Spin-photon entanglement in semiconductor quantum dots

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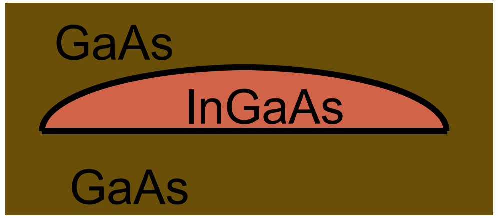
<u>Motivation</u>: realization of an efficient spin-photon quantum interface

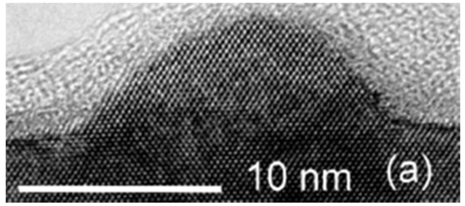
- Emission predominantly channeled into a zero-phonon-line
- Easy embedding in nano-cavity or waveguide structures

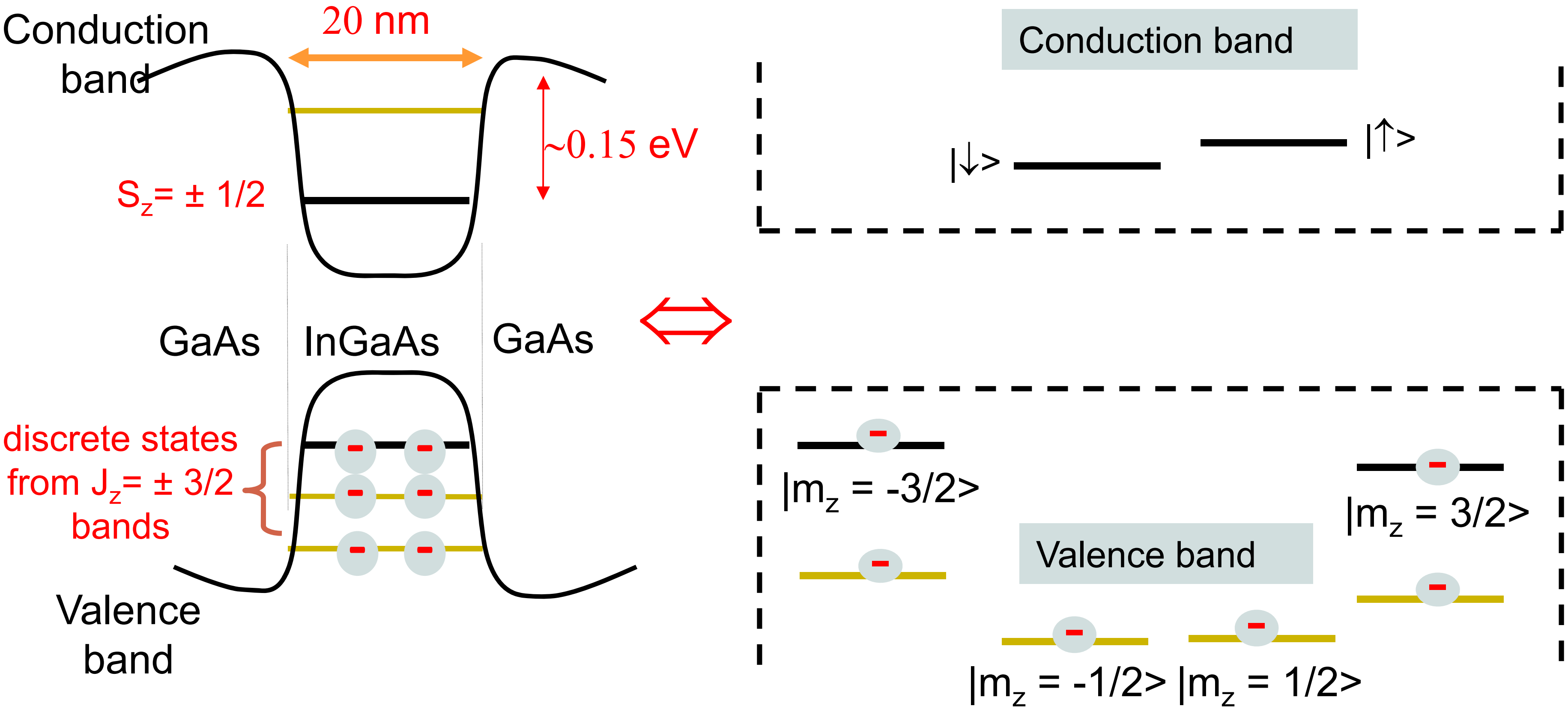
I. Overview of quantum dots

A QD is a mesoscopic semiconductor structure (~10nm confinement length-scale) with a discrete optical excitation spectrum



InGaAs Quantum dots (QD) embedded in GaAs

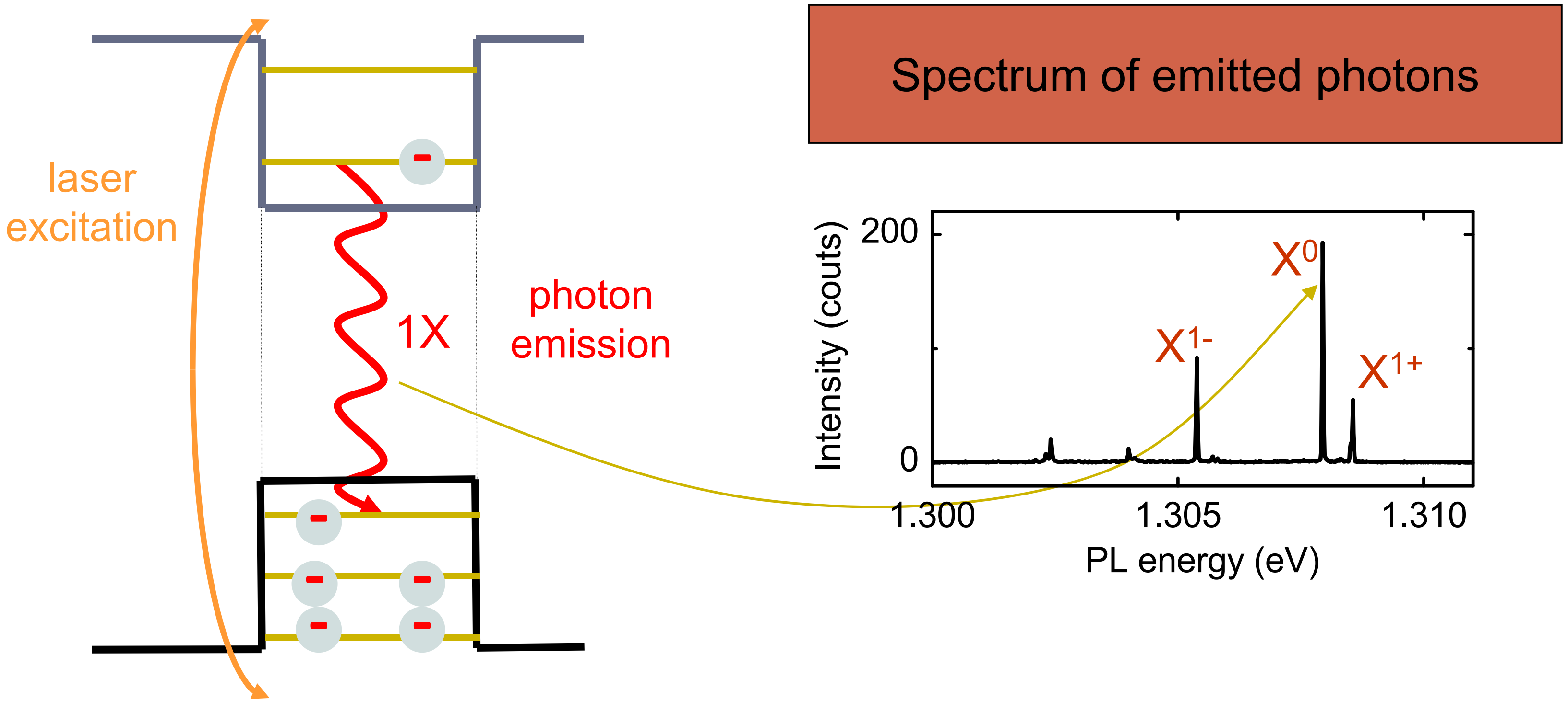




- Self-assembled QDs have discrete states for electrons & holes.
- Conduction band → anti-bonding s-orbitals; valence band → bonding p-orbitals.
- ~10^5 atoms (= nuclear spins) in each QD ⇒ a random magnetic field with $B_{rms} \approx 15$ mT

