Quantum optics in mesoscopic systems

Lecture II

A. Imamoglu
Quantum Photonics Group, Department of Physics
ETH-Zürich

Co-workers
M. Atature, J. Dreiser, T. Yilmaz, A. Badolato (ETH)
N. Vamivakas, S. Unlu (Boston University)
A. Hoegele, C. Galland (ETH)

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)

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

Strained QD system:
- 20 nm
- \( S_z = \pm 1/2 \)
- \( \sim 0.15 \text{ eV} \)

Split valence bands:
- \( m_z = -3/2 \)
- \( m_z = 3/2 \)
- \( m_z = -1/2 \)
- \( m_z = 1/2 \)
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: $e^2/C = 20 \text{ meV}$

(a) $V = V_1$

(b) $V = V_2$
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

Excitation

$|\downarrow\rangle$ \hspace{1cm} $|\uparrow\rangle$

Emission

$|\downarrow\rangle$ \hspace{1cm} $|\uparrow\rangle$

$|m_z = -3/2\rangle$ \hspace{1cm} $|m_z = 3/2\rangle$

$|m_z = -1/2\rangle$ \hspace{1cm} $|m_z = 1/2\rangle$

$|m_z = 3/2\rangle$

$\Rightarrow \sigma^+$ resonant absorption is Pauli-blocked

$\Rightarrow$ The polarization of emitted photons is determined by the hole spin
Trion transitions in a charged QD

\[ |\uparrow\downarrow, \downarrow\rangle \quad |\uparrow\downarrow, \uparrow\rangle \]

\[ \Gamma \quad \Omega \quad \gamma \quad \xi \]

- \( \Gamma \): spontaneous emission rate
- \( \Omega \): laser coupling (Rabi) frequency
- \( \gamma \): spin-flip spontaneous emission rate due to electron or hole state mixing
- \( \xi \): 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

- An expected Zeeman shift of the absorption plateau to higher laser frequencies
- The disappearance of absorption in the center of the plateau suggests optical pumping

B = 0 Tesla
B = 0.2 Tesla
Trion transitions in the center of the absorption plateau:
Hyperfine mixing of spin-states

\[ |\uparrow\downarrow, \nabla\rangle \quad |\uparrow\downarrow, \Lambda\rangle \quad |\uparrow\downarrow, \nabla\rangle \quad |\uparrow\downarrow, \Lambda\rangle \]

\[ |\downarrow\rangle \quad |\uparrow\rangle \quad |\downarrow\rangle \quad |\uparrow\rangle \]

\[ \Gamma \quad \Omega \quad \gamma \quad \Gamma \quad \Omega \quad \gamma \]

\( B = 0 \, \text{T: fast spin-flips (} \xi^{-1} \sim 3 \, \text{ns)} \quad B = 0.2 \, \text{T: slow spin-flips} \)

\[ \gamma^{-1} \sim 1 \, \mu\text{s,} \quad \Gamma^{-1} = 1 \, \text{ns} \]

\( \Rightarrow \) The electron is optically pumped into the \( |\uparrow\rangle \) state for \( B > 0.1 \, \text{T} \)
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 virtual state energy \( \sim \) 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 reappears due to spin-orbit mediated spin relaxation
- Electron is well isolated from reservoirs only for
  
  $0.1 \text{ Tesla} < B < 5 \text{ Tesla} \quad 500 \text{ mV} < V_{\text{gate}} < 530 \text{ mV}$
Spin cooling mechanism

- Cooling takes place due to one-way pumping by spin-flip spontaneous Raman scattering at rate $\gamma \sim 10^6 \text{ s}^{-1}$.
- There are three mechanisms for randomizing the spin state ($\sim 10^3 \text{ s}^{-1}$):
  a) **Hyperfine interactions**: Effective only for $B \sim 0$ due to energy conservation (i.e. incommensurate electronic and nuclear Zeeman energies)

$$H_{int} = \frac{\hbar A}{N} \sigma \cdot \sum_i \alpha_i I^i$$

$$= \frac{\hbar A}{N} \sum_i \alpha_i \left( \frac{1}{2} \sigma_z I^i_z + \sigma_- I^i_+ + \sigma + I^i_- \right)$$

b) **Exchange interactions with the electron reservoir** (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) **Phonon-assisted spin-flips due to spin-orbit interaction**:
   Effective only for $B > 5 \text{ Tesla}$.

$\Rightarrow$ 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 $\sigma_{\text{abs}}/A_{\text{laser}}$
Absorptive vs. Dispersive response of a QD

Initial electron spin-state determines whether the polarization rotation is $+\theta$ or $-\theta$; this rotation is measured by the difference signal.

\[ X = \pi^+ + \pi \]
\[ Y = \pi^+ - \pi \]
\[ \pm = X \pm Y \]

C
Relative Transmission (%)

\begin{align*}
\sigma^+ & \quad \text{Laser Detuning (GHz)} \\
\pi^+ & \quad -2 \quad 0 \quad 2
\end{align*}
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 \( \sim 1 - 10 \) in a measurement time (500 ms) yielding \( \text{SNR} = 1 \).

- Improvements in detector efficiency and the use of a solid-immersion lens that enhances \( \sigma_{\text{abs}}/A_{\text{laser}} \) 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
Quantum light from a 0.5 μm long carbon nanotube

Photoluminescence

Photon auto-correlation

\[ G(2)(\tau) \]

Time delay \( \tau \) (ns)

PL Intensity (cts/sec)

Wavelength (nm)

4.2 K

\( \Gamma = 4.4 \text{ meV} \)

33 K

9.1 meV

57 K

9.5 meV
Quantum light from a 0.5 μm long carbon nanotube

Photoluminescence

Photon auto-correlation

\[ G(2)(\tau) \]

![Graphs showing photoluminescence and photon auto-correlation at different temperatures (4.2 K, 33 K, 57 K).]

- At 4.2 K, \( \Gamma = 4.4 \text{ meV} \)
- At 33 K, \( 9.1 \text{ meV} \)
- At 57 K, \( 9.5 \text{ meV} \)
Why does a nanotube emit quantum light?
Exciton localization vs. Auger processes

Energy (eV)

<table>
<thead>
<tr>
<th>Energy (eV)</th>
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<tbody>
<tr>
<td>1.425</td>
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<tr>
<td>1.400</td>
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<td>1.375</td>
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PL Intensity (cts/sec)

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<tr>
<th>Wavelength (nm)</th>
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<tr>
<td>870</td>
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<tr>
<td>880</td>
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<tr>
<td>890</td>
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<td>900</td>
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G(2)(τ)

<table>
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<th>Time delay τ (ns)</th>
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<tbody>
<tr>
<td>-30</td>
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<tr>
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<tr>
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</tr>
<tr>
<td>10</td>
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<tr>
<td>20</td>
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<td>30</td>
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auto-correlation

0.39 ± 0.08

cross-correlation

0.27 ± 0.08
Lifetime and saturation

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