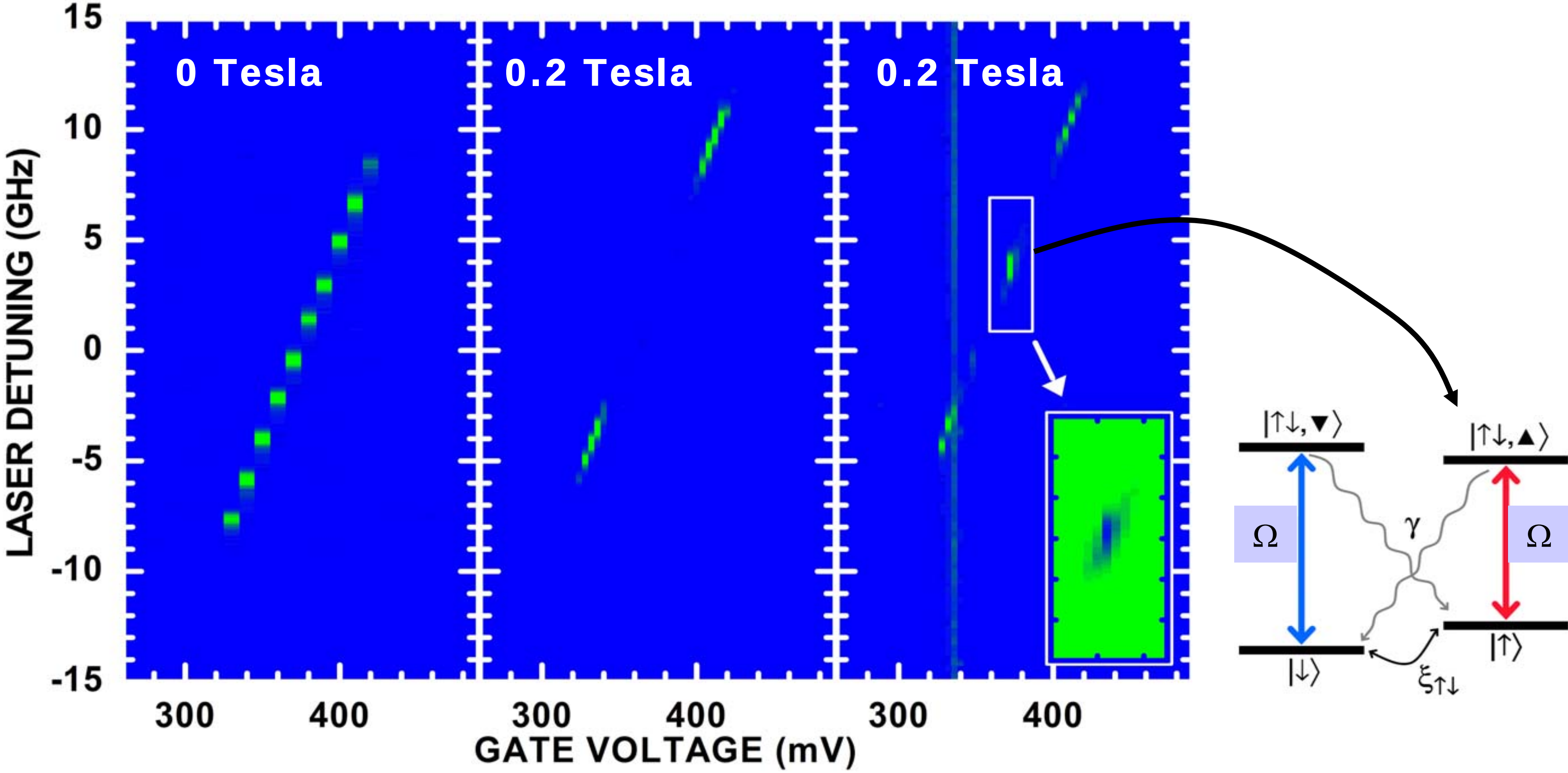


B = 0 T: fast spin-flips (ξ^{-1} ~3 ns) **B = 0.2 T: slow spin-flips**

$\gamma^{-1} \sim 1\ \mu s$, **$\Gamma^{-1}$ = 1 ns**

⇒ The electron is optically pumped into the |↑> state for B > 0.1 T

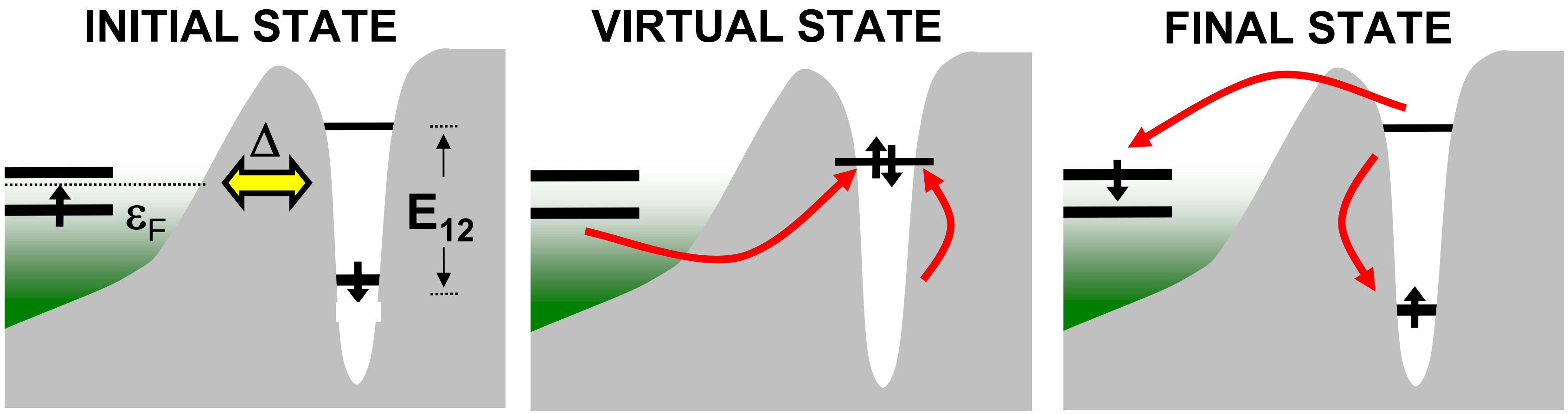
Recovery of absorption in a single-electron charged QD

