Spin-photon quantum interface in quantum dots

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1. Spin-photon entanglement (see also Peter McMahon's talk)
2. Quantum teleportation of a photonic qubit to a spin qubit

Spin-photon quantum interface

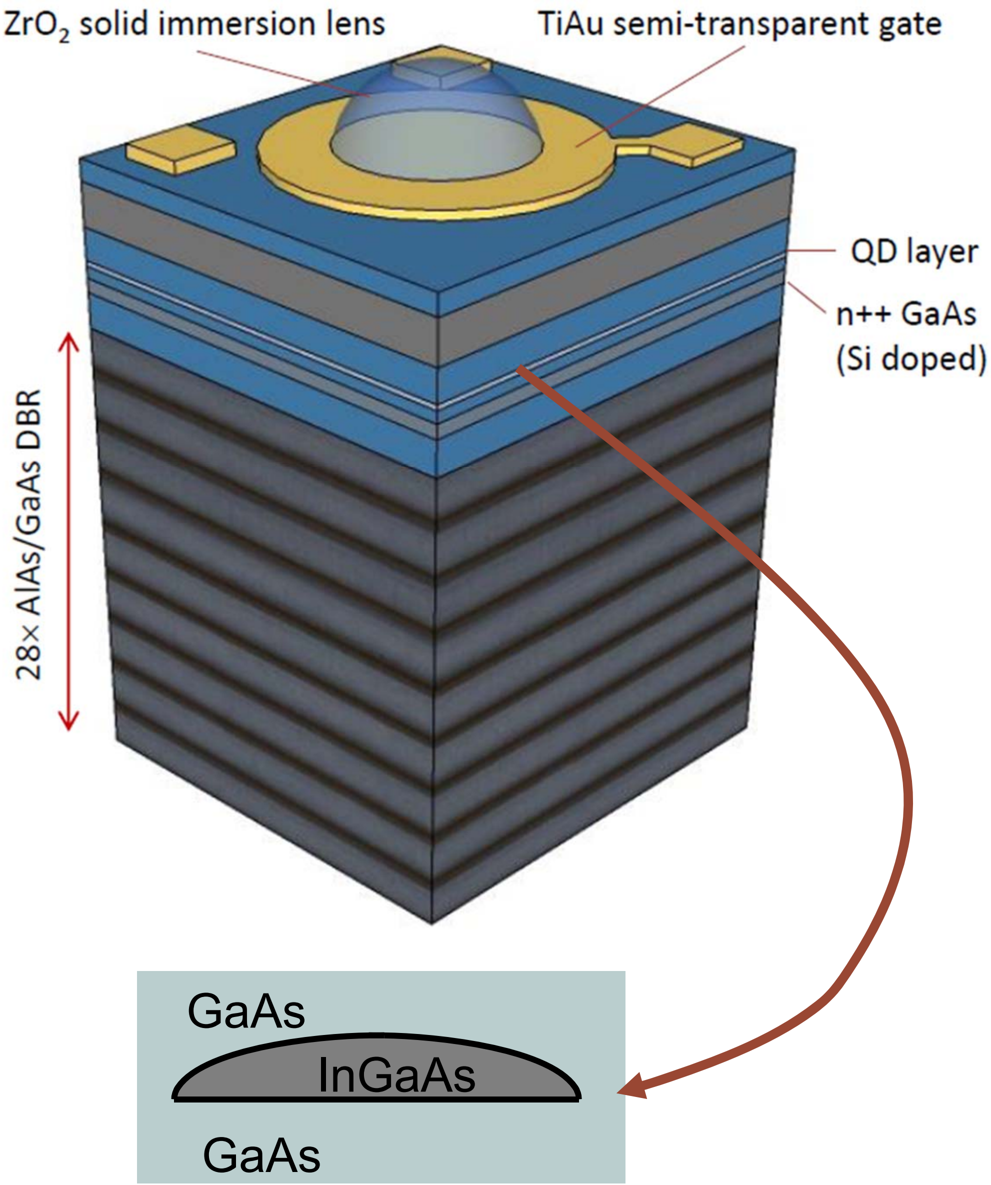
- GaAs based semiconductors exhibit highly efficient spin-dependent optical transitions

