A solid-state quantum interface between stationary and flying qubits

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<u>Thanks to</u>:
Weibo Gao, Yves Delley, Emre Togan, Aymeric Delteil, Sun Zhe

Spin-photon quantum interface

- Goal: to use single-photon pulses to link (distant) quantum nodes. Applications:
  - quantum repeaters
  - distributed quantum information processing

- Resource: indistinguishable photonic qubits (= the same spatio-temporal profile, center frequency & polarization) or entangled spin-photon pairs

$$|\psi\rangle = (\uparrow, H\rangle + |\downarrow, V\rangle)/\sqrt{2}$$

H,V could denote any «internal» degree of freedom (color, polarization, orbital angular momentum, etc) of the photon

Outline

- A bright source of indistinguishable single photons
- Creation of quantum entanglement between a single photon and a condensed matter spin
- Teleportation from a propagating qubit to a solid-state spin

Solid-state spins & emitters

- Solid-state emitters (artificial atoms) can be used to realize high brightness long-lived single-photon sources:
  - no need for trapping
  - easy integration into a directional (fiber-coupled) cavity
  - up to 10^9 photons/sec with >70% efficiency

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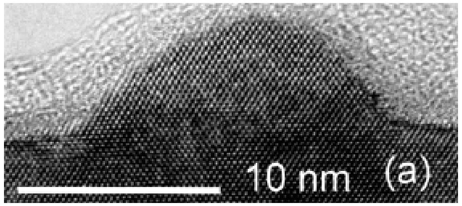
- Three different type of emitters:
  - rare-earth atoms embedded in a solid matrix (Er in glass)
  - Deep defects (NV centers in diamond)
  - Shallow defects in semiconductors (quantum dots)

Note: While the concepts & techniques apply to a wide range of solid-state emitters, we focus on quantum dots

Quantum dots

A quantum dot (QD), is a mesoscopic semiconductor structure (~10nm confinement length-scale) consisting of 10,000 atoms and still having a discrete (anharmonic) optical excitation spectrum.



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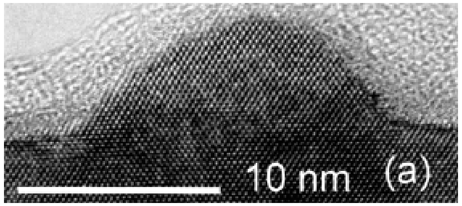
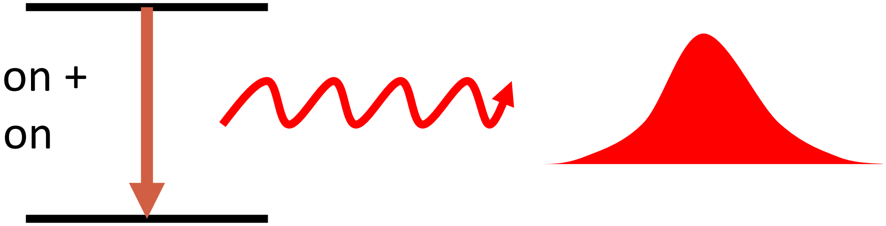


- Neutral quantum dots (QD) are ideal for generation of single and entangled indistinguishable photons, thanks to near-transform limited emission lines.



|excited>

Pulsed laser excitation + spontaneous emission

|ground>

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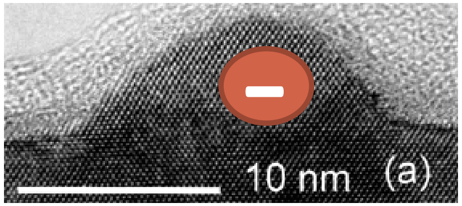

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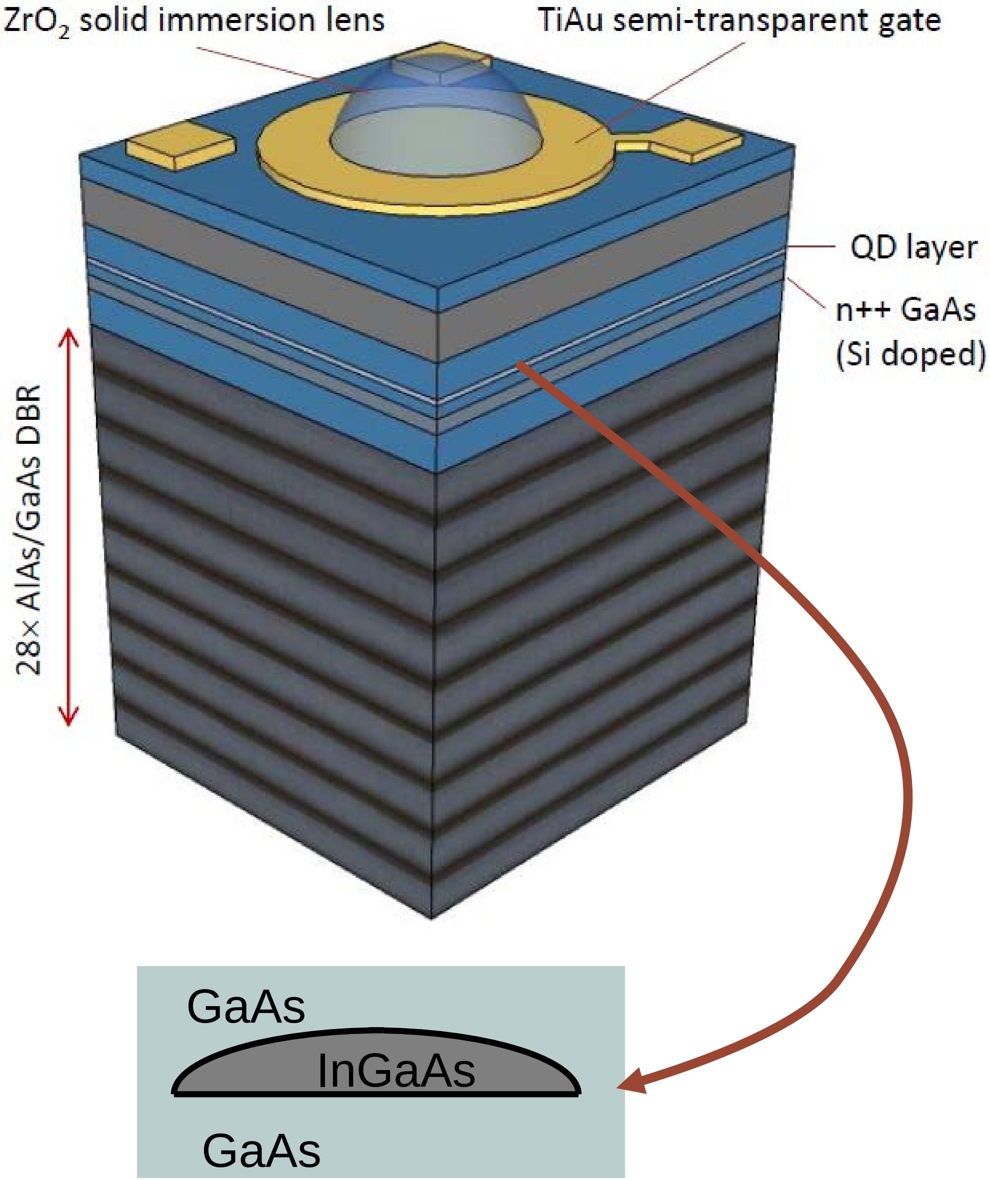
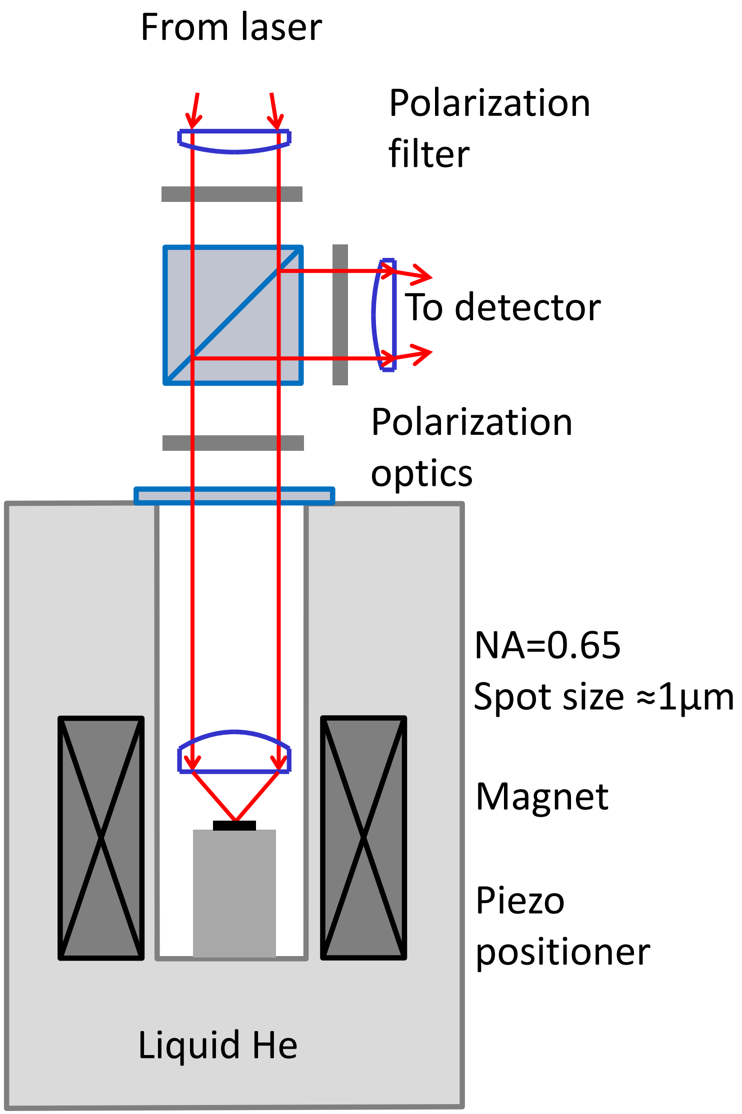
- Single-electron charged QDs allow for realization of a quantum interface between electron spin and generated photon via spin-state dependent light scattering, leading to spin-photon entanglement.