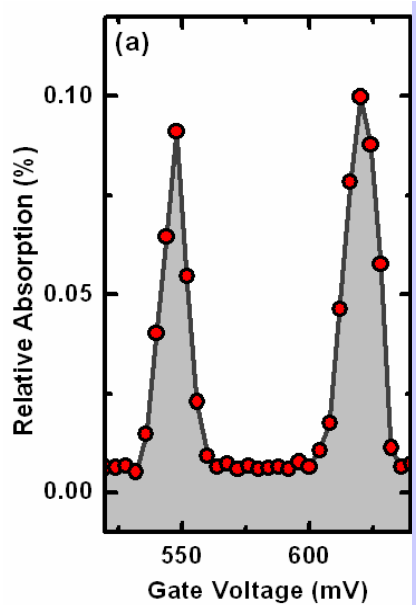


⇒ Absorption is recovered fully by applying a second laser.

⇒ Spin pumping only occurs in the center of the plateau?

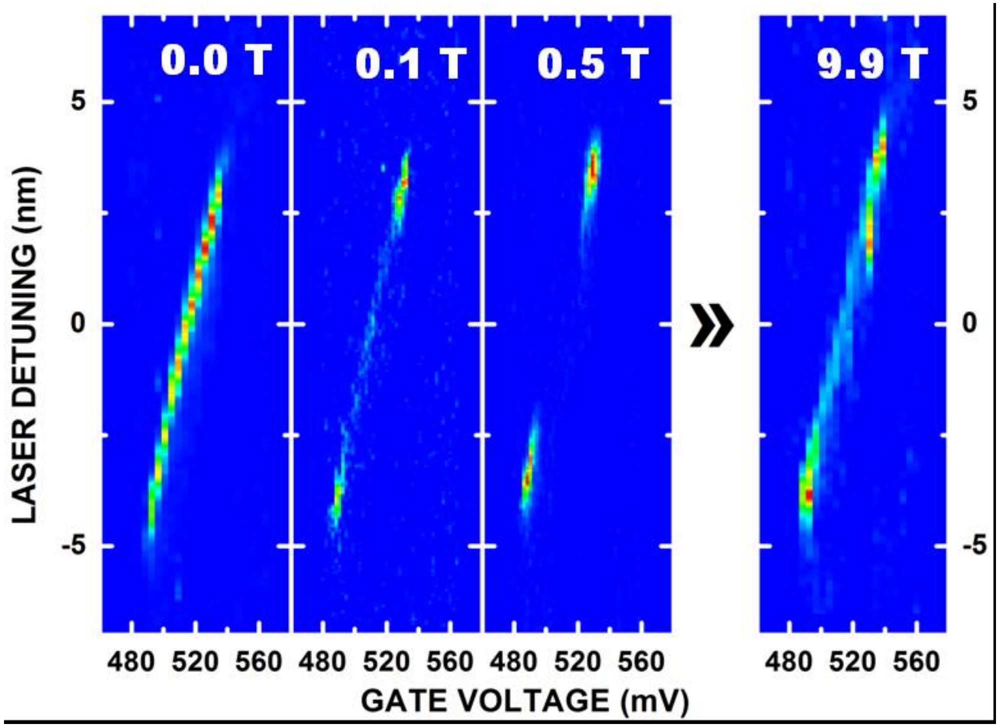
Exchange interactions with the Fermi-sea induce spin-flip co-tunneling





- Co-tunneling is enhanced at the edges of the absorption plateau where the virtaul state energy ~ initial/final state energy
- Co-tunneling rate changes by 5-orders-of-magnitude from the plateau edge to the center

QD absorption as a function of an external field



- For B > 5 Tesla, absorption reappaears due to spin-orbit mediated spin relaxation
- Electron is well isolated from reservoirs only for

  0.1 Tesla < B < 5 Tesla $\quad$ 500 mV < V_{gate} < 530 mV

Spin cooling mechanism

- Cooling takes place due to <u>one-way</u> pumping by spin-flip spontaneous Raman scattering at rate $\gamma \sim 10^6$ s^{-1}.
- There are three mechanisms for randomizing the spin state ($\sim 10^3$ s^{-1}):

a) **<u>Hyperfine interactions</u>**:

Effective only for B ~0 due to energy conservation (i.e. incommensurate electronic and nuclear Zeeman energies)

$$H_{int} = \hbar \frac{A}{N} \sigma \cdot \sum_i \alpha_i \mathbf{I}^i$$
$$= \hbar \frac{A}{N} \sum_i \alpha_i \left(\frac{1}{2} \sigma_z I_z^i + \sigma_- I_+^i + \sigma_+ I_-^i \right)$$

b) **<u>Exchange interactions with the electron reservoir</u> (co-tunneling):**

Effective only at the edges of the plateau: co-tunneling rate differs by 5 orders of magnitude from the edge to the center of the plateau

c) **<u>Phonon-assisted spin-flips due to spin-orbit interaction</u>**:

Effective only for B > 5 Tesla.

⇒QD behaves like an artificial atom only for a certain range of the applied gate voltage and the magnetic field.

Measurement of a single QD spin

- The spin-state selective absorption: right (left) hand circularly polarized laser sees substantial absorption if the electron spin is in $|\uparrow>$ ($|\downarrow>$) and perfect transmission otherwise.

  $\Rightarrow$ Optical pumping of spin destroys the information about the initial spin before it can be measured.