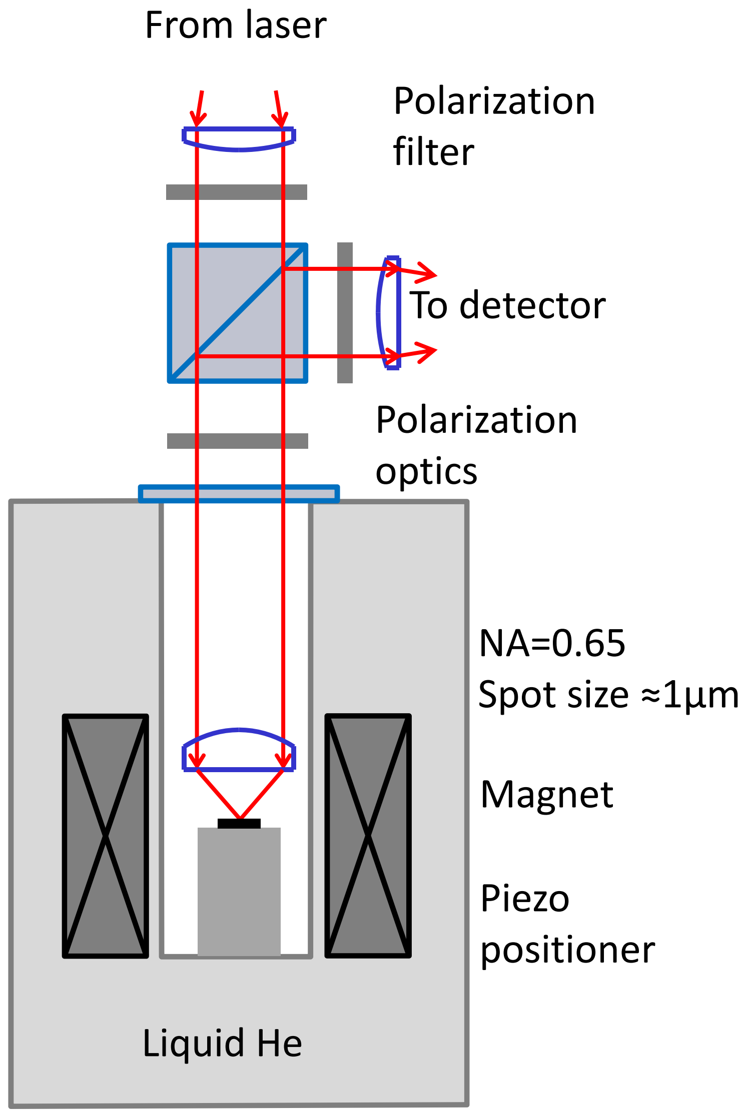
$\Rightarrow$ optical manipulation of spin qubits

- Quantum dots in photonic nanostructures allow for efficient extraction of photons

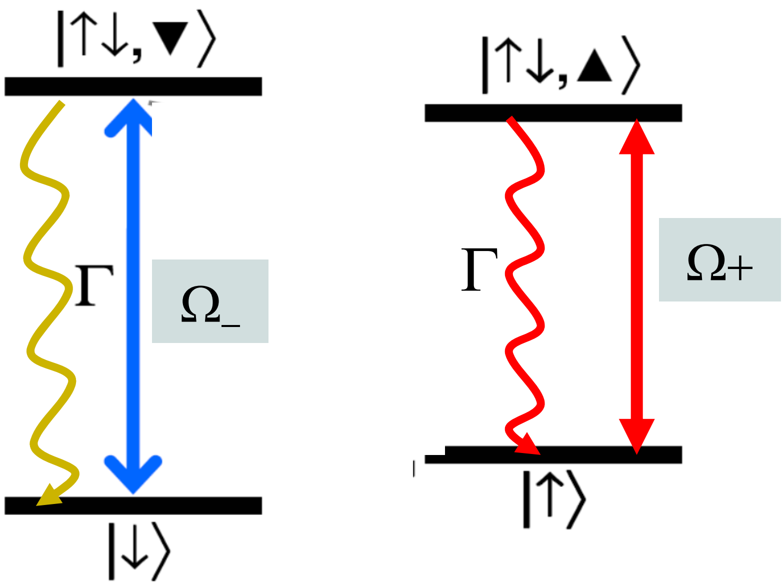
$\Rightarrow$ high efficiency single-photon sources