Quantum dot Spectroscopy

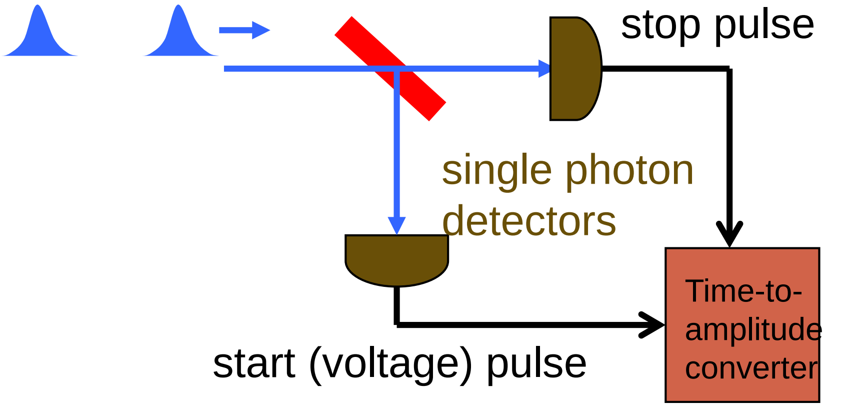




How do we make sure that a light pulse contains a single photon: Photon correlations from a single QD

- Intensity (photon) correlation function: $g^{(2)}(\tau) = \dfrac{\langle : I(t) I(t+\tau) : \rangle}{\langle I(t) \rangle^2}$

- To measure $g^{(2)}(\tau)$, photons from a quantum emitter are sent to a Hanbury-Brown Twiss setup



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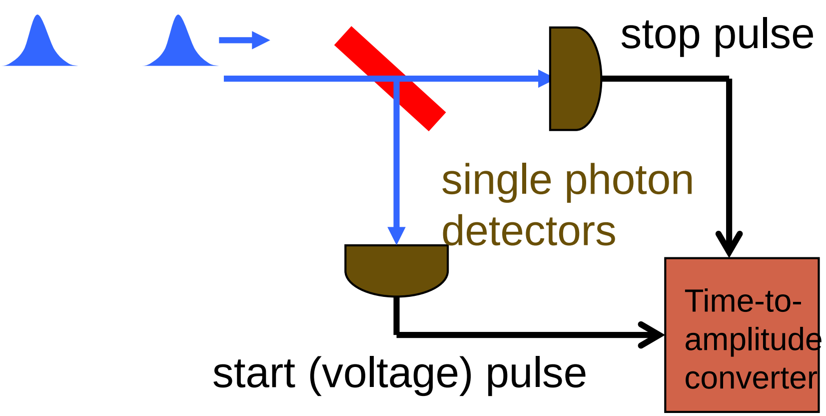
- Photon correlations from a weak pulsed laser (<n> ~ 1); detection of a photon does not change the likelihood of detecting a second.

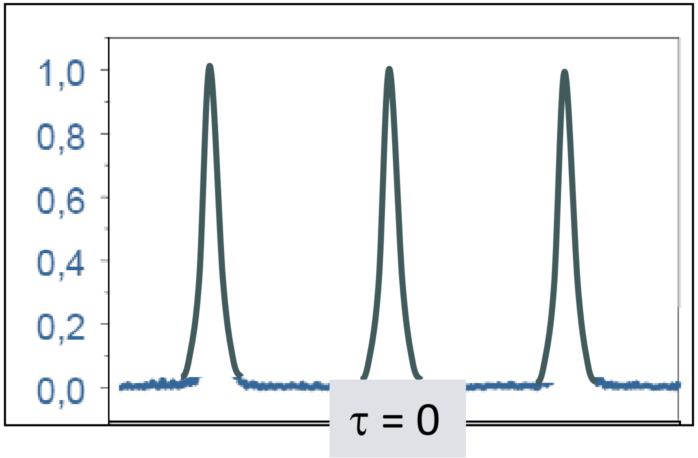


stop pulse

single photon detectors

Time-to-amplitude converter

start (voltage) pulse



$\tau = 0$

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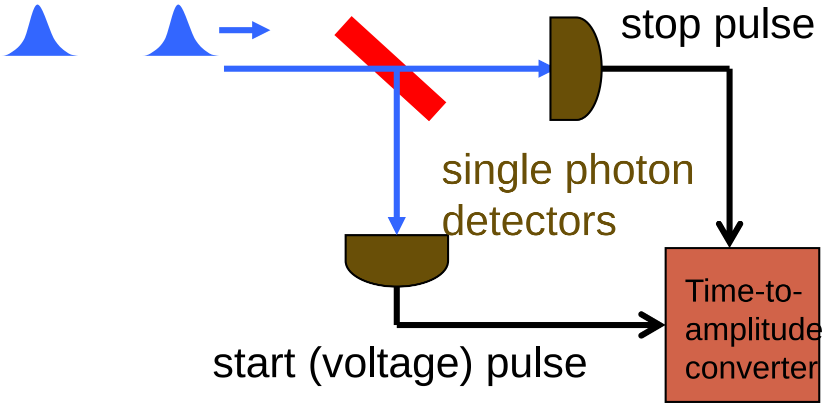
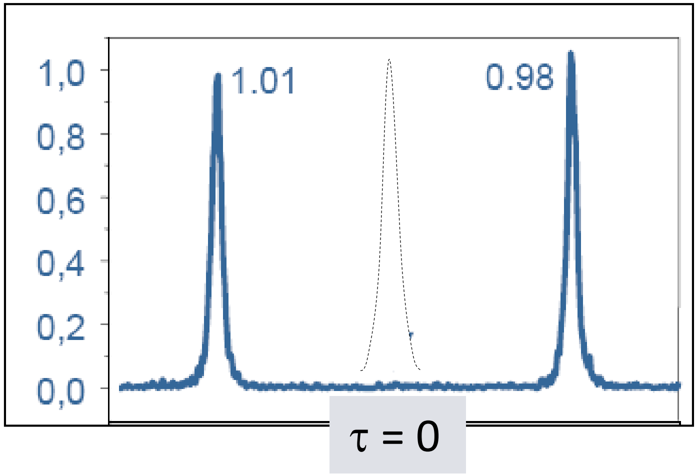


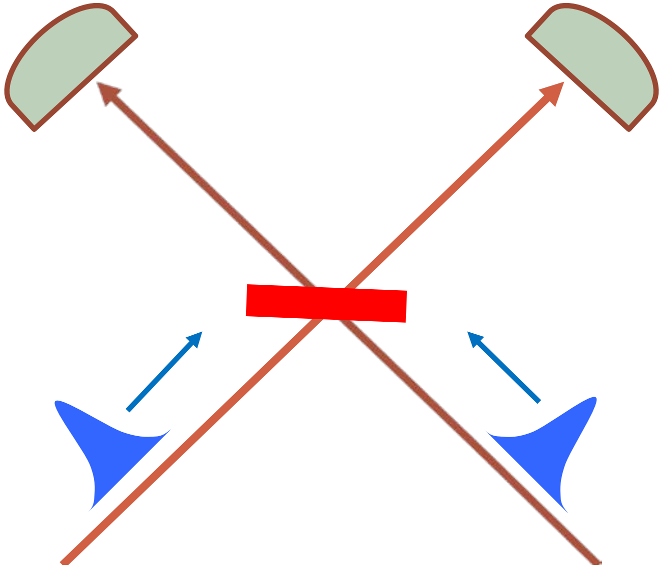
- To measure $g^{(2)}(\tau)$, photons from a quantum emitter are sent to a Hanbury-Brown Twiss setup
- Single quantum emitter driven by a pulsed laser: absence of a center peak indicates that none of the pulses have > 1 photon (Robert, LPN).