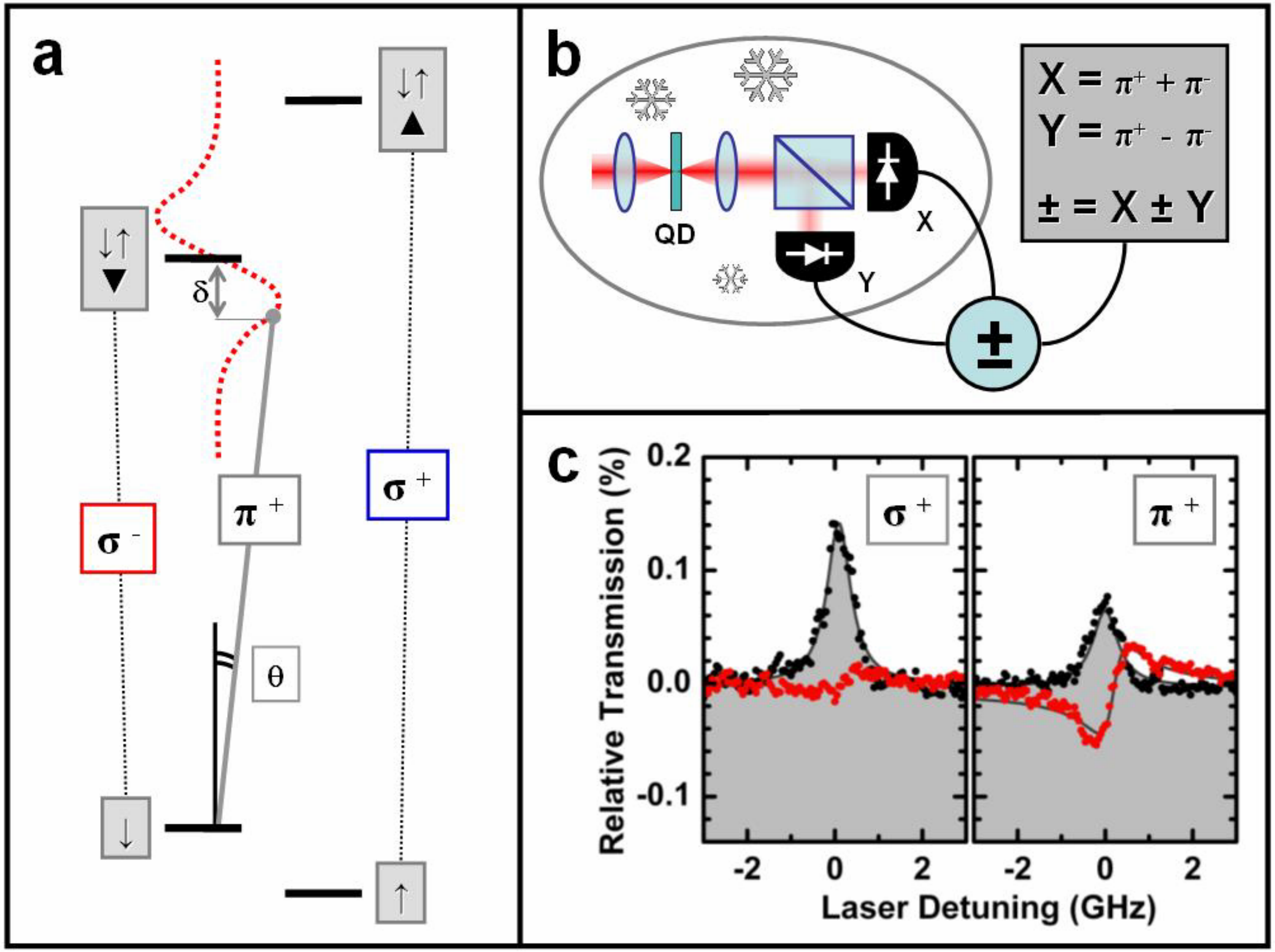
- Faraday rotation of an off-resonant laser field (dispersive response) allows for shot-noise limited measurement, without inducing optical pumping.

- It is possible to obtain Faraday SNR>1 while keeping spin-flip Raman scattering events negligible (no need for a cavity):