Resonant quantum dot Spectroscopy





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



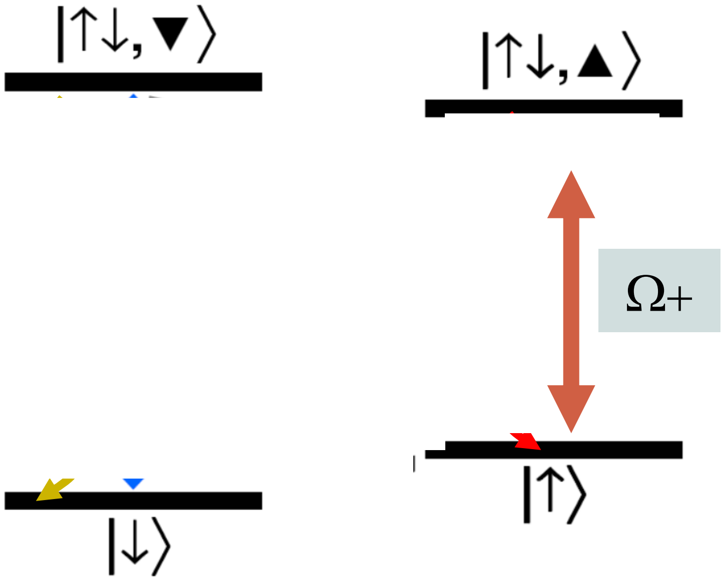
Γ: spontaneous emission rate

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



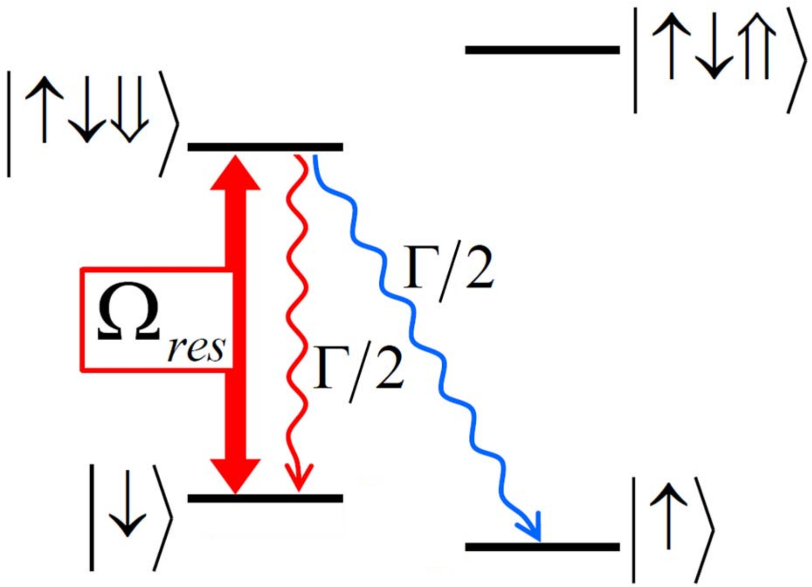
- QD with a spin-up (down) electron only absorbs and emits σ+ (σ-) photons – a recycling transition similar to that used in trapped ions.

  ⇨ Spin measurement

- An off-resonant σ+ laser causes ac-Stark shift only for the |↑> state, acting as an effective magnetic field along the z-direction.

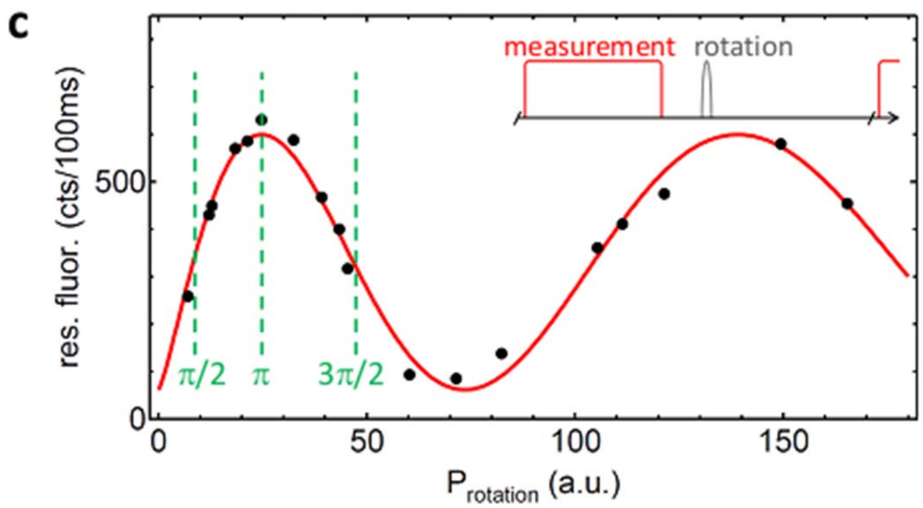
Different selection rules in Voigt geometry ($B_{ext} = B_x$)

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.



Spin rotation using off-resonant circularly polarized lasers

- External field along x ($B_{ext} = B_x$): quantization axis orthogonal to the laser-induced effective field



Awschalom, Yamamoto

Selection rules in Voigt geometry
($B_{ext} = B_x$)

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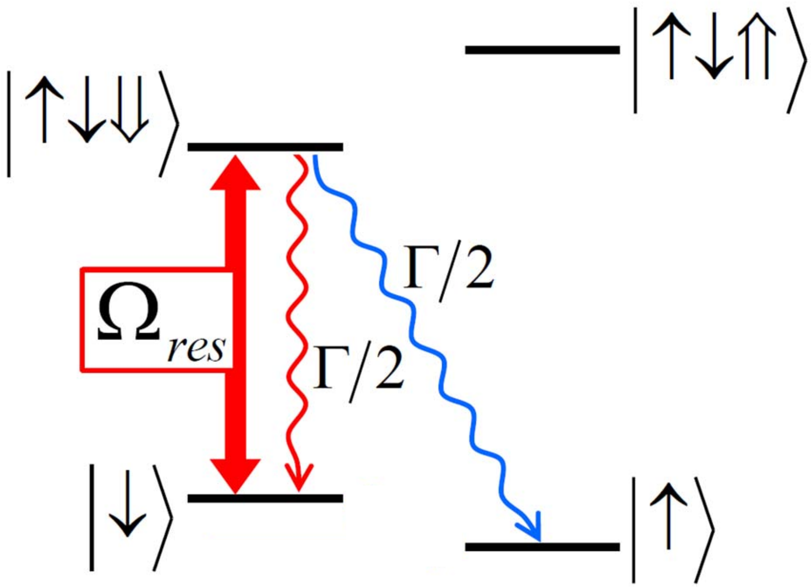