Optical measurements

- Photoluminescence (PL): we excite non-resonantly and monitor the characteristic emission lines/resonances of the QD



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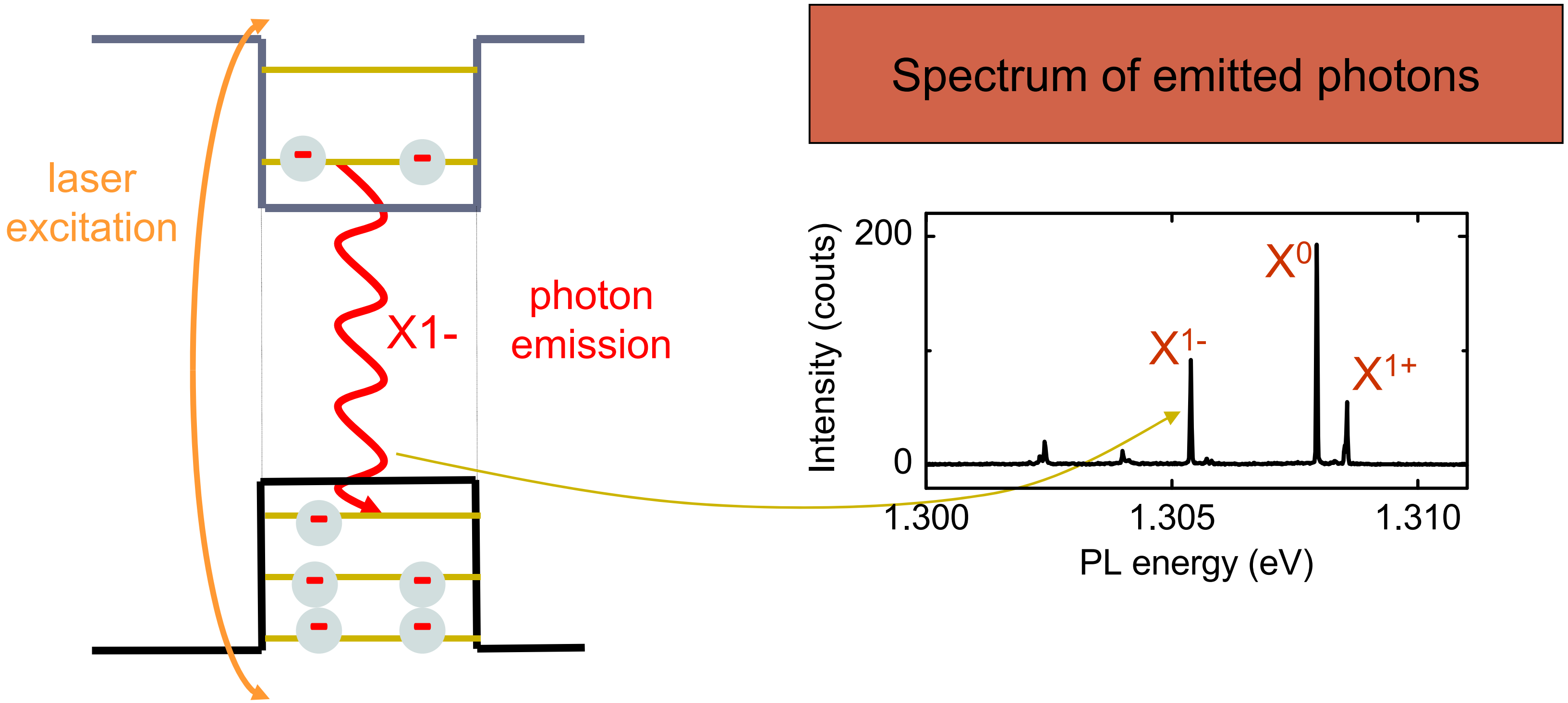
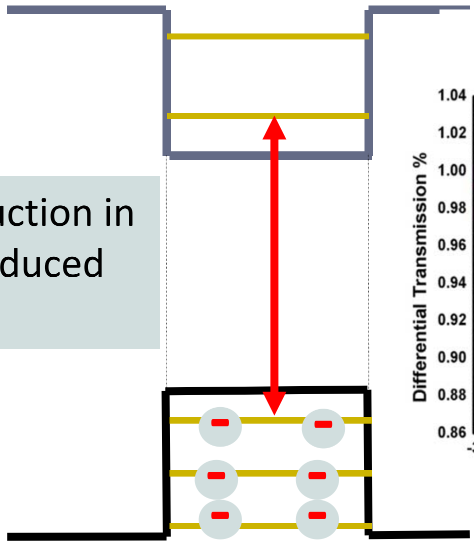
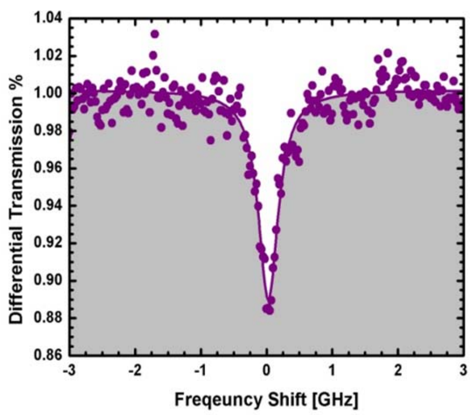


Optical measurements

- Photoluminescence (PL): we excite non-resonantly and monitor the characteristic emission lines/resonances of the QD
- Absorption measurement (DT): we tune the laser frequency across the resonance and monitor the transmitted field intensity
  - ⇨ An interference experiment since the total field is the superposition of the transmitted laser and the QD source field that spatially overlaps with the laser