⇒ Signature of a single-photon source



How do we make sure that single-photons are not quantum correlated with any other system: Two-photon (HOM) interference

- Two completely indistinguishable single-photon pulses incident on a beam-splitter never lead to coincidences at the output due to a quantum interference effect.



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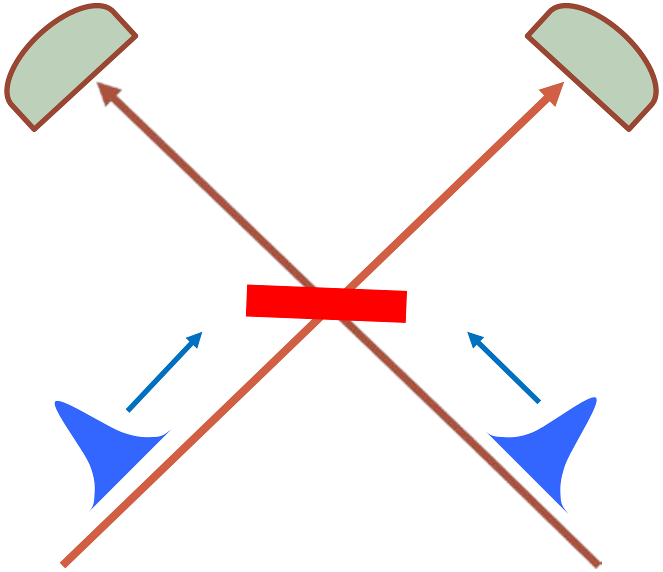
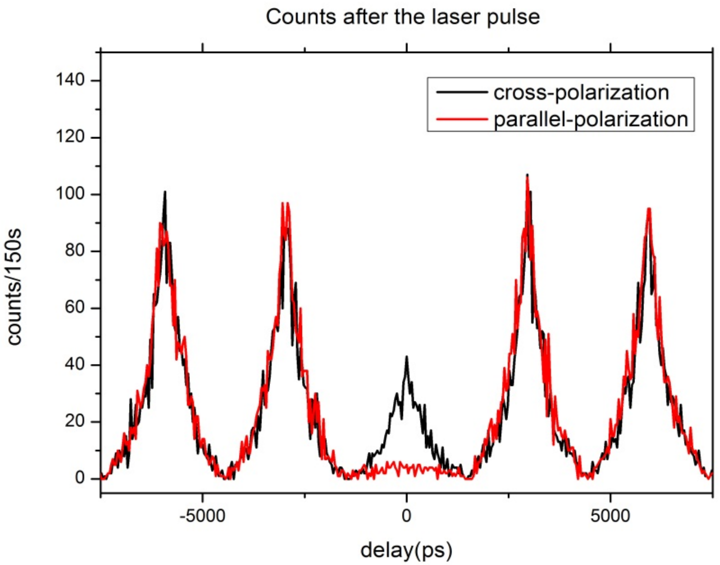
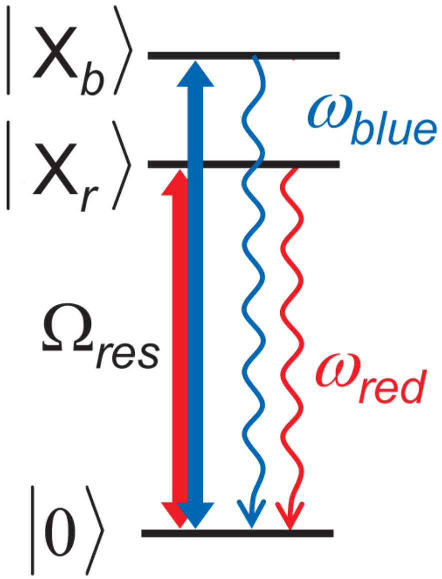


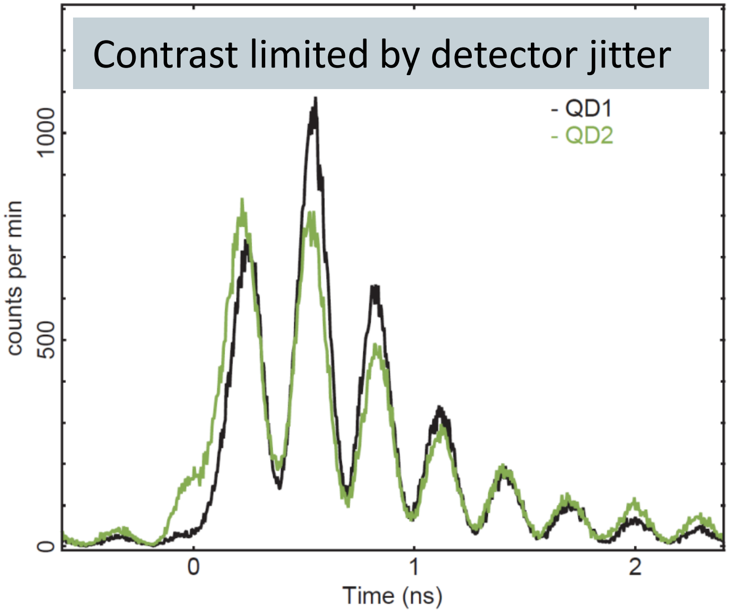


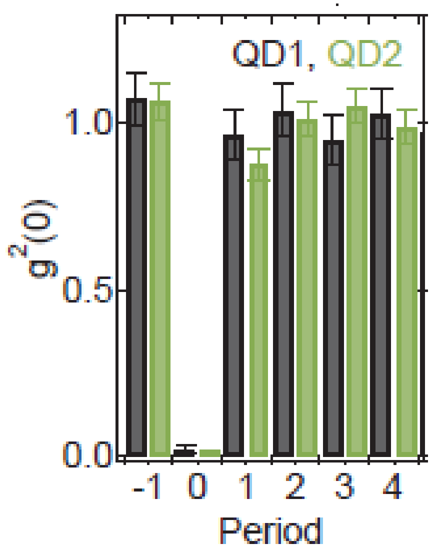
- The single photon pulses have to have the same spatio-temporal profile, center frequecy, polarization.
- Indistinguishability ensures the absence of entanglement of single photons with uncontrolled degrees of freedom.

A single-photon frequency-qubit from a QD: $|\psi\rangle = \alpha|\text{blue}\rangle + \beta|\text{red}\rangle$

In a neutral QD, the elementary optical excitations are excitons (X0); the two linearly polarized exciton X0 lines are split due to electron-hole exchange by ~ 5 GHz