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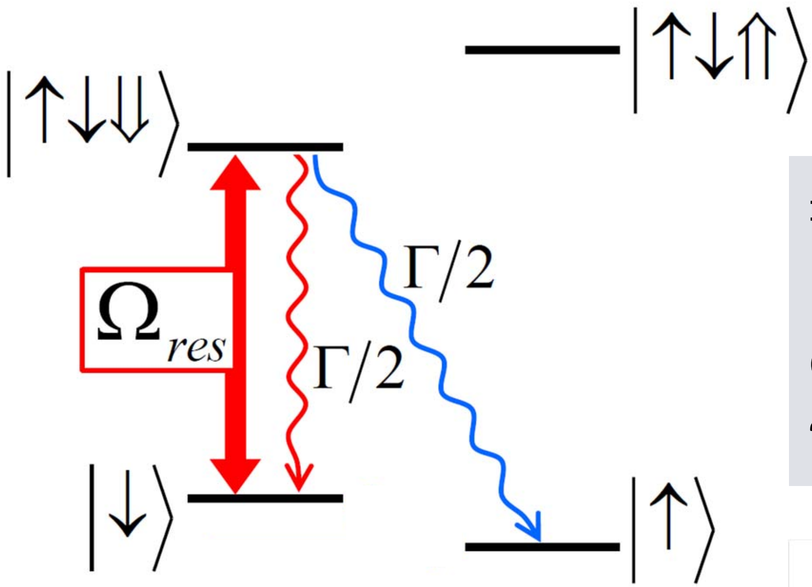
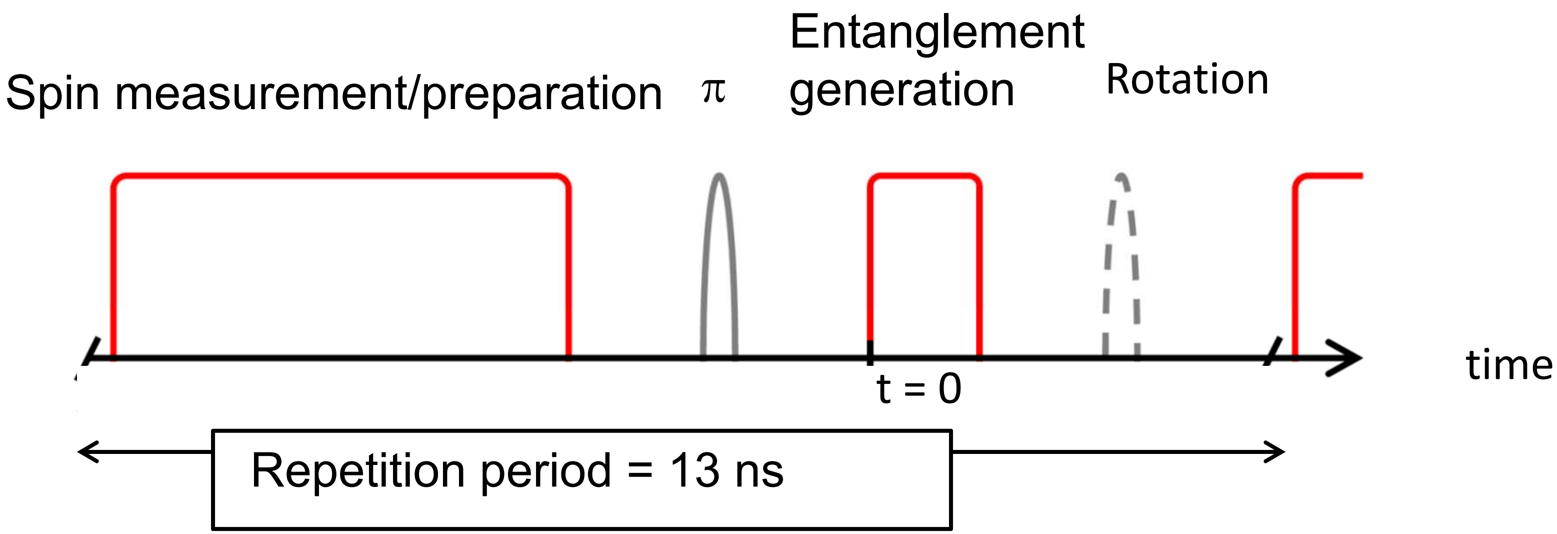


⇒ Spin-photon entanglement: potentially near-deterministic entanglement generation at ~1 GHz rate

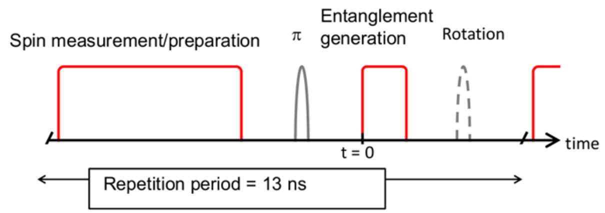
$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\downarrow\rangle|\omega_{red};H\rangle + i|\uparrow\rangle|\omega_{blue};V\rangle)$$

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

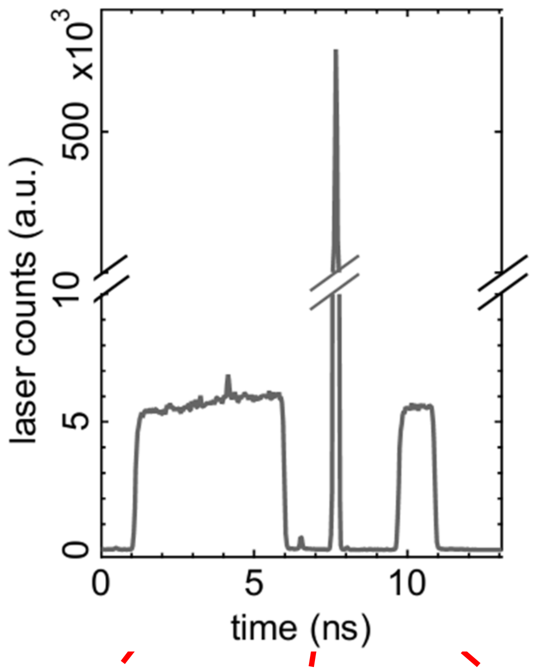
Procedure for spin-photon entanglement generation