  $\Rightarrow$ maximize σ_{abs}/A_{laser}

Absorptive vs. Dispersive response of a QD

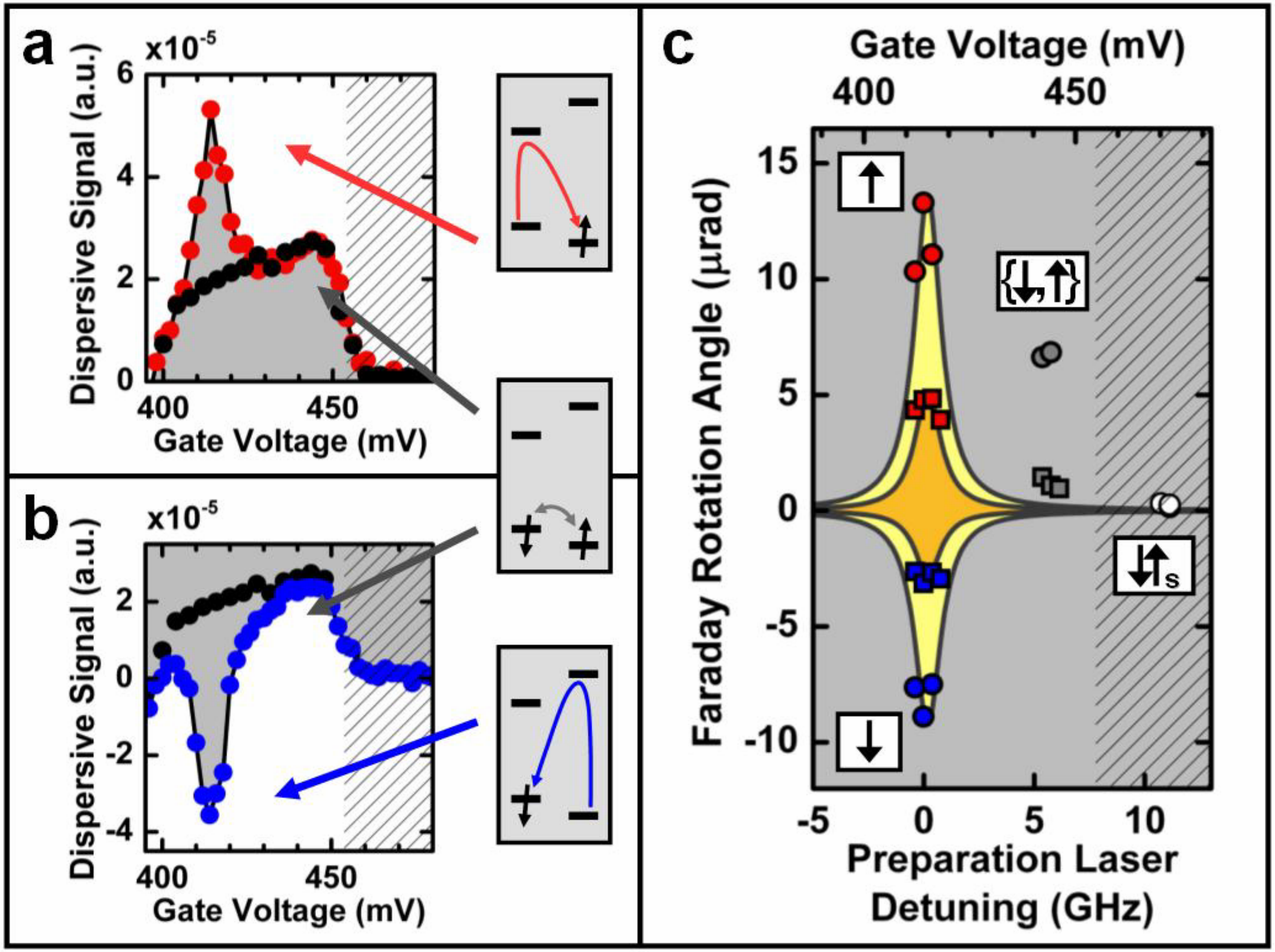
Initial electron spin-state determines whether the polarization rotation is +θ or –θ; this rotation is measured by the difference signal



Measurement of an optically prepared single spin-state using Faraday rotation of a far detuned (~50 GHz) linearly-polarized laser

electron prepared in spin-up state using a resonant laser

electron prepared in spin-down state using a resonant laser



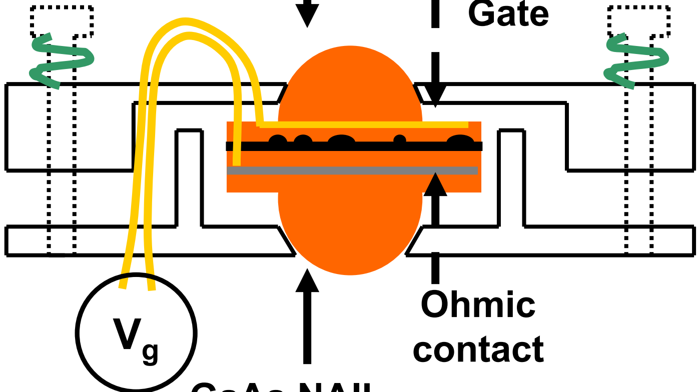
Towards quantum nondemolition read-out of a single spin

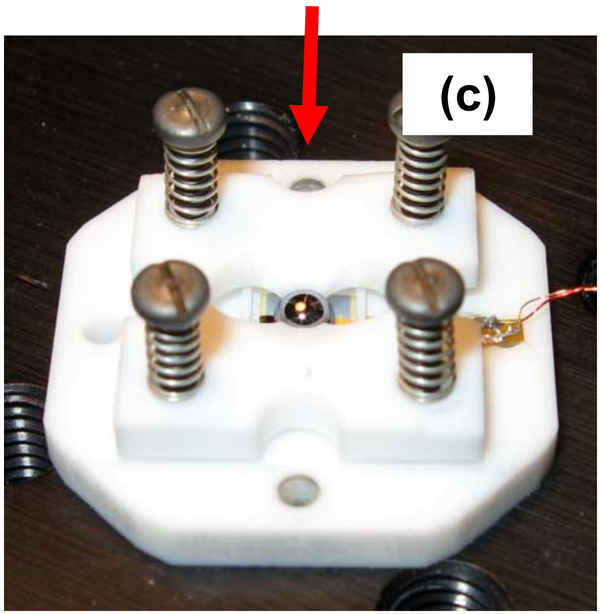
- Single-spin read-out will be a key tool for assessing the fidelity of various quantum information processing protocols.

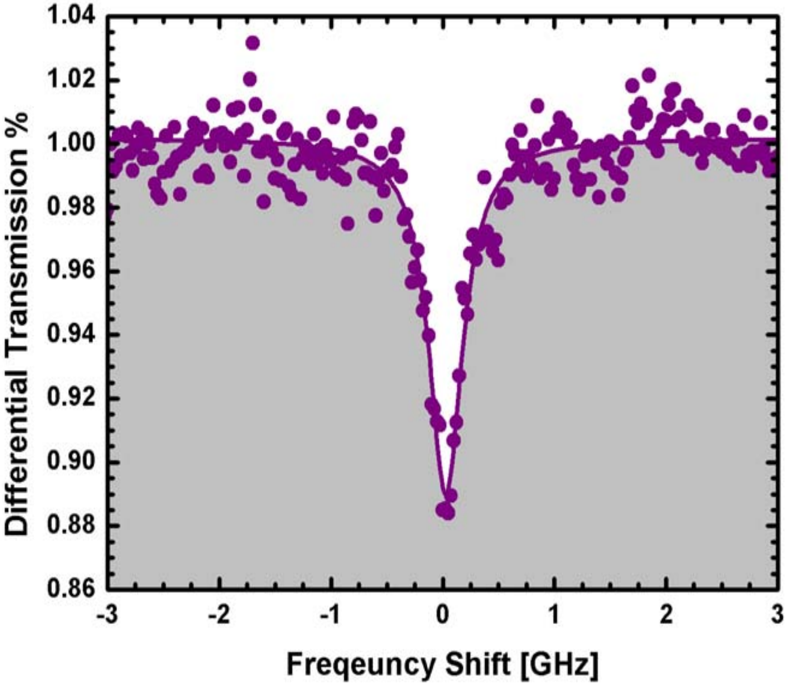
- Currently, back-action in the form of spin-sflip Raman scattered photons is at the level of ~ 1 - 10 in a measurement time (500 ms) yielding SNR = 1.