Up to 12% reduction in transmission induced by a single QD





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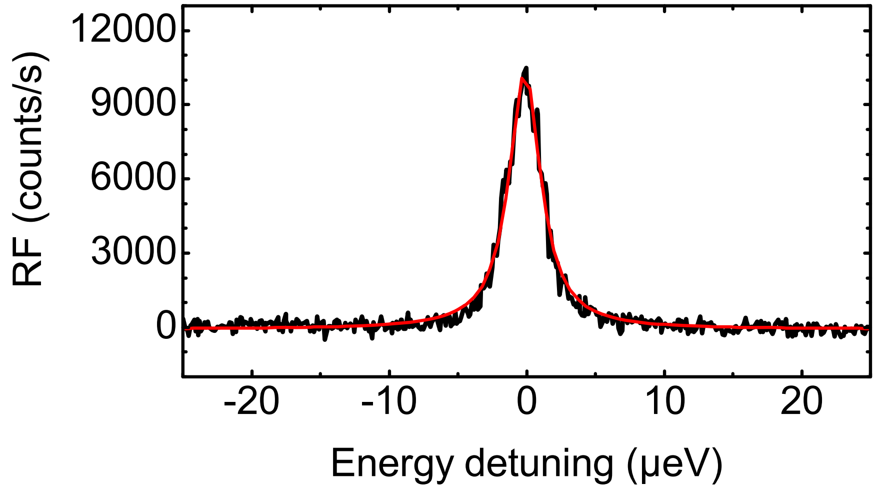
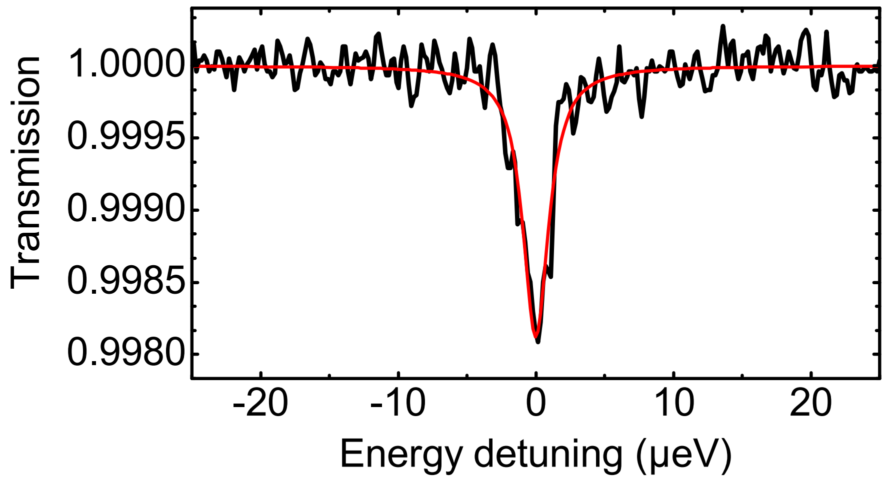
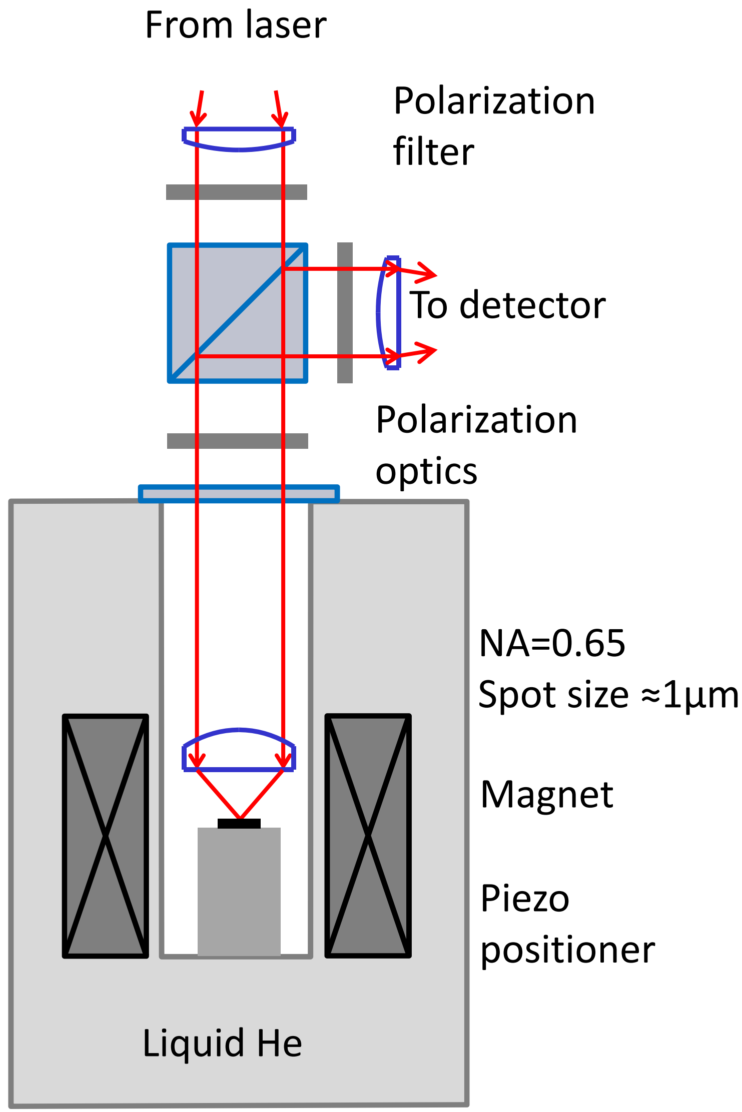
- Resonance fluorescence (RF): we eliminate the background laser scattering by a polarizer and monitor the strength or the frequency dependence of the generated photons.

Note: Photon correlation measurements could be carried out either using PL or RF.

Resonant Laser Spectroscopy

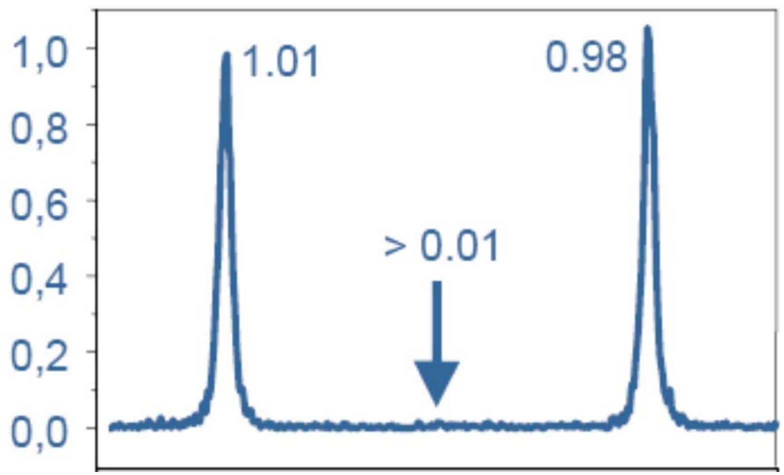






Photon correlations from a single QD

- Pulsed excitation of a QD yields near perfect antibunching (Robert, LPN)



- QDs can be ideal single photon sources
- Photon extraction efficiency > 80% has been achieved