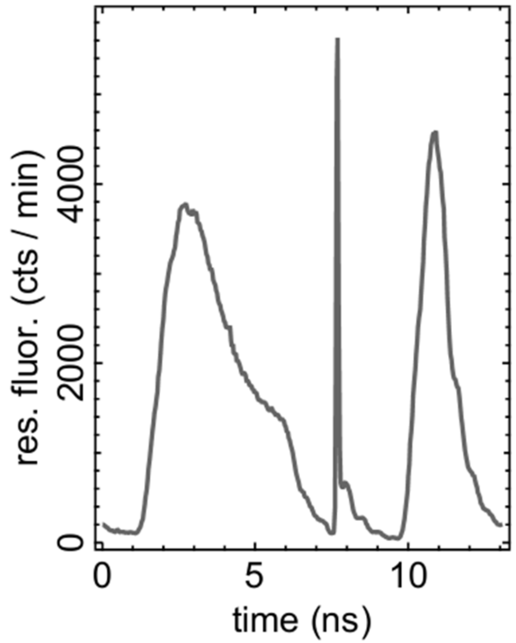
Time resolved resonance fluorescence (RF)

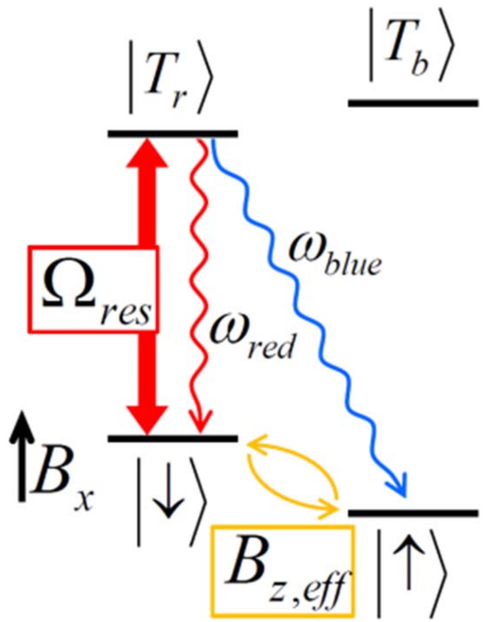


Partially suppressed
laser reflection counts



Time-resolved
RF measurements



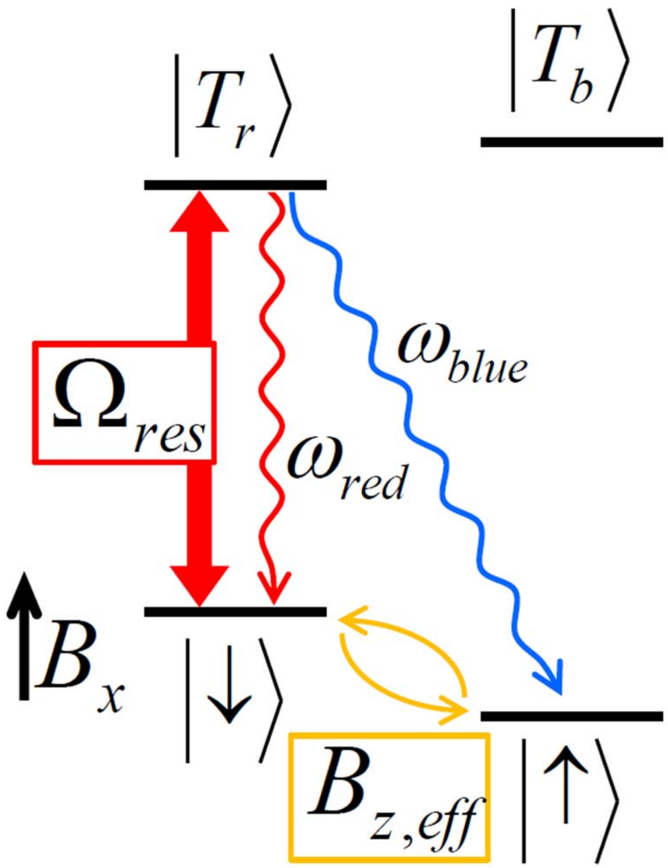


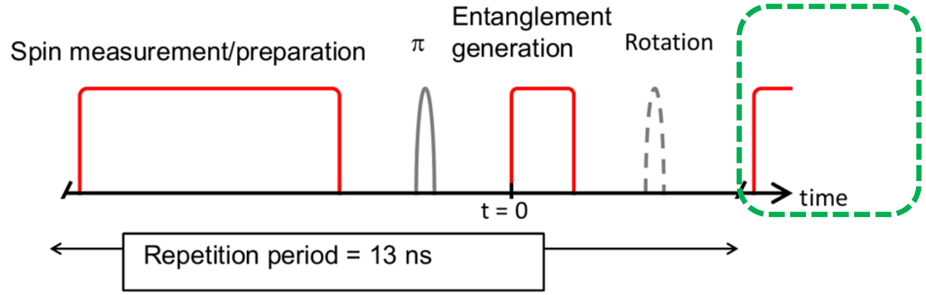
5 ns
spin pumping

4 ps
Rotation pulse

1.2 ns
entanglement pulse

Spin measurement and pumping



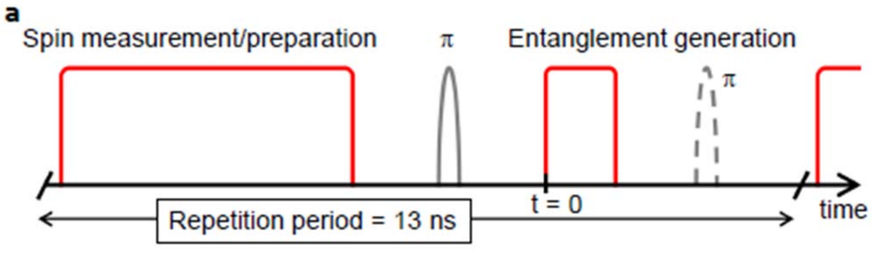


$|\downarrow\rangle$ ➔ ~2 photons/pulse.

$|\uparrow\rangle$ ➔ Nothing.