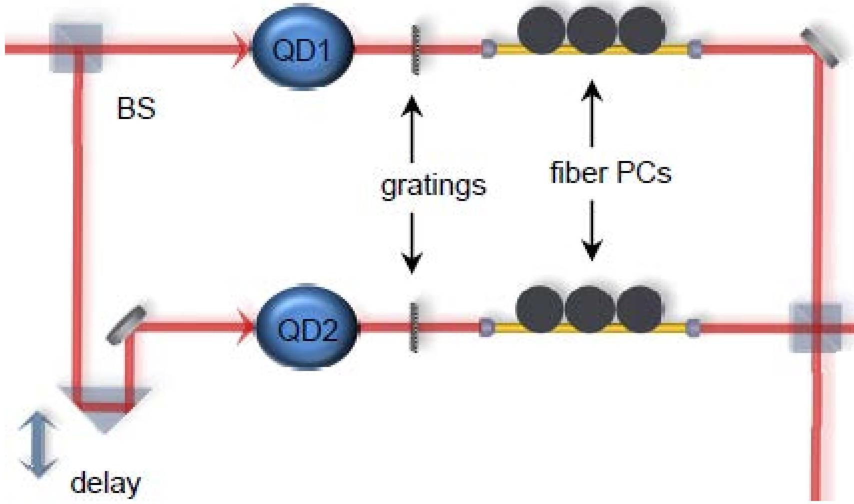



Contrast limited by detector jitter

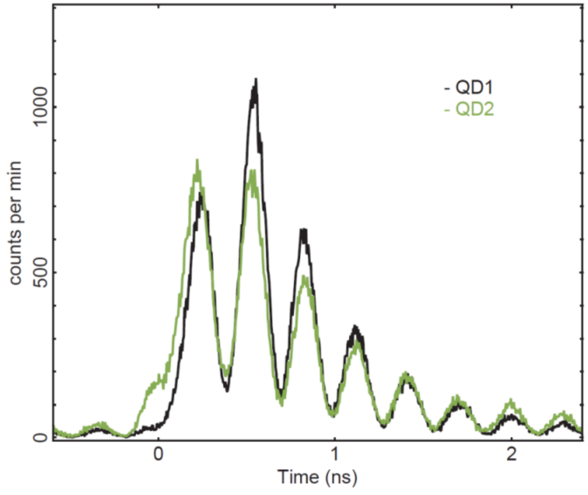


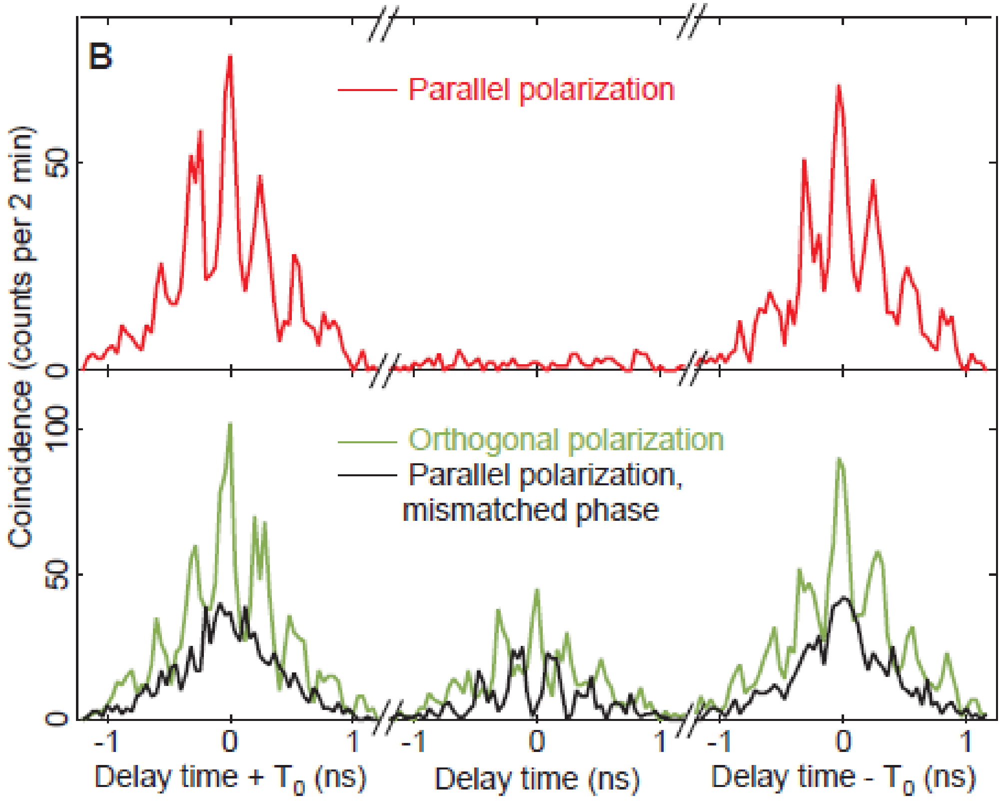
By controlling the pulse-shape, detuning and polarization of the resonant laser, we could generate a single-color photon or a two-color photonic qubit

Interference of photonic qubits (superposition of blue and red photons) coming from two quantum dots



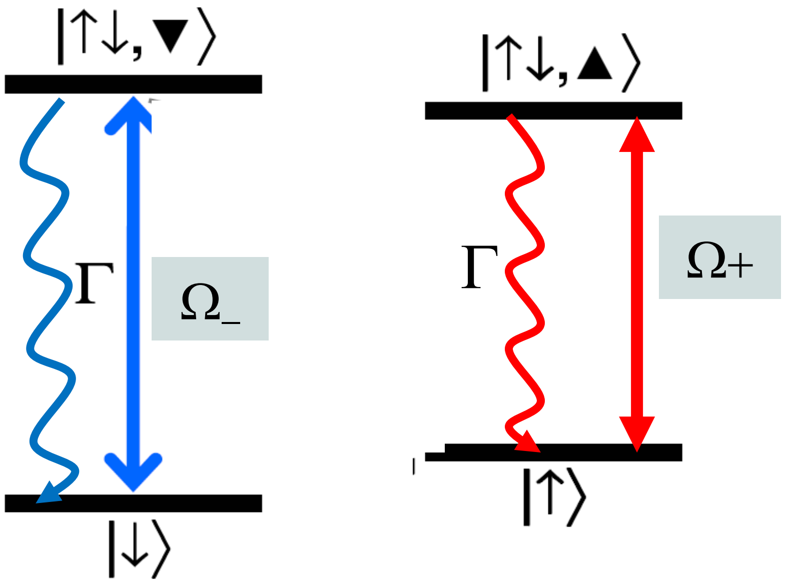
- Two distant QDs rendered «identical» using local electric and magnetic fields.
- 80% visibility in intereference of two photonic (color) qubits





Quantum dots and spin qubits:

Faraday geometry ($B_{ext} = B_z$)



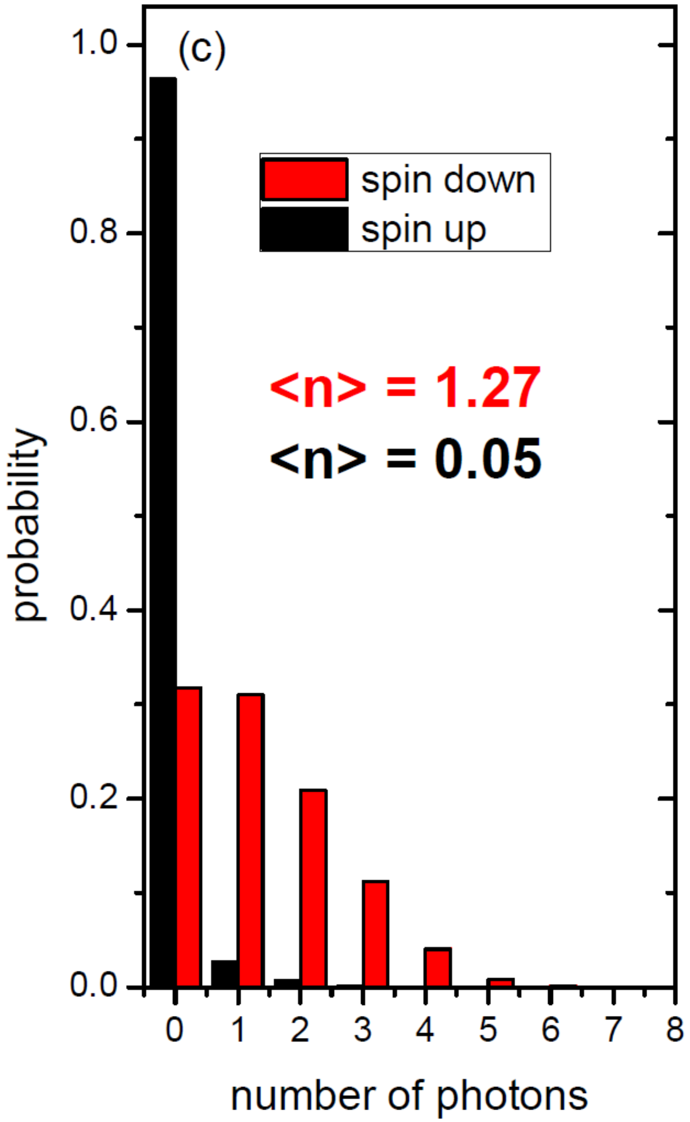
Γ: spontaneous emission rate

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.

  ⇨ Measurement of a spin qubit: $|\psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$

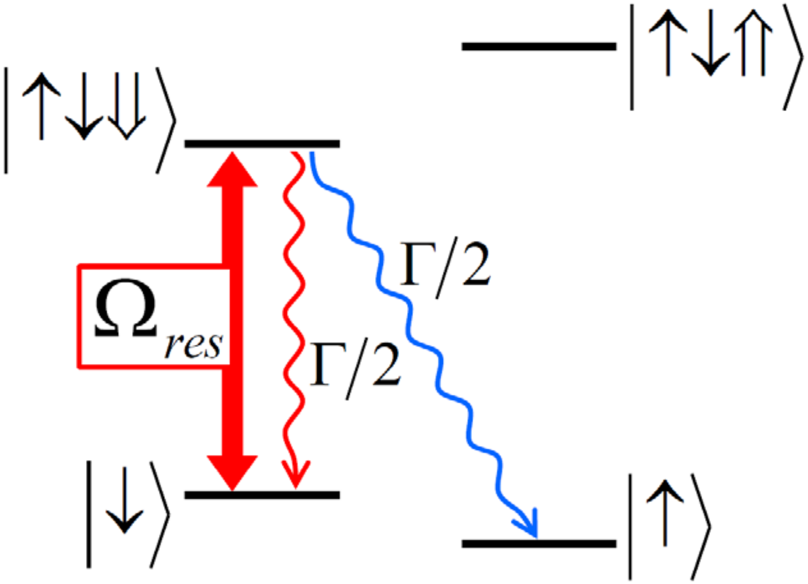
Single-shot measurement of electron spin



- Prepare the electron spin in |↑> or |↓>
- Apply a 0.8 μs resonant laser pulse on the trion transition corresponding to |↓>
- Single-shot measurement fidelity ~ 80% in 0.8 μs
- Fidelity is limited by spin pumping into|↑> - long duration of excitation leads to initialization of the qubit.