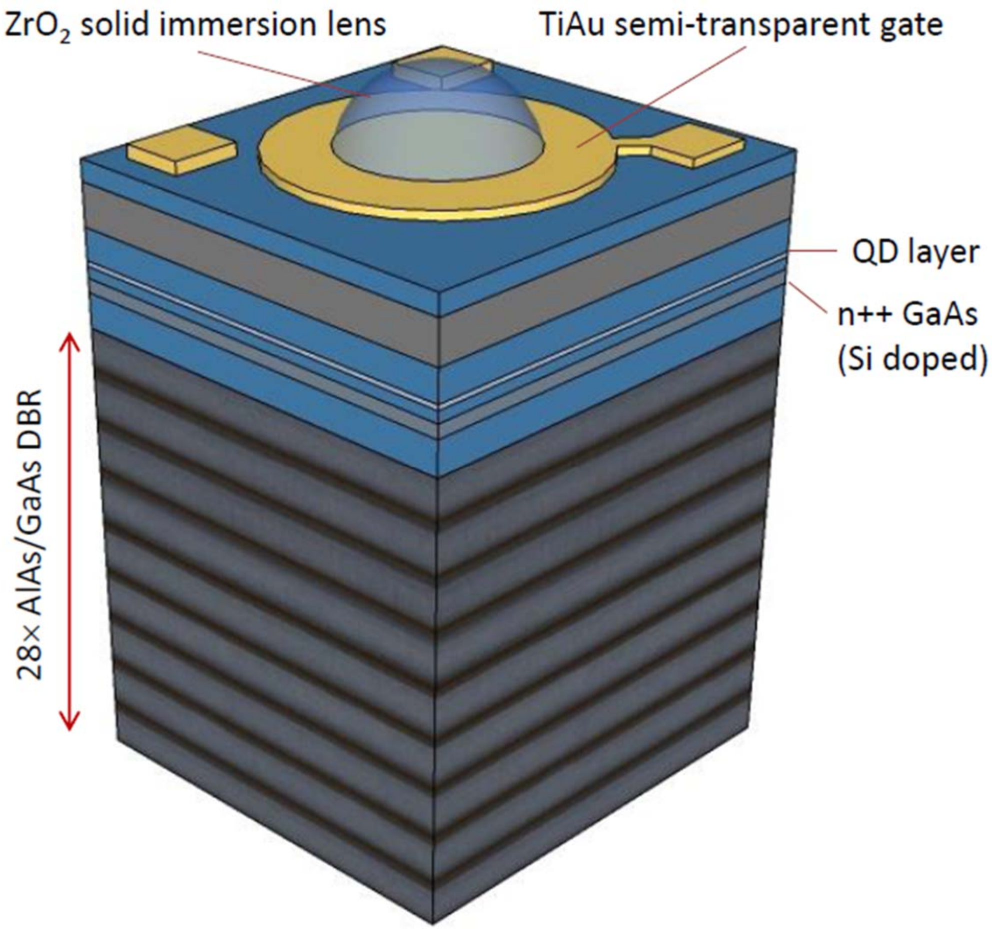
II. Quantum dot spin physics

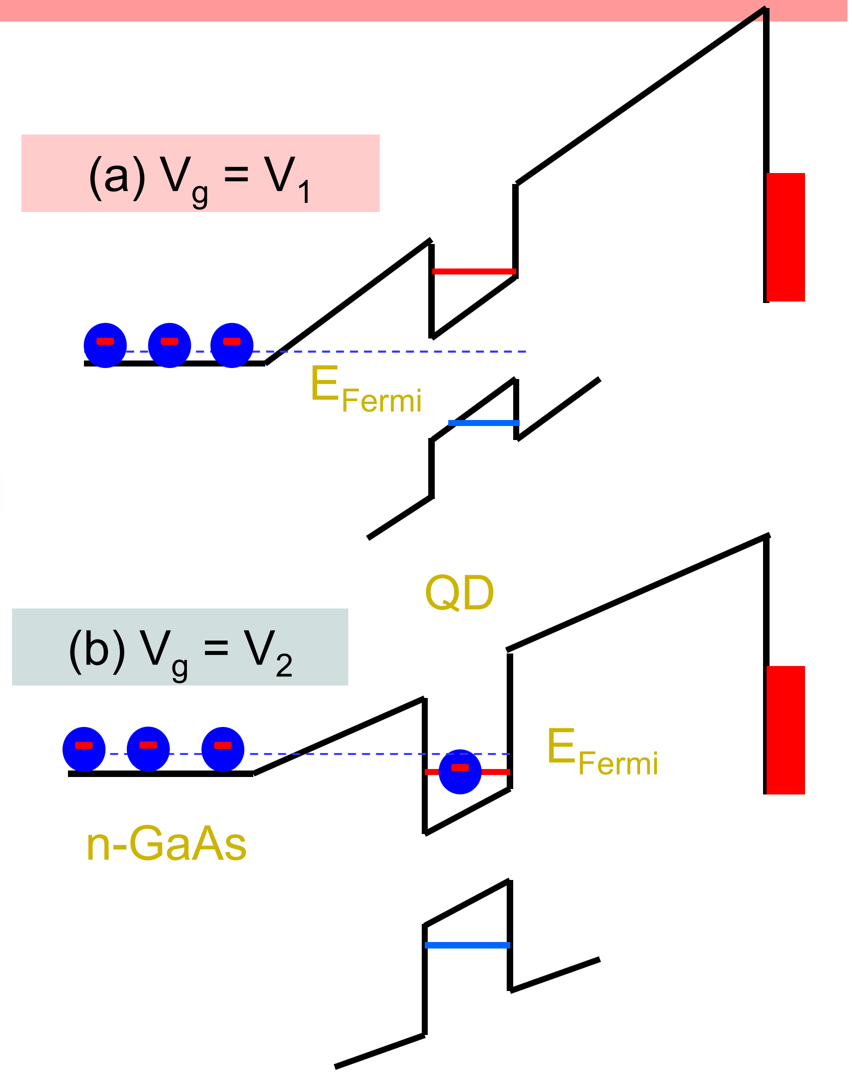
To study spin physics, we need to fix the charging state of the QD such that even under resonant excitation there are no charge fluctuations.

QD spins: controlled charging of a single QD

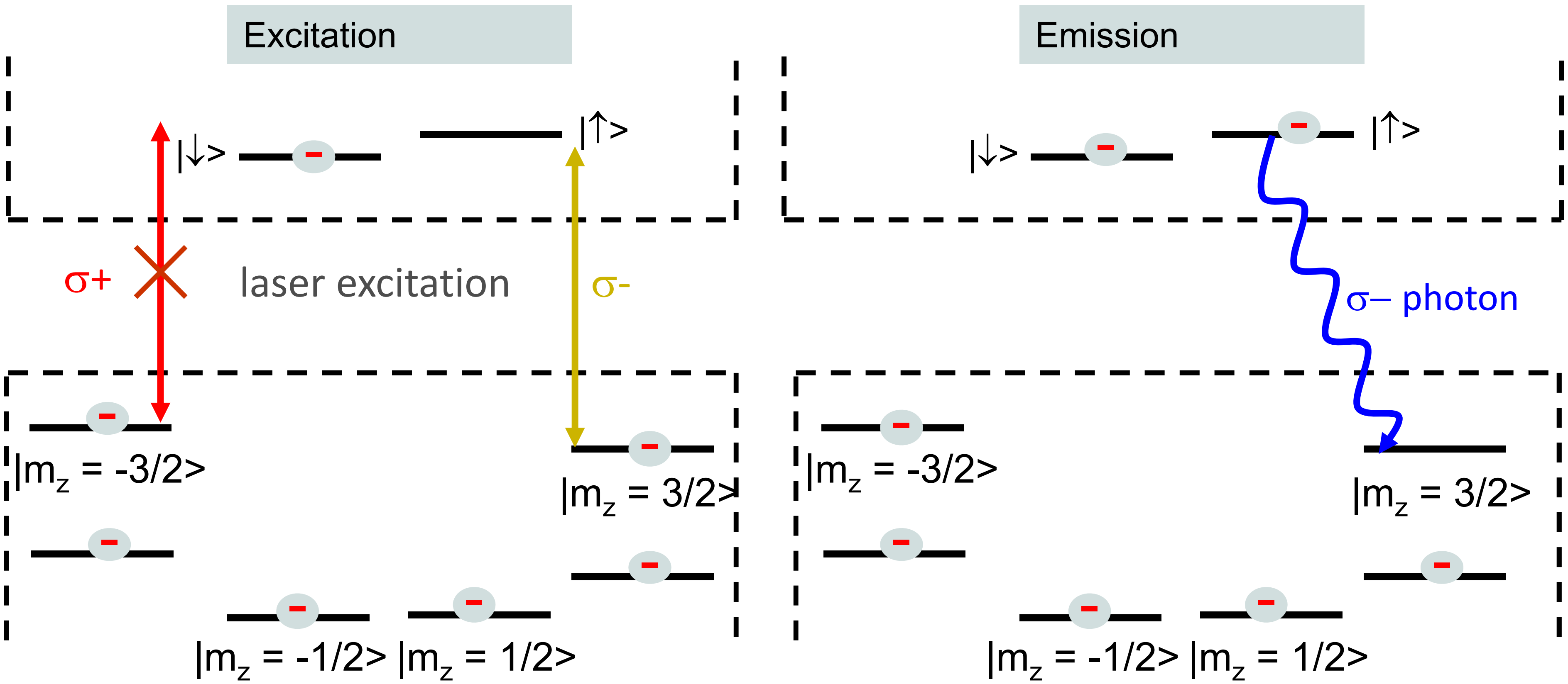
Quantum dot embedded between n-GaAs and a top gate: applied gate voltage V_g allows for tuning of the charging state. DBR mirror+SIL ensures high collection.