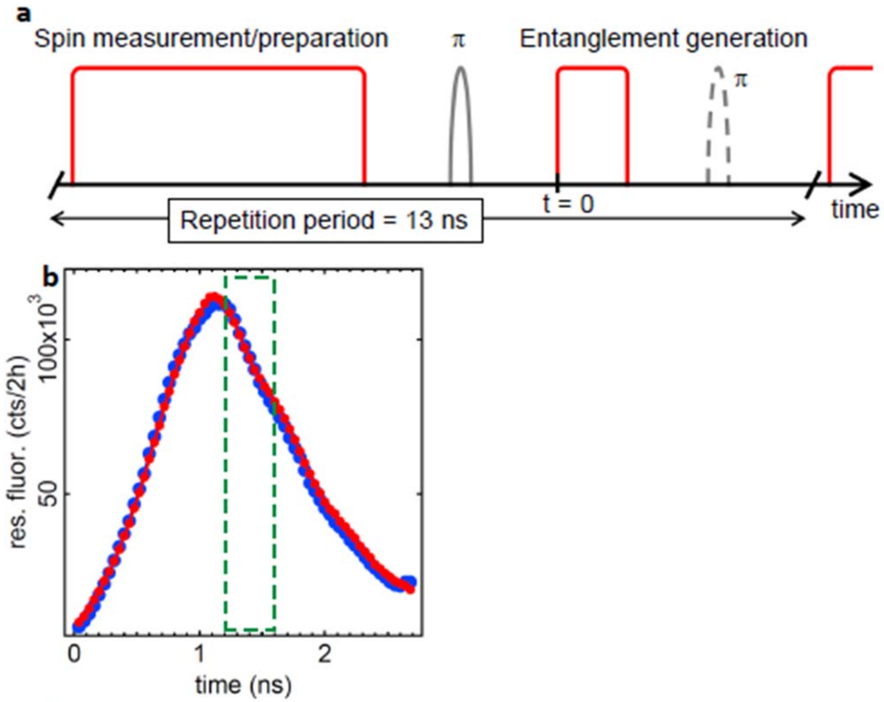
- The detection of a photon shows the spin is in the state $|\downarrow\rangle$
- At the end of the pulse, the spin is prepared in $|\uparrow\rangle$

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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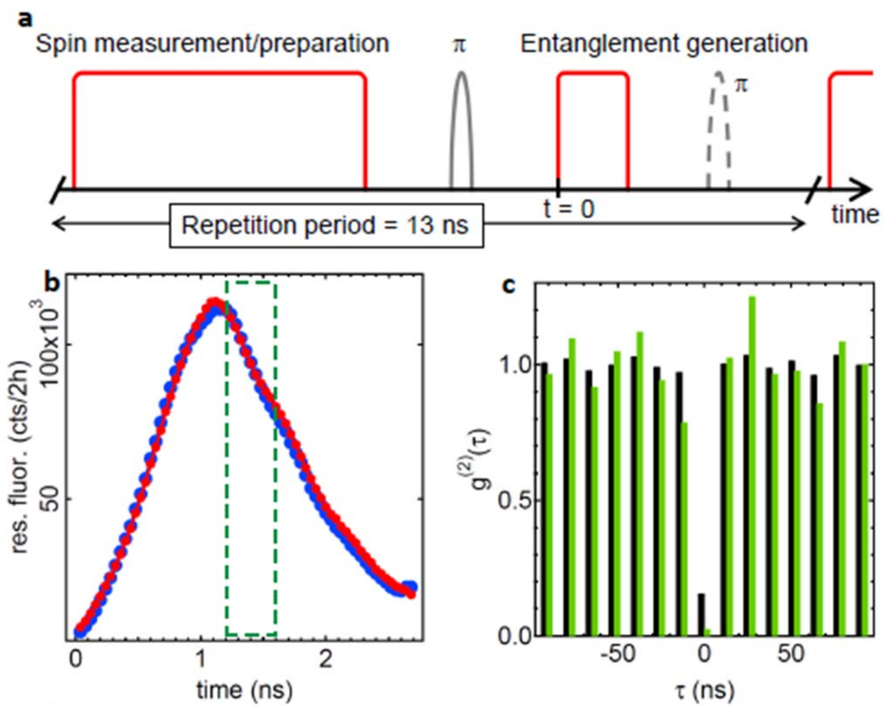

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The g(2) measurement shows that for the [1.2ns, 1.64ns] time range, probability of two-photon emission is negligible.