Optical transition from a quantum dot spin qubit in 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.



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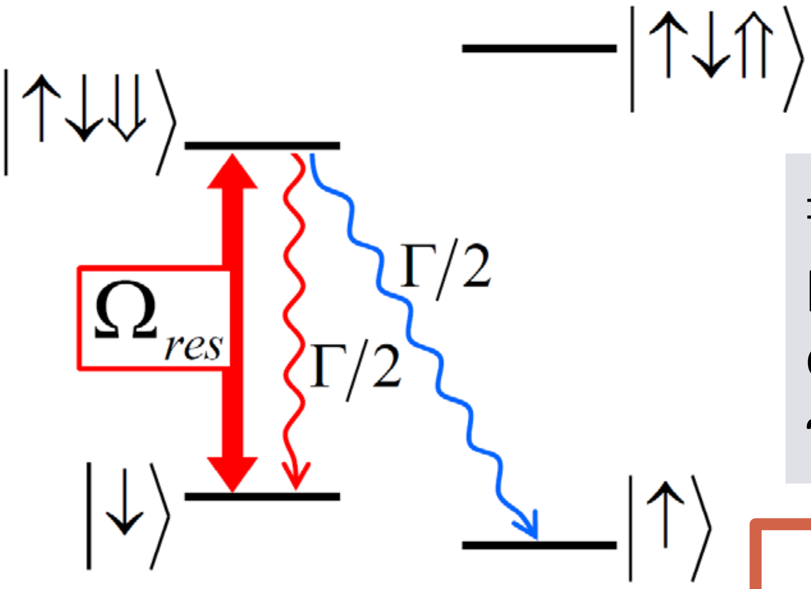
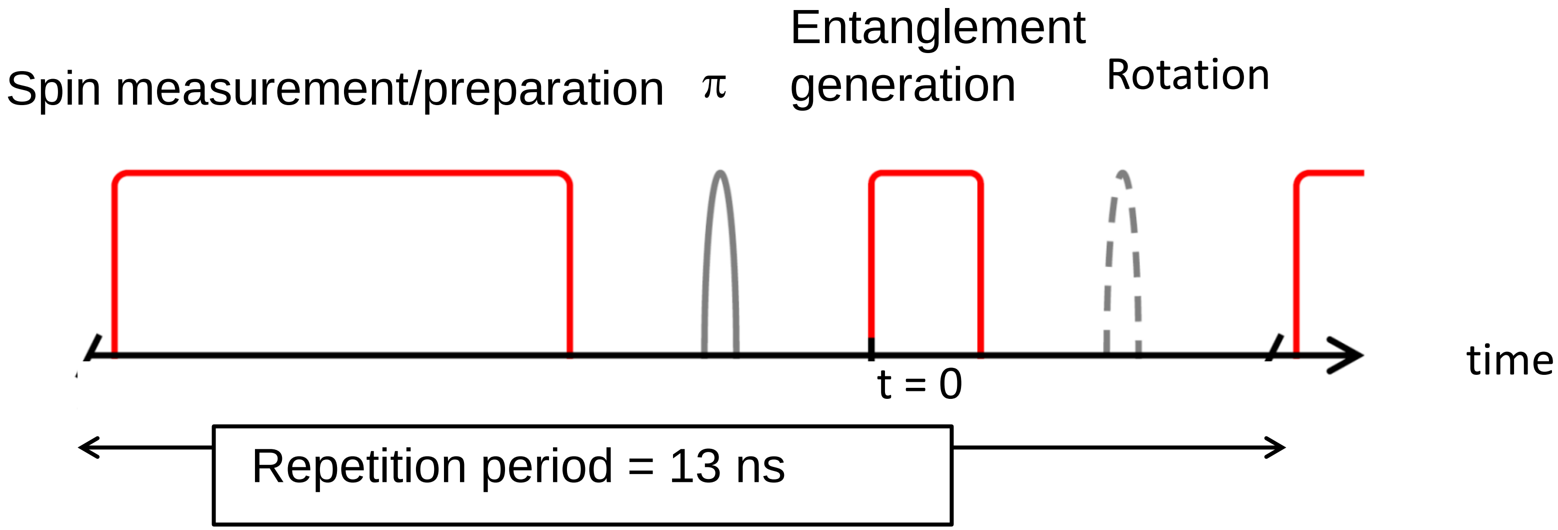


⇒ Spin-photon entanglement: potentially near-deterministic entanglement generation at ~1 GHz rate

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

Similar results by Yamamoto, Steel groups; earlier work by Monroe,Lukin

Procedure for spin-photon entanglement generation



Spin measurement/preparation

π

Entanglement generation

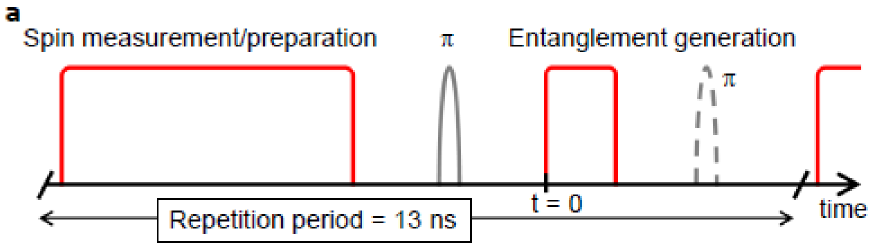
Rotation

t = 0

time

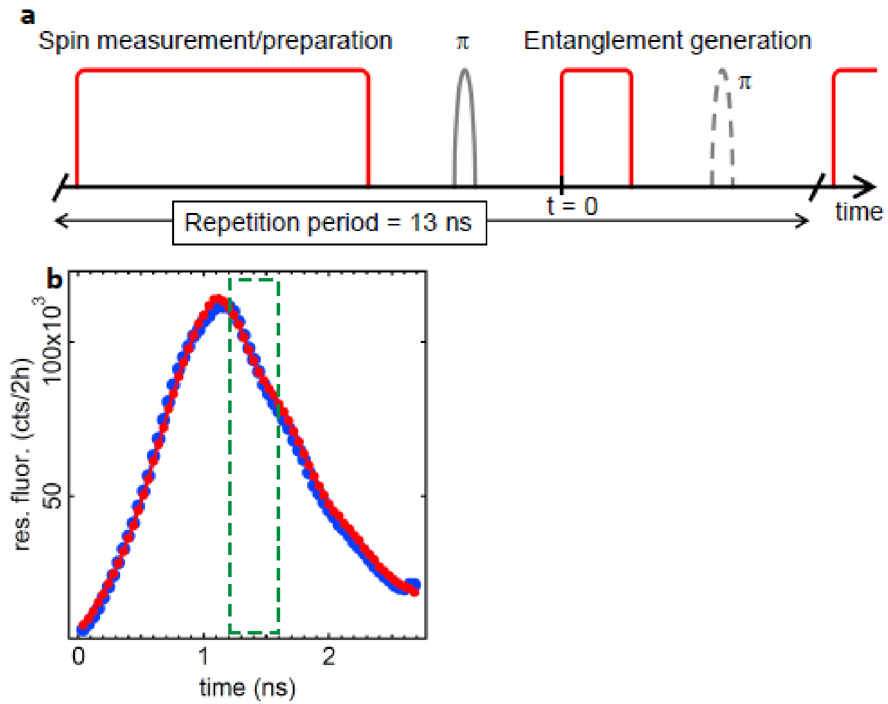
Repetition period = 13 ns

Measurement of classical correlations



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

Measurement of classical correlations



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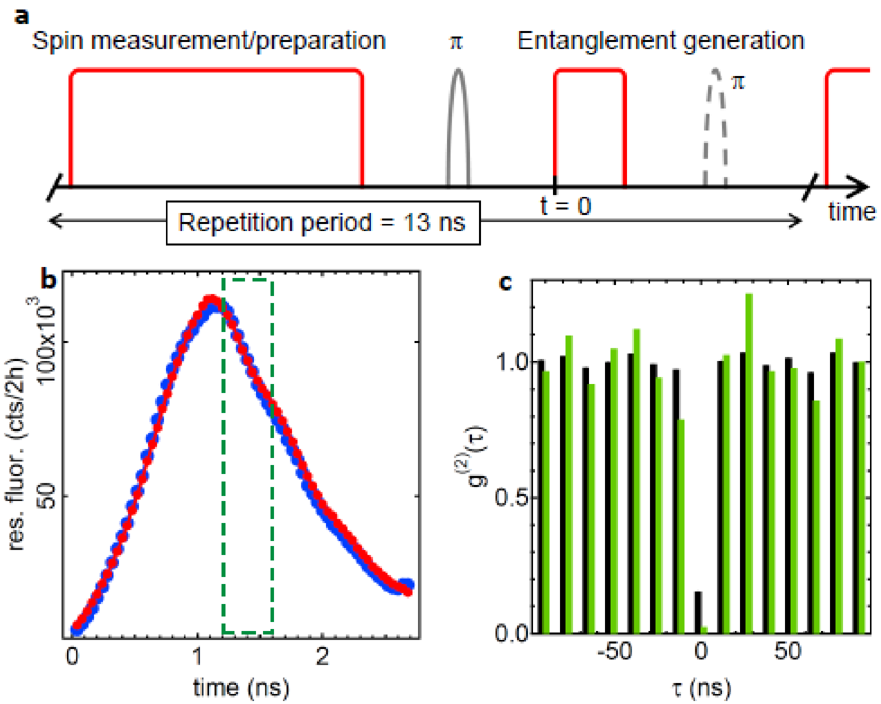