- Improvements in detector efficiency and the use of a solid-immersion lens that enhances σ_{abs}/A_{laser} should enable back-action evading read-out, without the need for a cavity.

Transmission measurements: the next generation

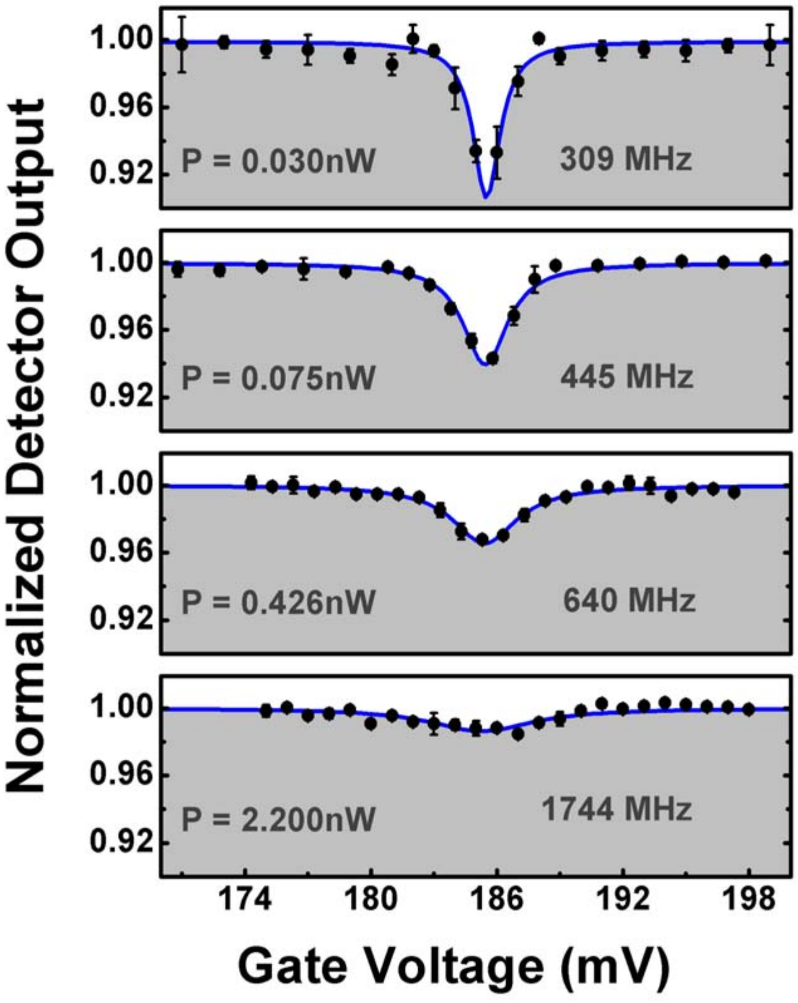


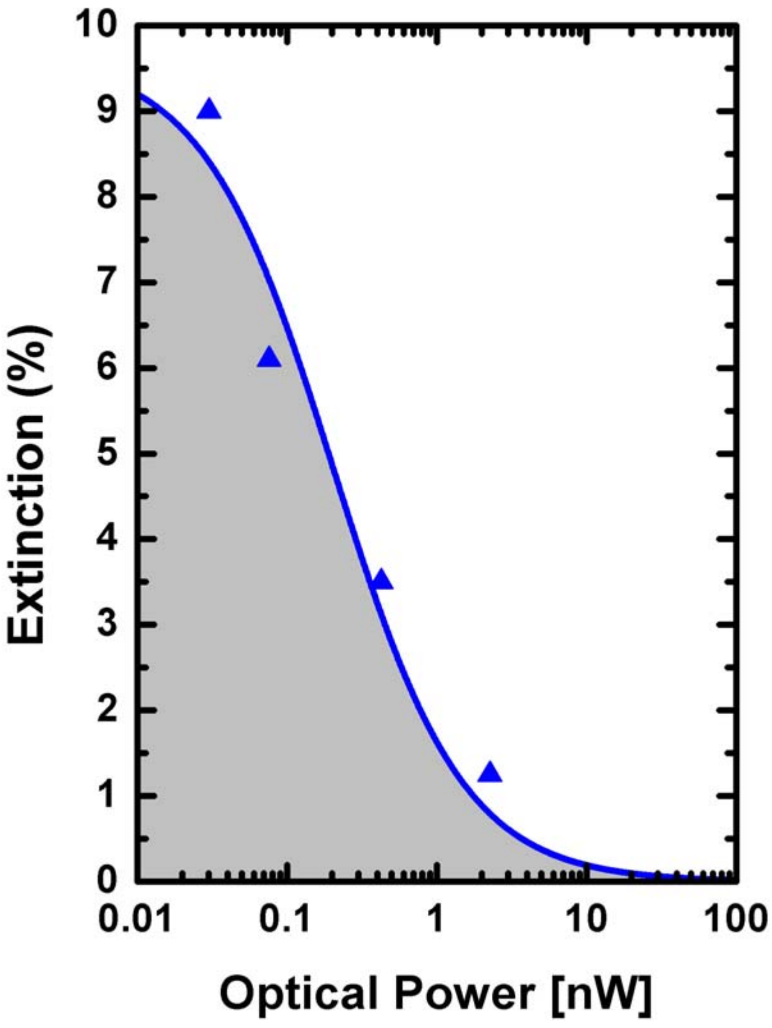




The laser extinction is 12% with a solid-immersion-lens

Saturation of QD absorption: direct measurement (no lock-in)