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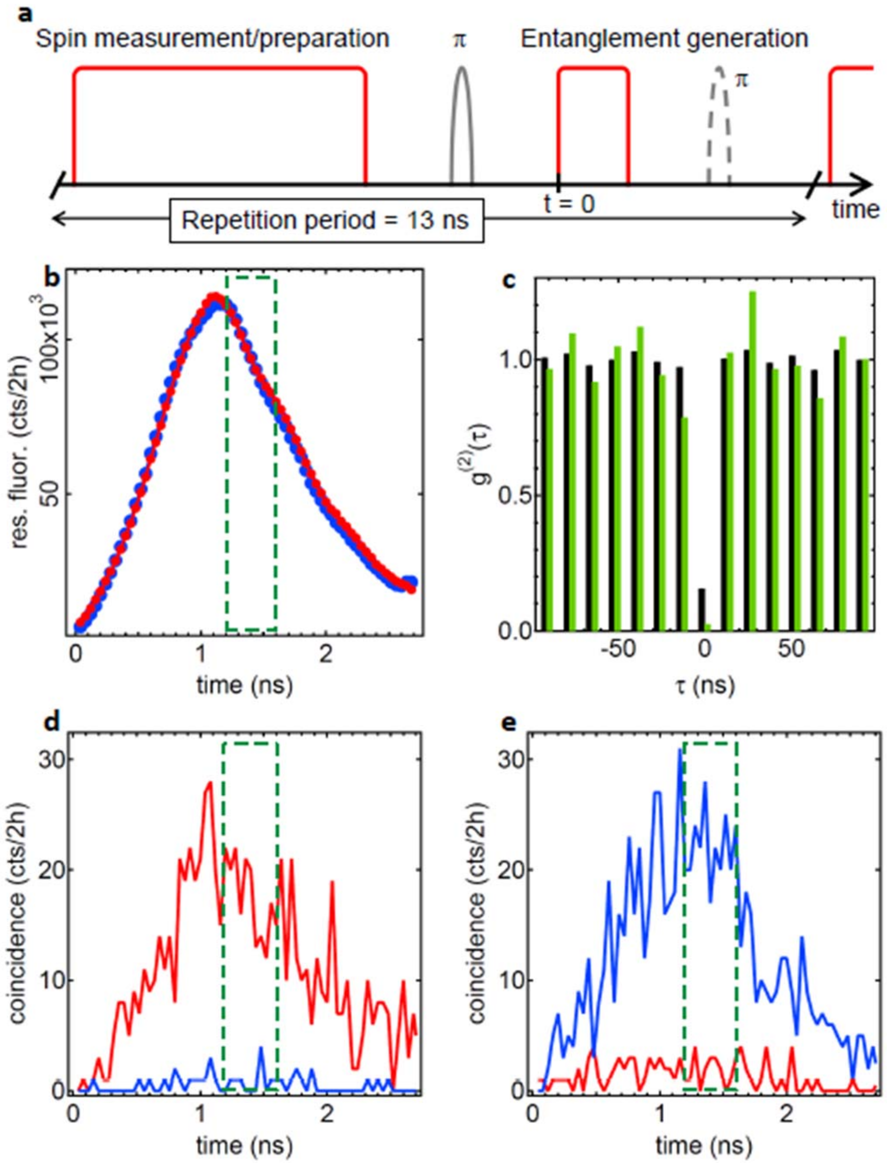

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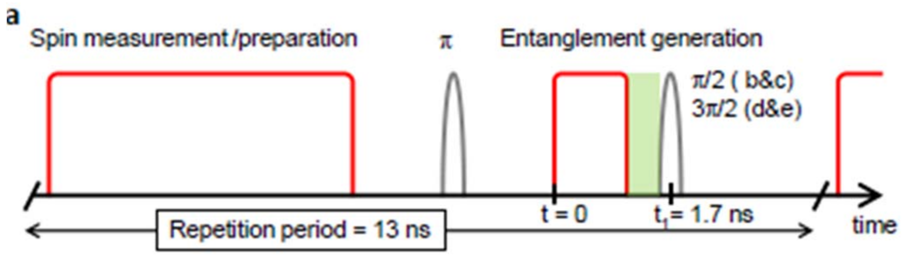
A spin down (up) measurement event ensures that the detected photon is red (blue).