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





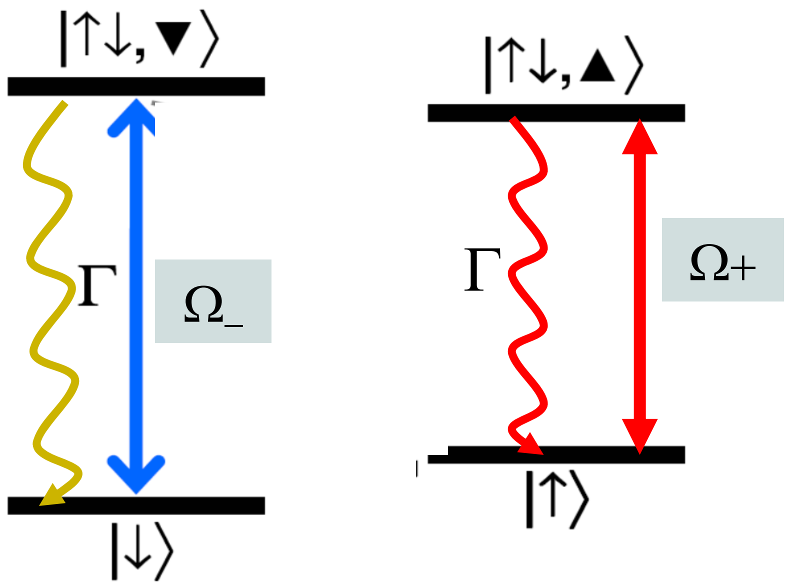
Charged QD X^{1-} (trion) absorption/emission



⇒ σ+ resonant absorption is Pauli-blocked

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

Strong spin-polarization correlations: Faraday geometry ($B_{ext} = B_z$)



Γ: spontaneous emission rate

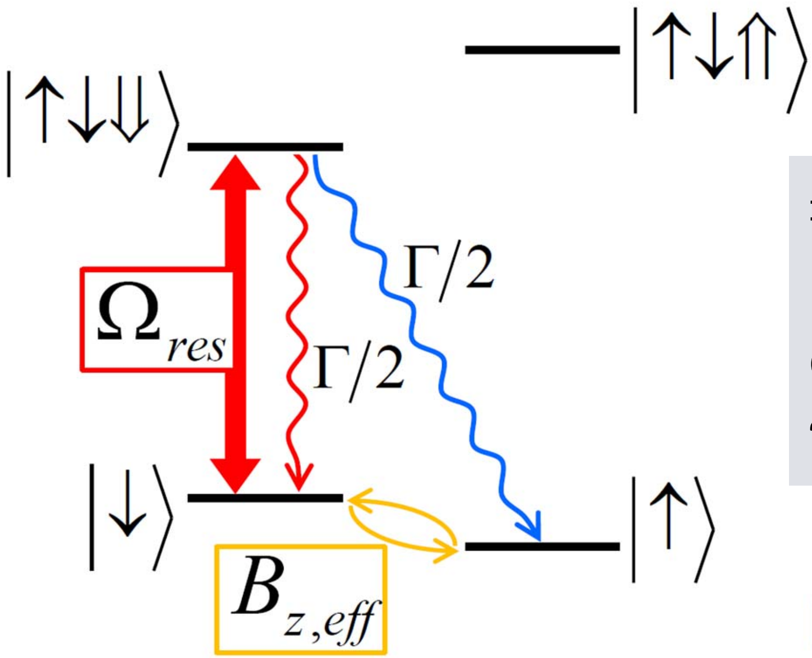
Ω: laser coupling (Rabi) frequency

- QD with a spin-up (down) electron only absorbs and emits σ+ (σ-) photons – a recycling transition similar to that used in trapped ions.

  ⇨ Spin measurement

Strong spin-polarization correlations: Voigt geometry ($B_{ext} = B_x$)

Excitation of a trion state results in either emission of a H polarized red photon to |↓> state or a V polarized blue photon to |↑> state, with equal probability.



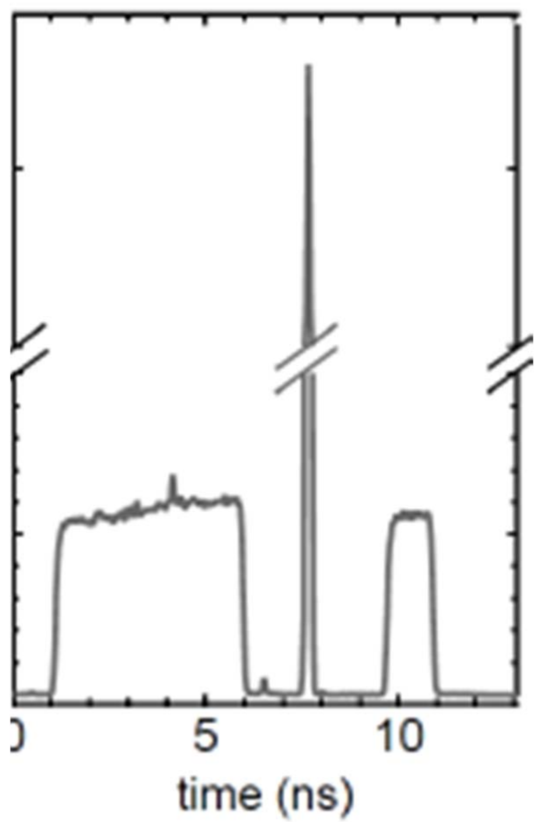
⇒ Spin-photon entanglement: potentially near-determinsitic entanglement generation at ~1 GHz rate

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\downarrow\rangle|\omega_{red}; H\rangle + i|\uparrow\rangle|\omega_{blue}; V\rangle)$$

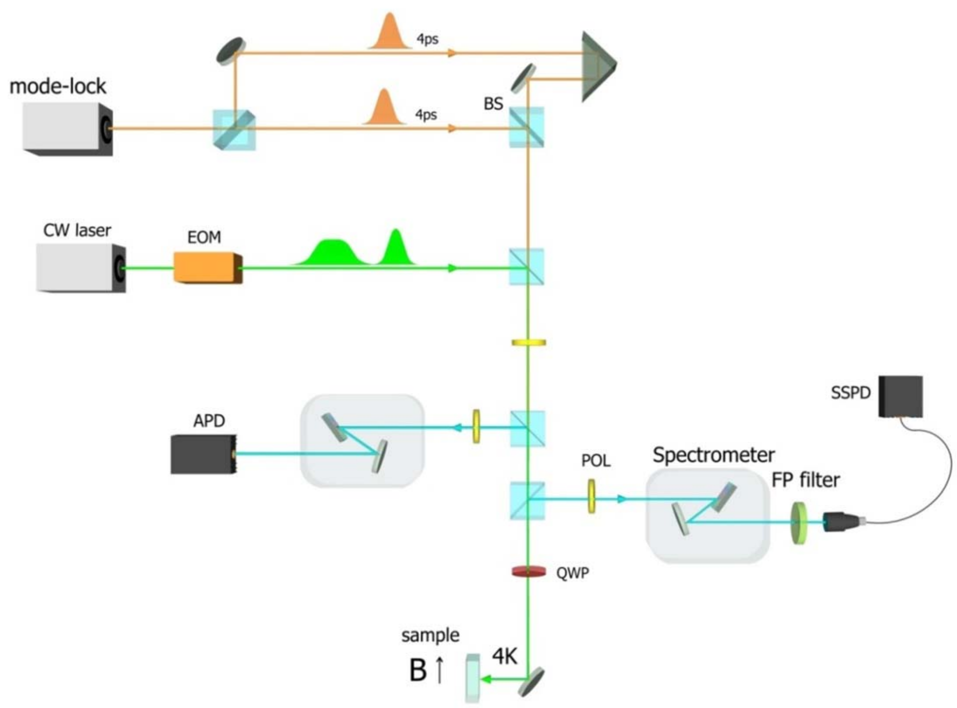
Generation of spin-photon entanglement

Pulse sequence for entanglement generation and verification:

- 5 ns long resonant laser pulse that ensures spin pumping into |↑>, while yielding information about the spin state.
  - photon detection implies that prior to measurement spin was in |↓>
  - no click means no information
- 4 ps long non-resonant pulse implements an effective magnetic field along z and is used to rotate the spin.
- 1 ns long resonant laser pulse excites the trion, which in turn generates spin-photon entanglement as it decays.

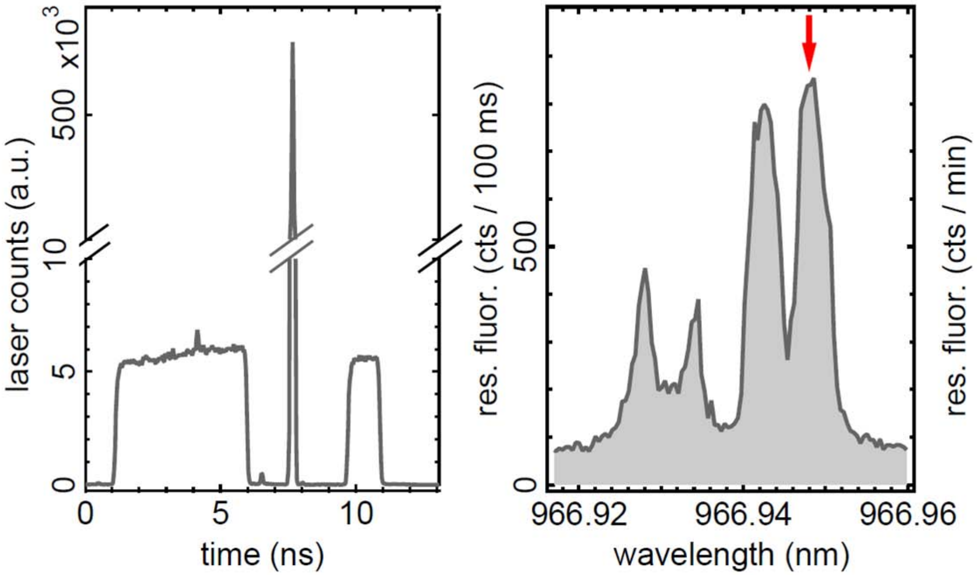


Experimental setup



- The relative delay of the 4 ps pulses is adjusted with a translation stage.
- A polarizer (POL) and a quarter-wave-plate (QWP) ensure that the lasers are circularly polarized.
- Emitted QD photons are detected by an APD and a SSPD, after polarization information is erased by a polarizer.
- In each path, a combination of a polarizer and a spectrometer suppresses the laser background.

Time resolved Resonant fluorescence

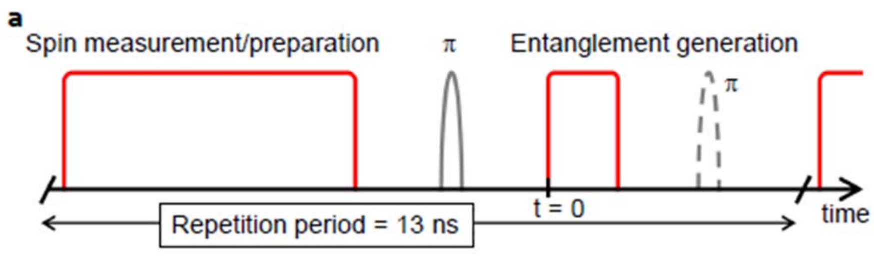


- Right: Partially suppressed reflected laser photons, showing the pulse sequence used to characterize the quantum dot transitions.

- Middle: Resonance fluorescence spectrum as the laser frequency is scanned across the QD

- Left: Time-dependence of resonance fluorescence obtained when the laser is on resonance with the red transition (red-arrow)

Measurement of classical correlations



An additional π-pulse (dashed curve) is applied to realize a heralded measurement in the spin-up state.

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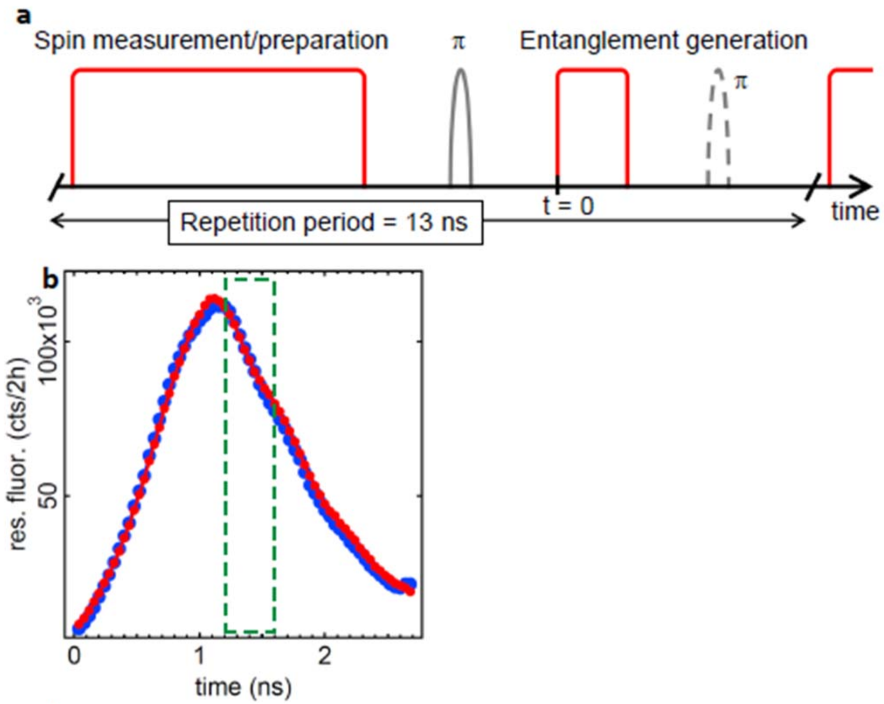