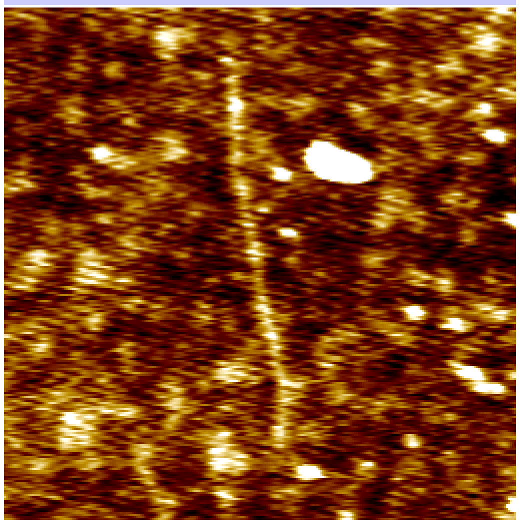




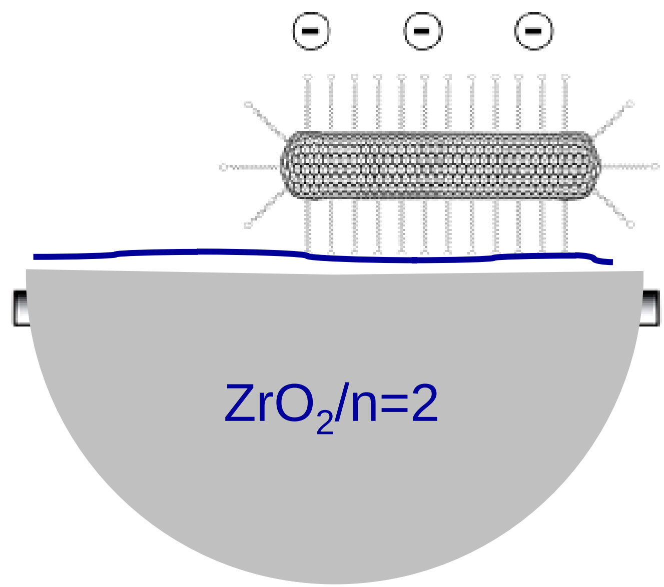
Semiconducting carbon nanotubes
(with A. Hoegele & C. Galland)

- A solid-state system with vanishing hyperfine and spin-orbit interaction
- Due to strong exciton binding and diameter-dependence of emission energy, fast emitters over a broad wavelength range