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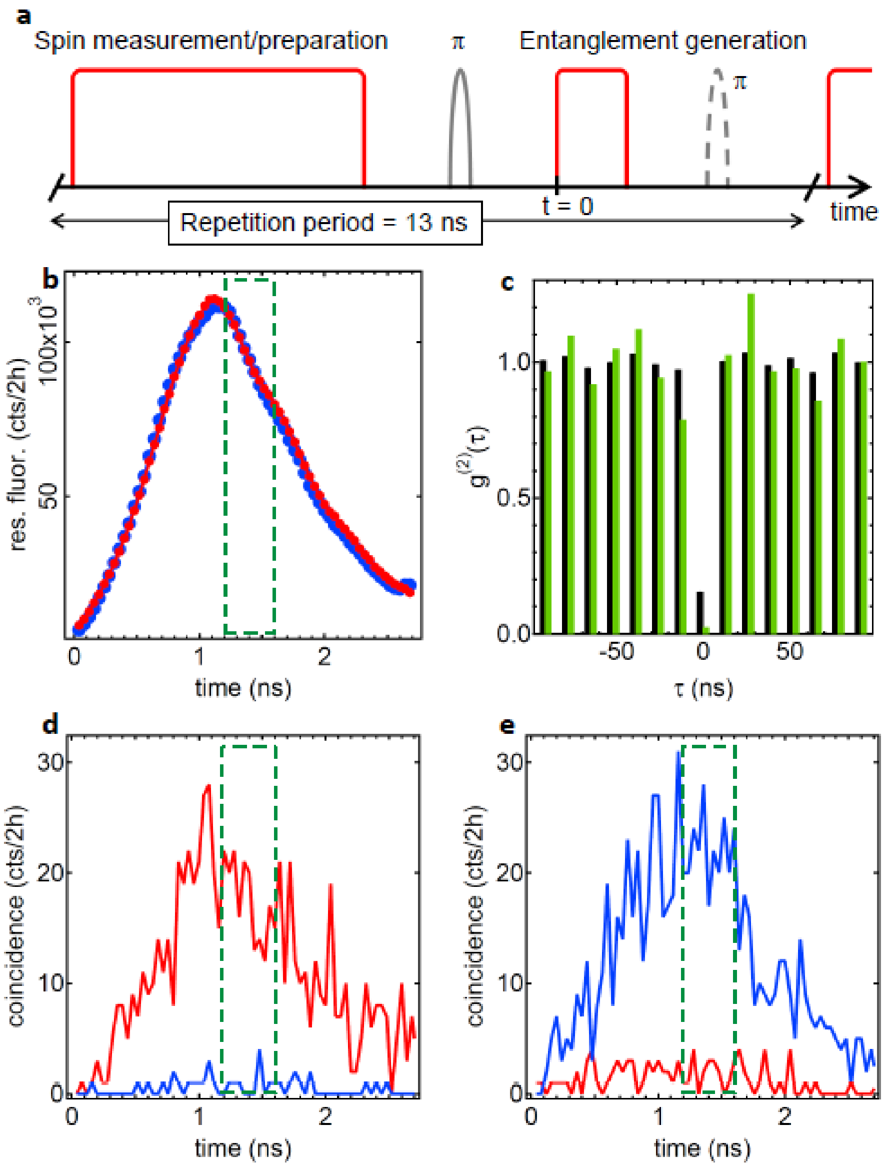

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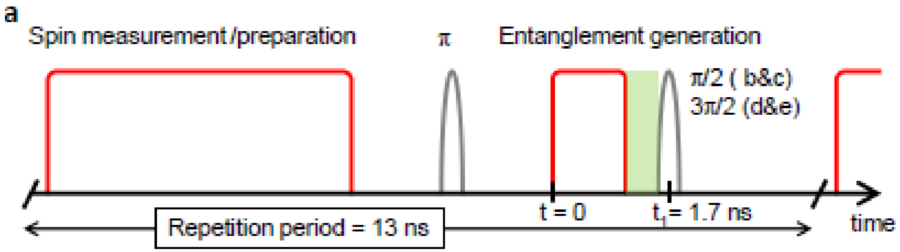
A spin down (up) measurement event ensures that the detected photon is red (blue).

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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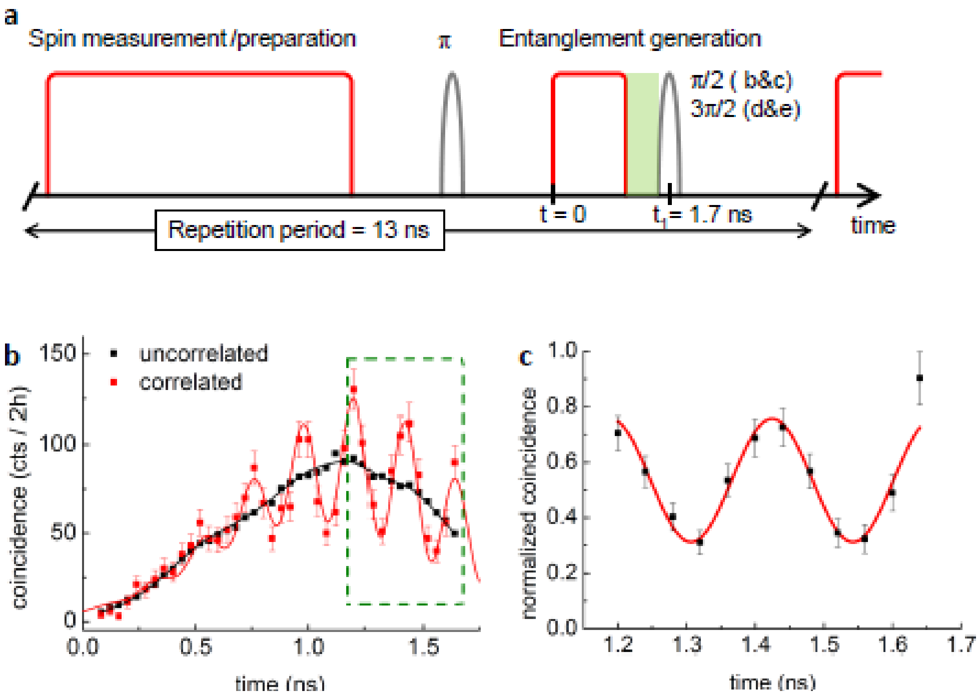

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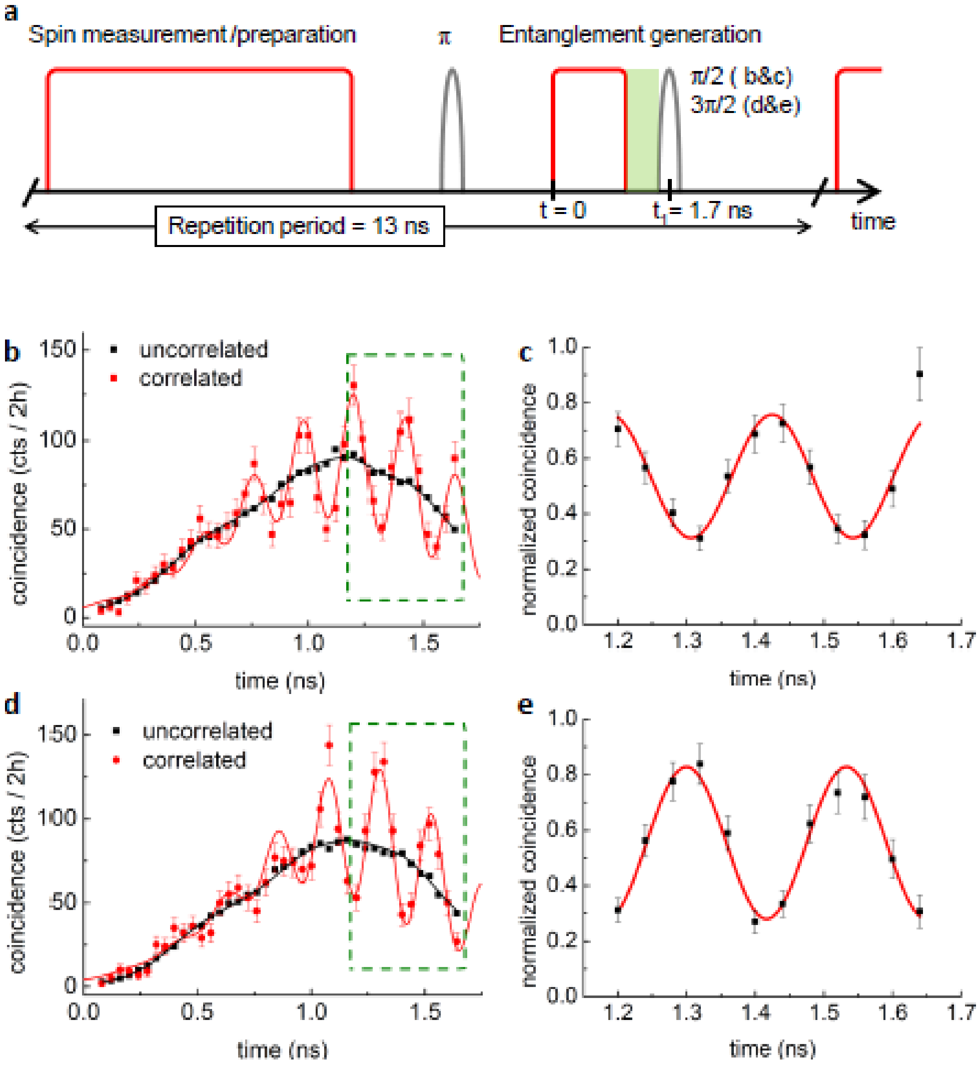
- The data in b & c shows the coincidence measurement when π/2-pulse is applied.