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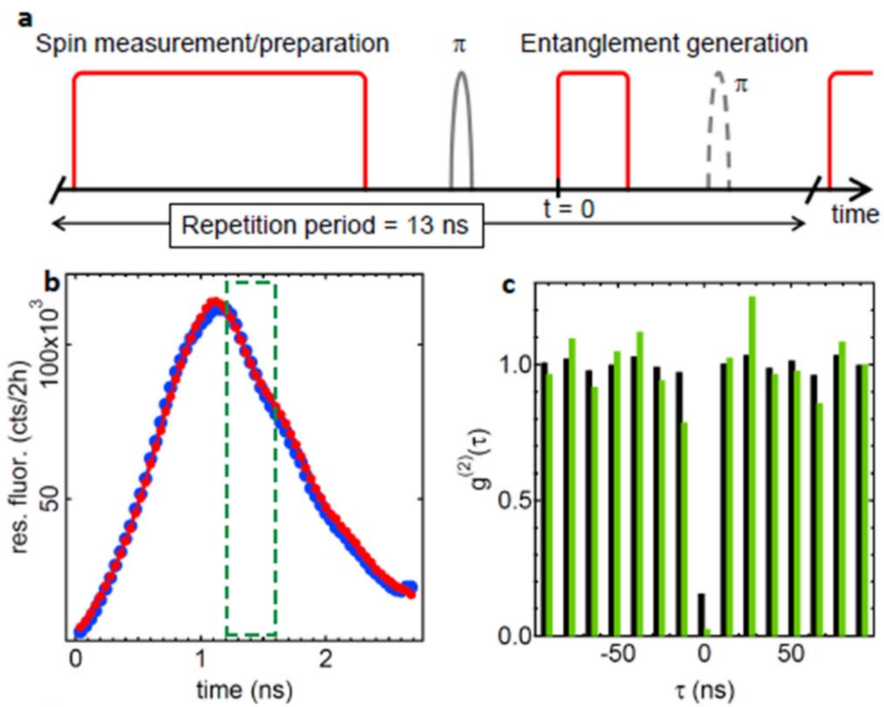

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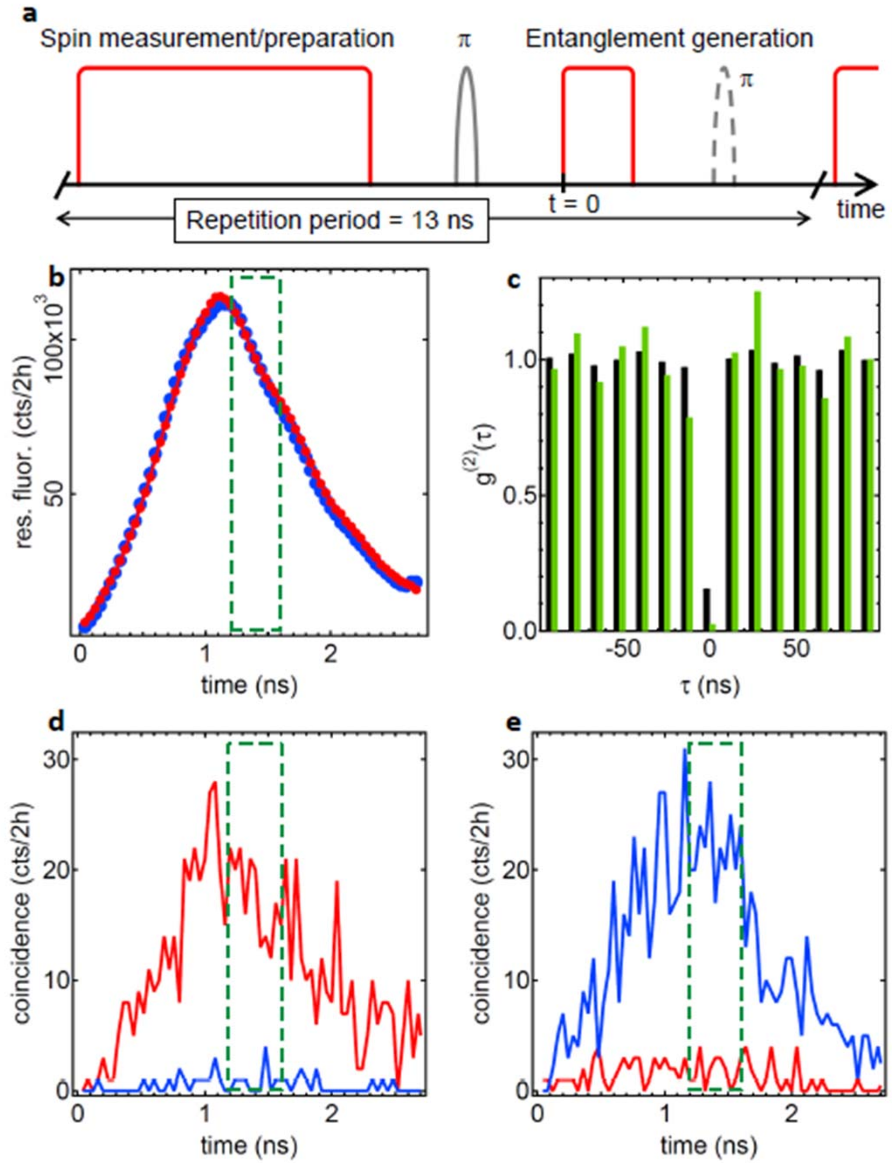

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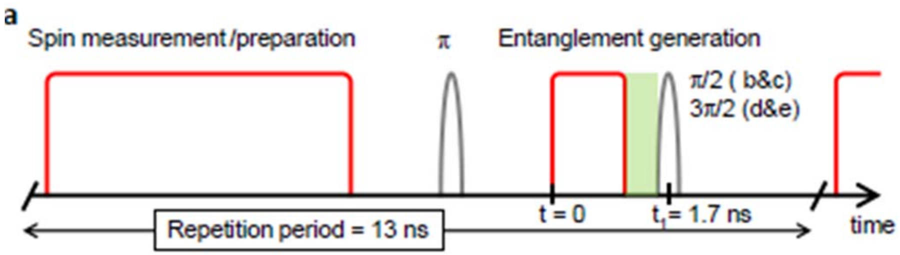
A spin down (up) measurement event ensures that the detected photon is red (blue).

F1=0.87 ± 0.05 in the computational basis measure.ment

Measurement of quantum correlations



- An additional π/2 or 3π/2-pulse (dashed curve) is applied to measure the spin in |↑> ± |↓>.