AFM Topography

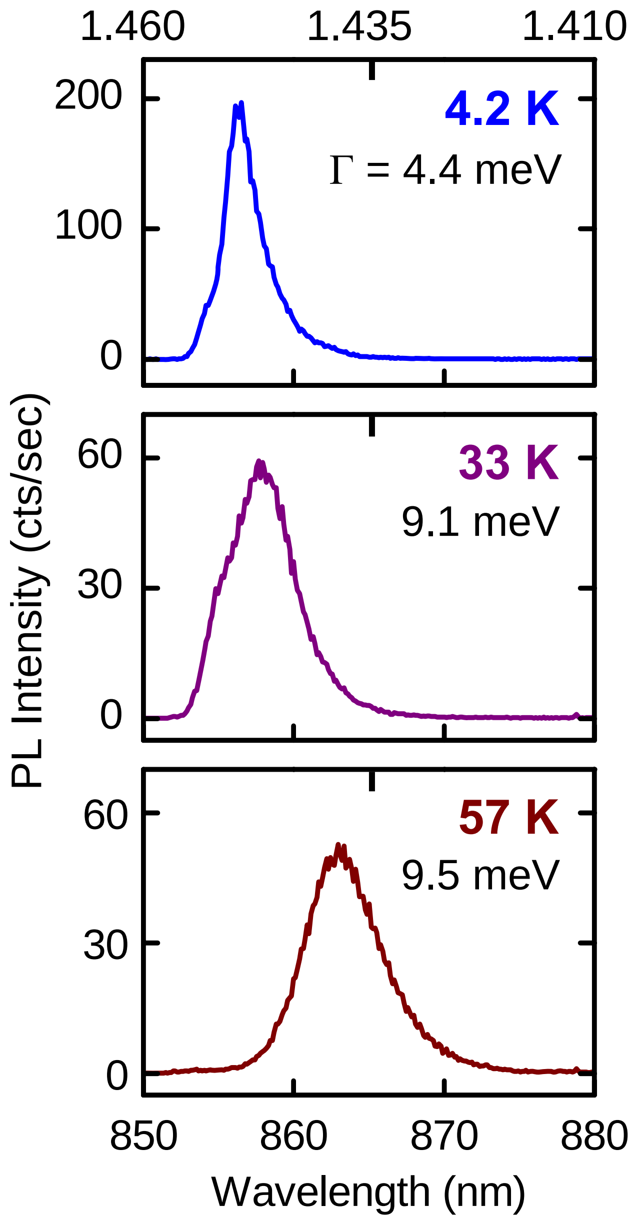


CoMoCat nanotubes on functionalized solid-immersion lens



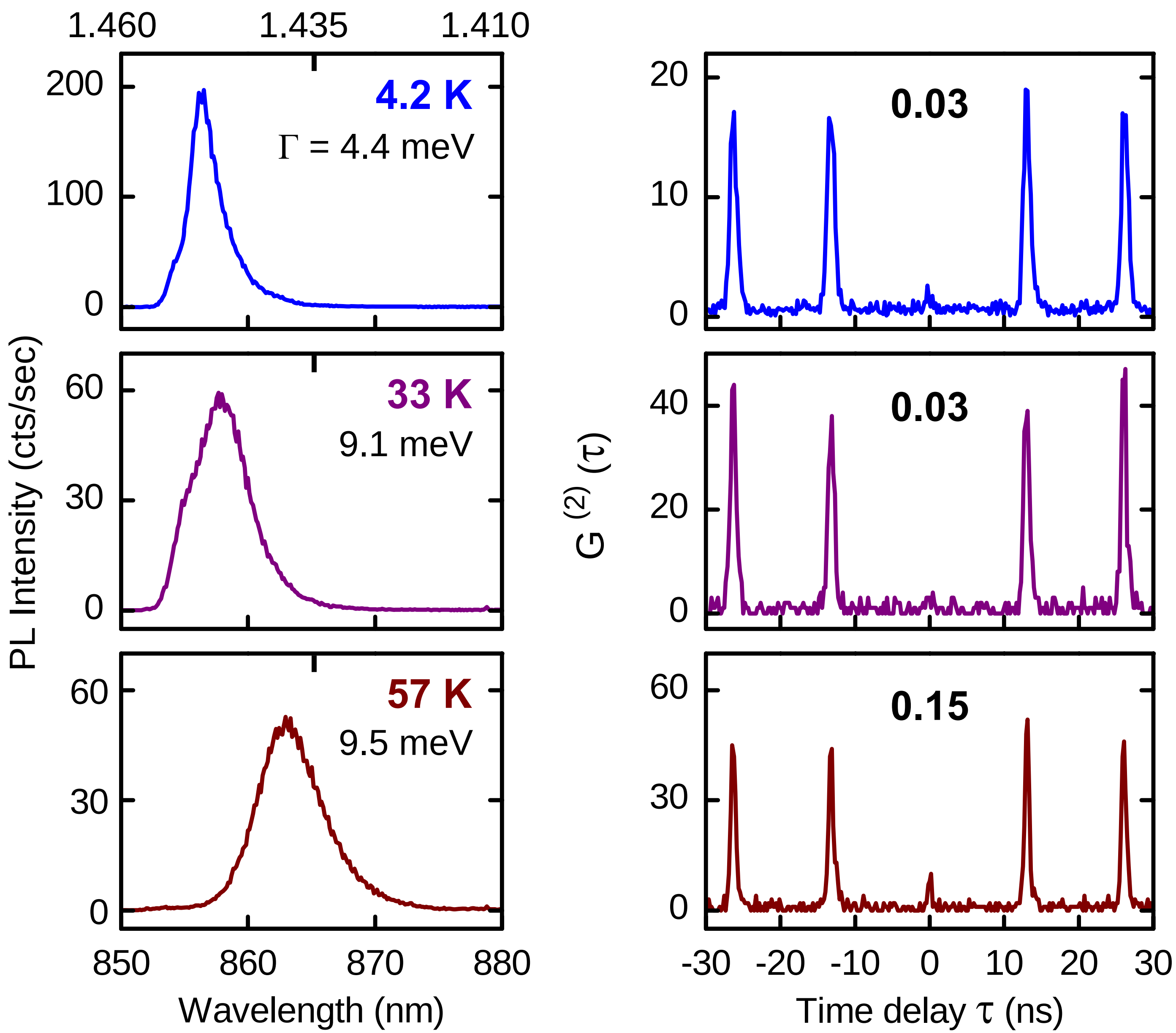
Quantum light from a 0.5 µm long carbon nanotube