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

⇒ Coherent oscillations in conditional detection demonstrate quantum correlations between spin and photon

Measurement of quantum correlations

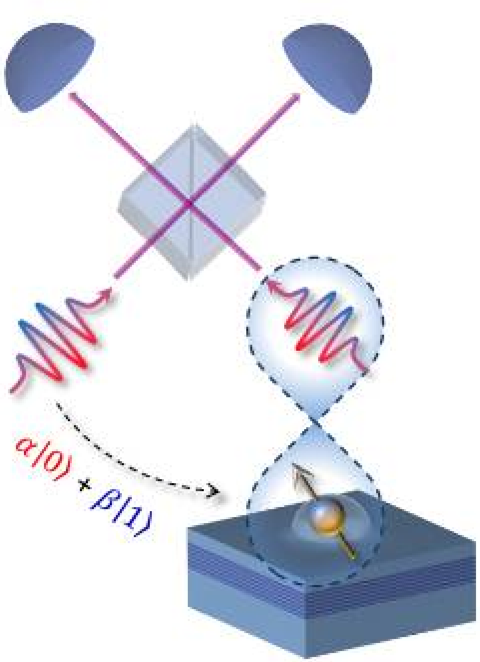


- An additional π/2 or 3π/2-pulse (dashed curve) is applied to measure the spin in |↑> ± |↓>.
- The data in b & c shows the coincidence measurement when π/2-pulse is applied.
- The data in d & e shows the coincidence measurement when 3 π/2-pulse is applied.
- F2=0.46 ± 0.04 in the rotated basis measurement; overall fidelity F = 0.67 ± 0.05

W. Gao et al. Nature (2012)

Teleportation from a photonic qubit to a solid-state spin qubit

- Using spin-photon entanglement as a resource, we can transfer the quantum state of a flying photon onto a confined spin (W. Gao, Nat. Comm. (2013)



Input: photonic qubit:

Output: spin qubit

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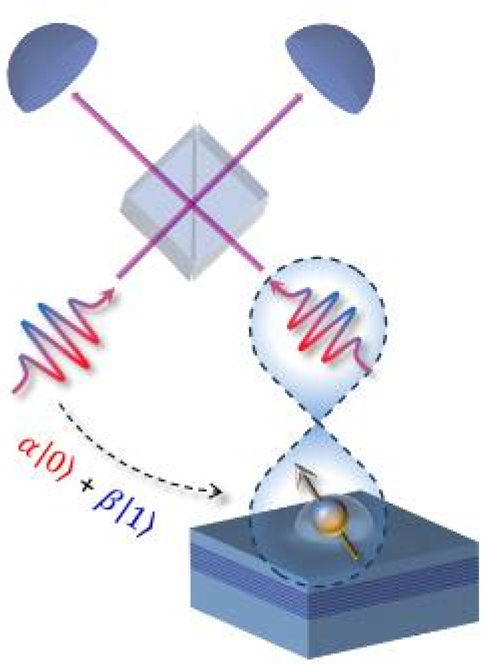
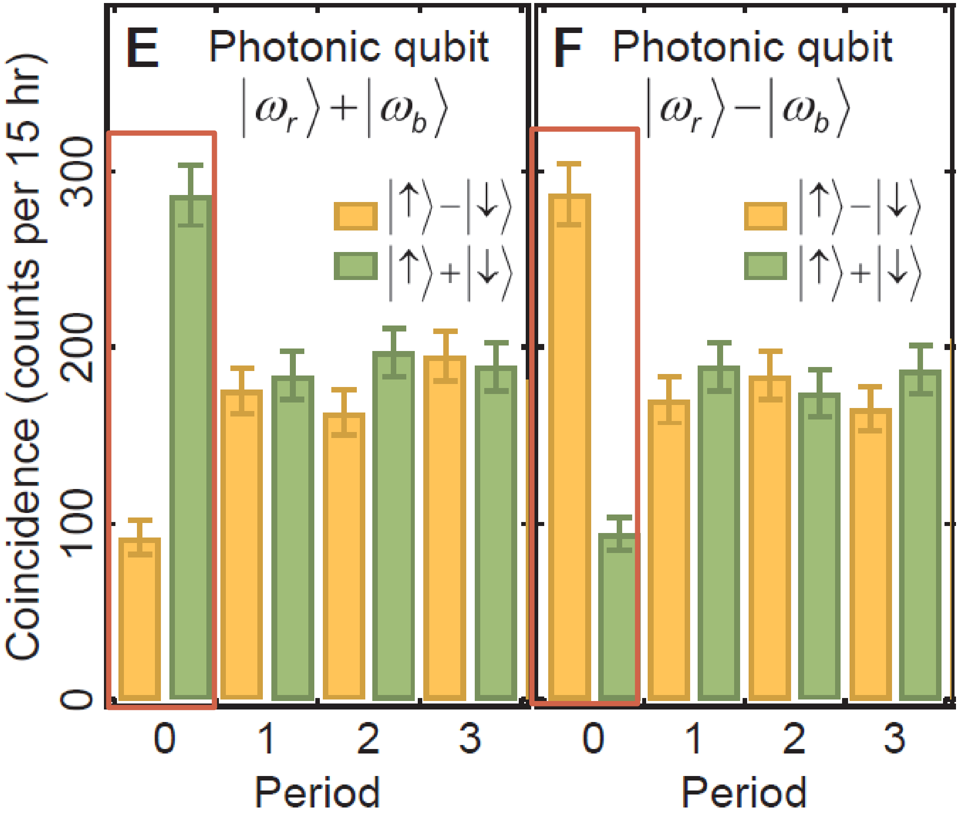