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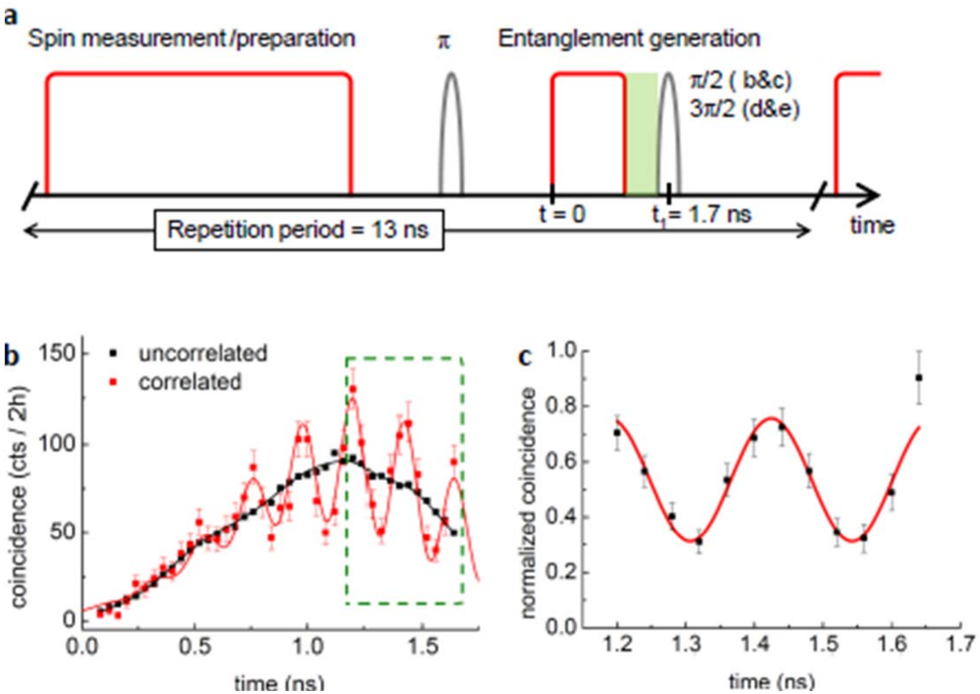
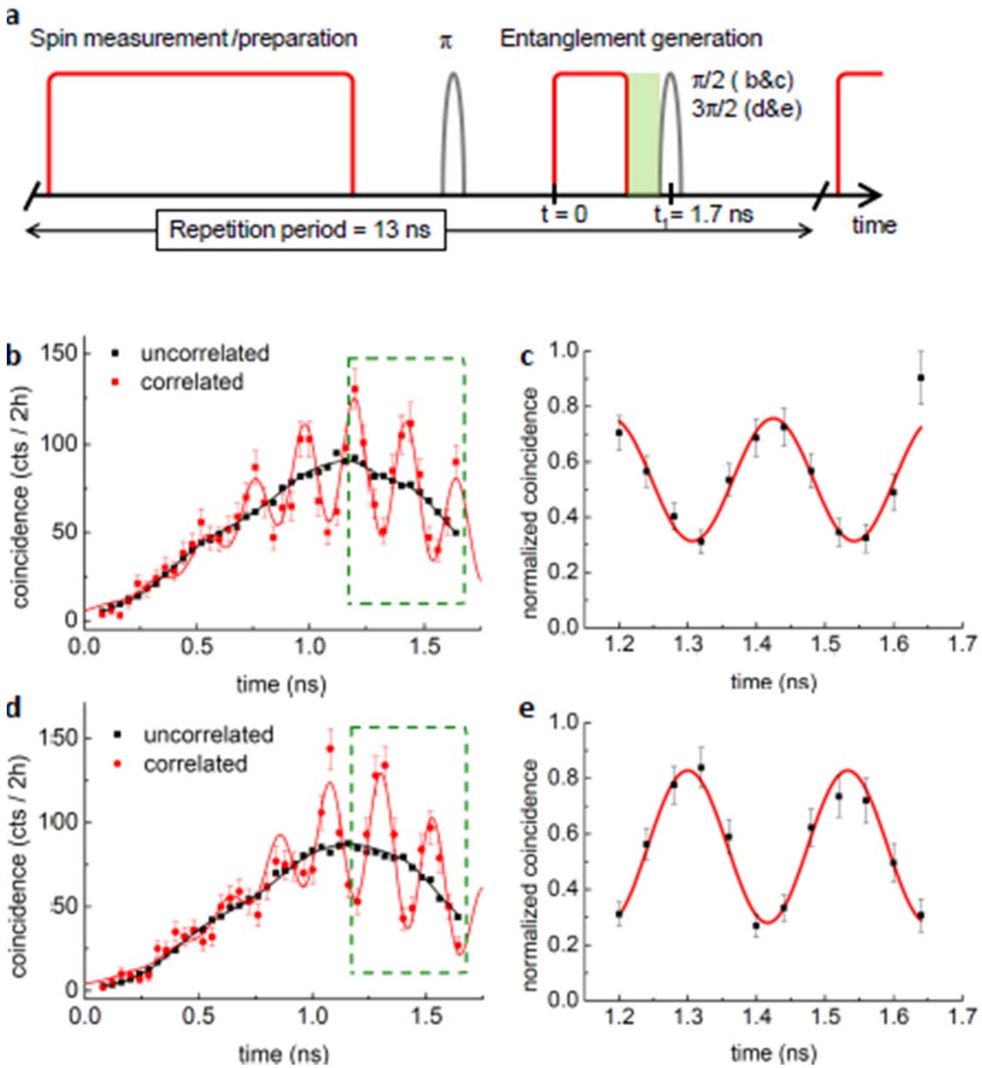


- An additional π/2 or 3π/2-pulse (dashed curve) is applied to measure the spin in |↑> ± |↓>.
- The data in b & c shows the coincidence measurement when π/2-pulse is applied.

$$|\tilde{\Phi}\rangle = \frac{1}{\sqrt{2}}(|\omega_{red}\rangle e^{-i\omega_z(t_1-t_g)} - i|\omega_{blue}\rangle)$$

⇒ Photon generation events at different times correspond to a measurement of the photonic wave-function in different basis.

Measurement of quantum correlations



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- The data in d & e shows the coincidence measurement when 3 π/2-pulse is applied.

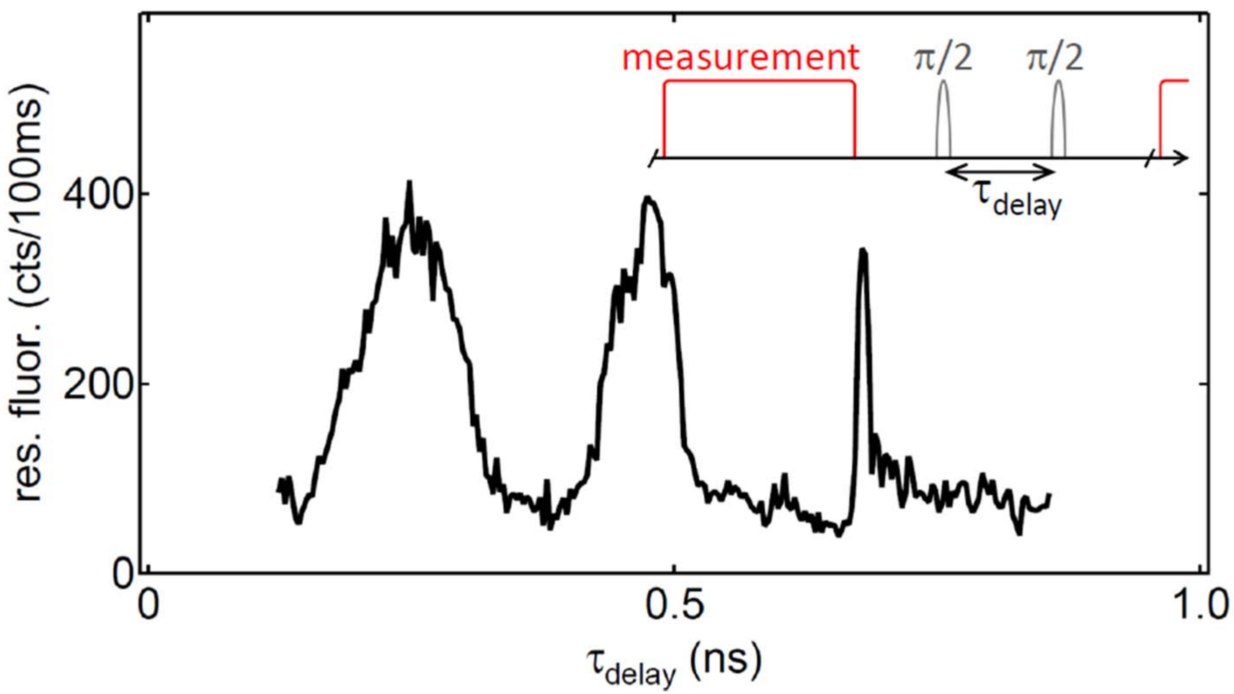
- F2=0.46 ± 0.04 in the rotated basis measurement; overall fidelity F = 0.67 ± 0.05

Outlook

- Teleportation from a single photon to a solid-state spin
- Spin-Spin entanglement
- Understanding and suppressing the role of hyperfine interactions.

Quantum control: unavoidable interference from nuclear spins

- Ramsey experiment on a single electron charged QD:



- Instead of Gaussian decay of Ramsey fringes, we observe a spike at ~0.7 ns followed by complete suppression!

Thanks to

- **Weibo Gao**
- Emre Togan, Parisa Fallahi, Javier Sanchez