Photoluminescence

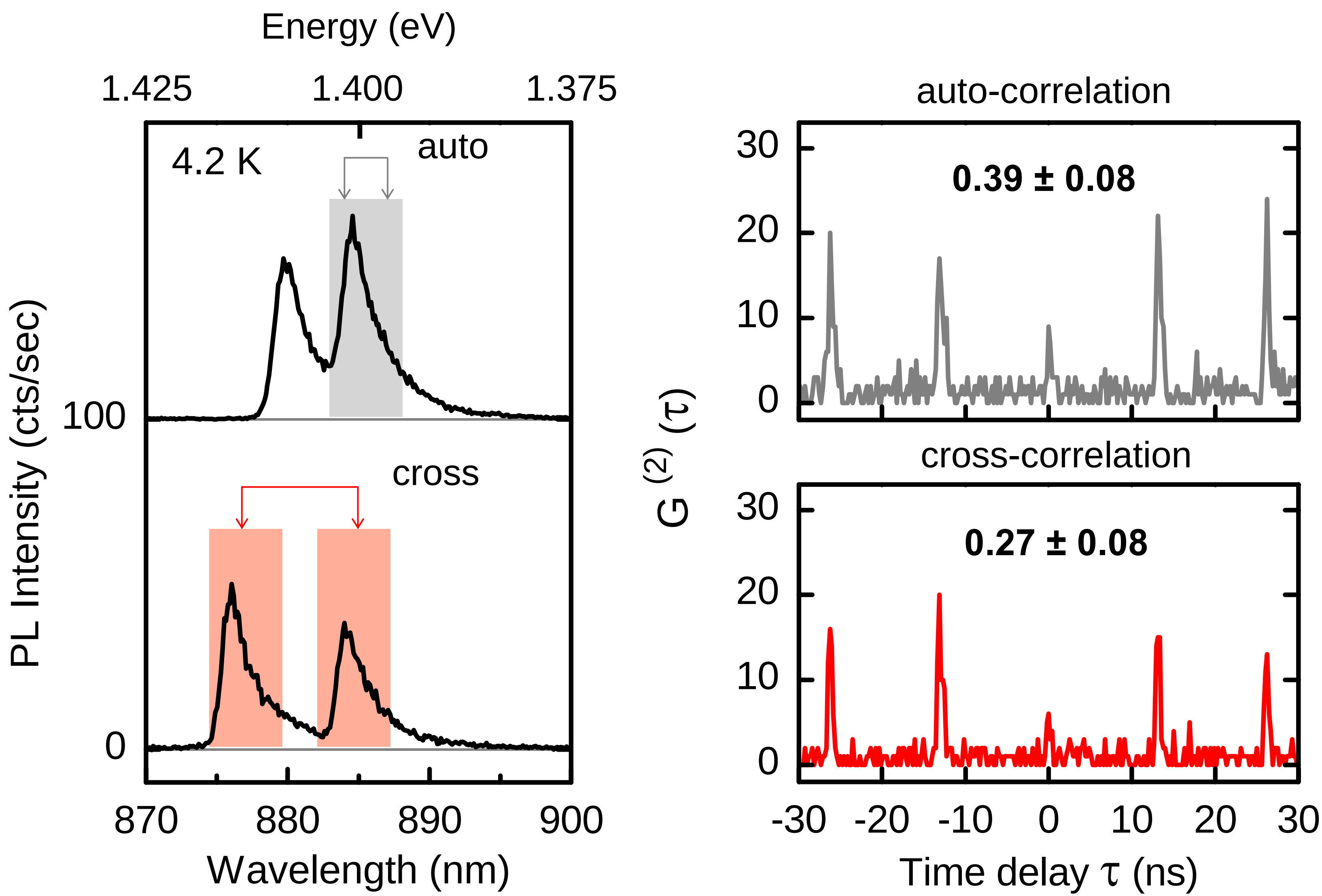


Quantum light from a 0.5 µm long carbon nanotube

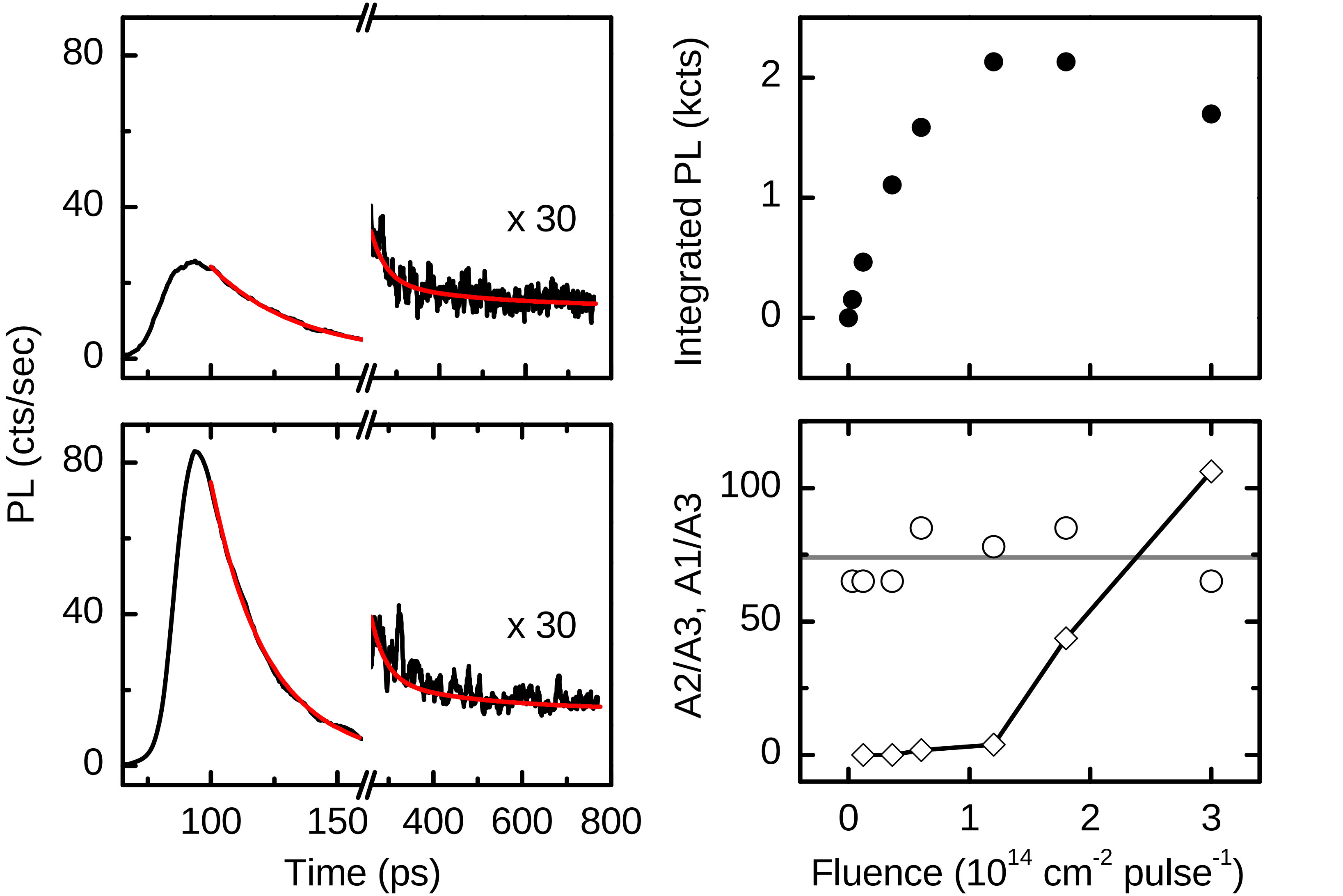
Photoluminescence | **Photon auto-correlation**



Why does a nanotube emit quantum light?
Exciton localization vs. Auger processes



Lifetime and saturation



⇒ Fast decay component dominating at high pump powers suggests that Auger processes play a key role in observed photon antibunching – QDs for free!