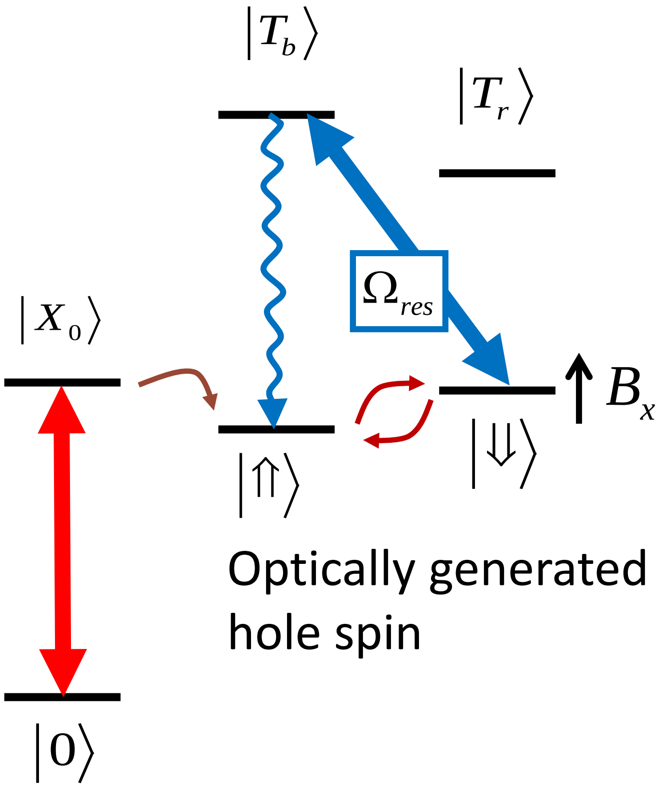
Output: spin qubit



<u>Next step</u>: probabilistic entanglement of two distant spins

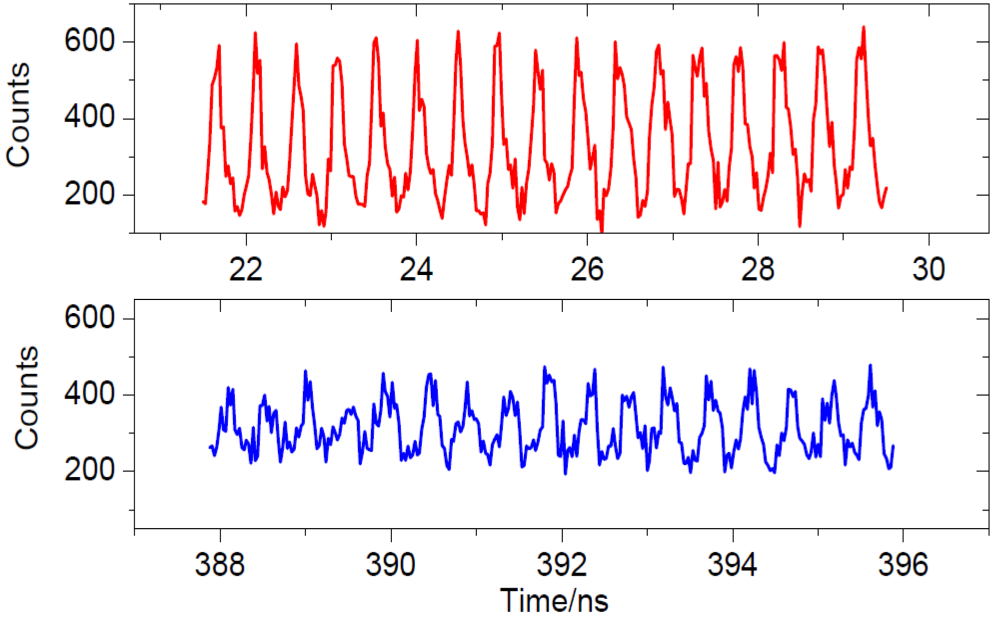
Entanglement of distant spins

- We need spins with long coherence time: hole spin



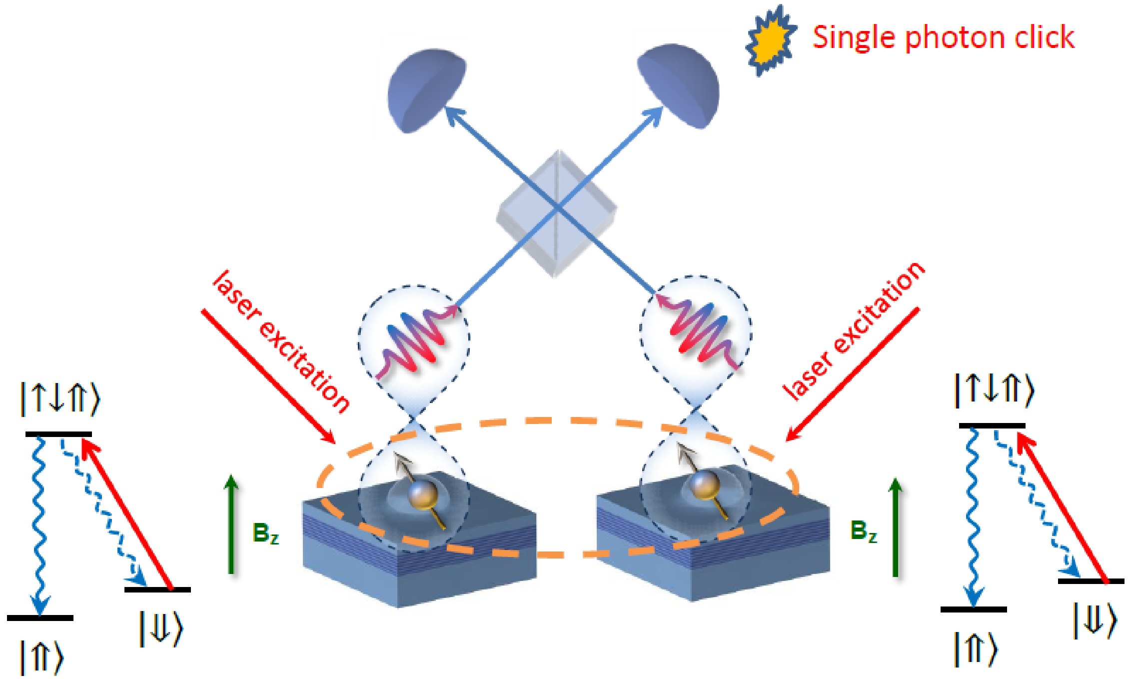
Optically generated hole spin

Ramsey measurements



Entanglement of distant spins

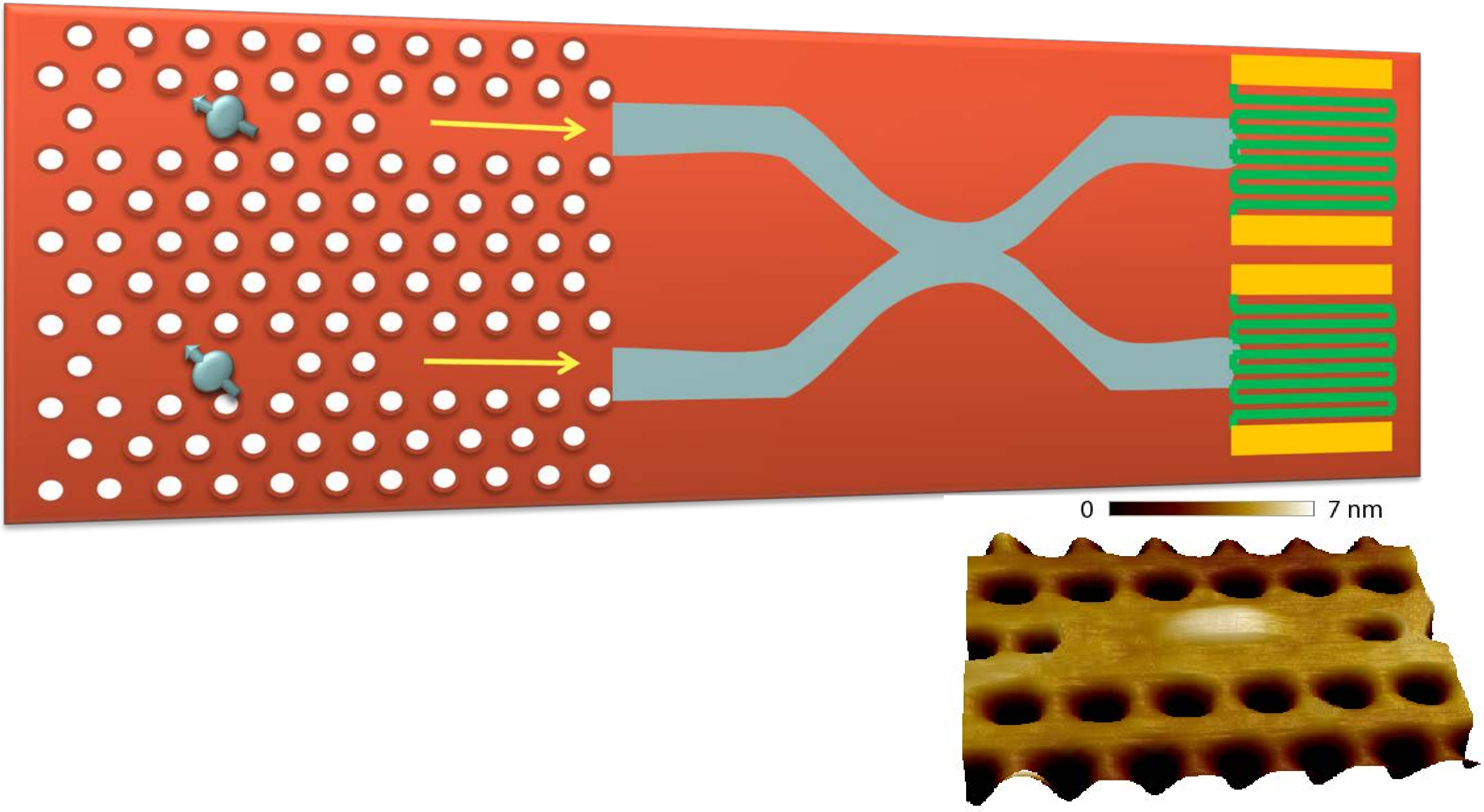
- Erasing which-path information in single-photon scattering from distant spins, leads to entanglement upon detection.
- Proposal by Cabrillo et al. Phys. Rev. A 59, 1025 (1999)



Future: Integrated spin photonics

Spin-photon entanglement

On-chip manipulation and detection



Outlook

- Spin-photon quantum interface with decoherence-free spin qubits (singlet-triplet states in QDs)
- Demonstration of nearly deterministic source of entangled photons using neutral QDs