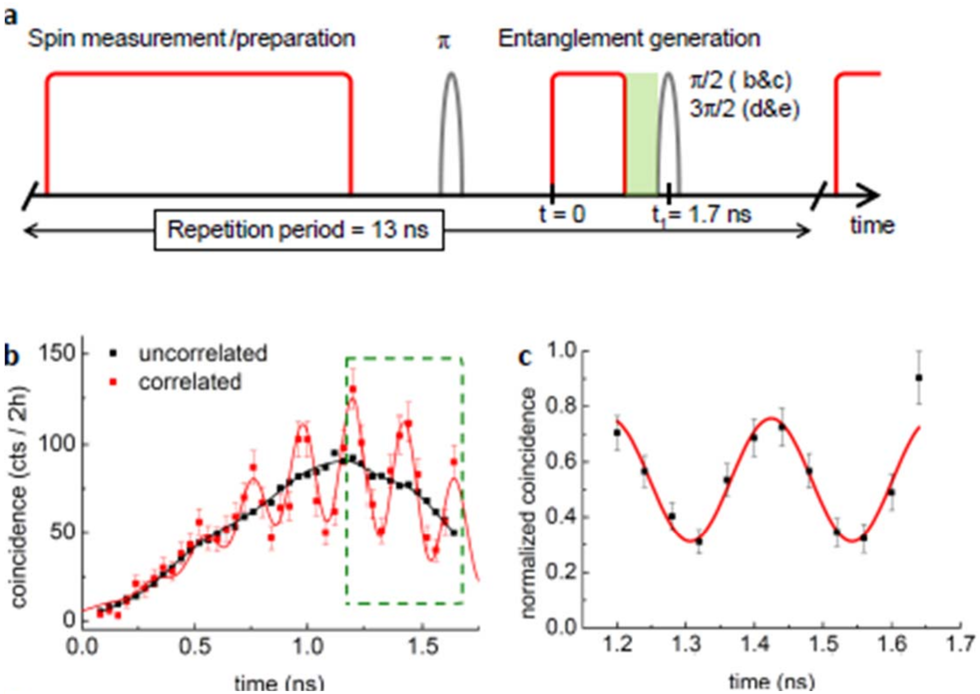
F1=0.87 ± 0.05 in the computational basis measure.ment

Measurement of quantum correlations



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

Measurement of quantum correlations

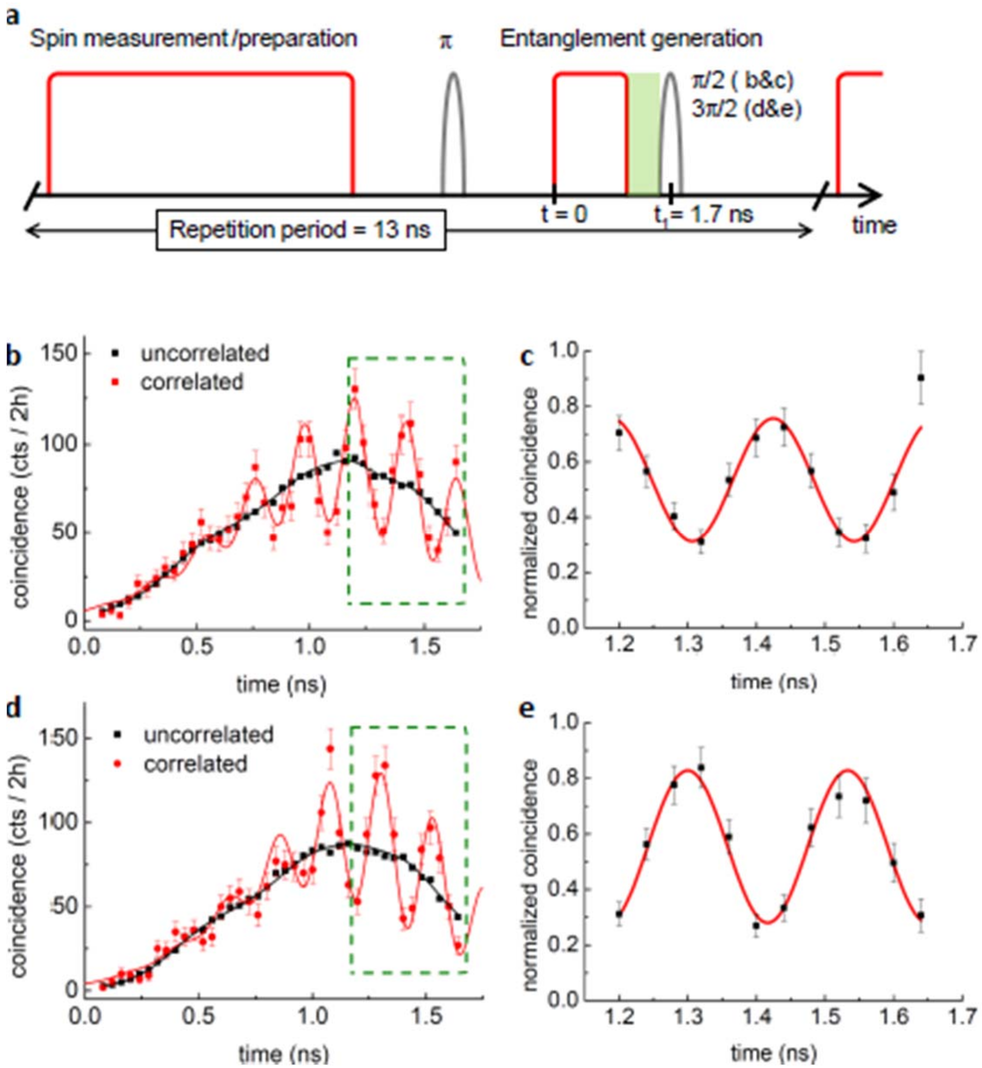


- An additional π/2 or 3π/2-pulse (dashed curve) is applied to measure the spin in |↑> ± |↓>.
- The data in b & c shows the coincidence measurement when π/2-pulse is applied.

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

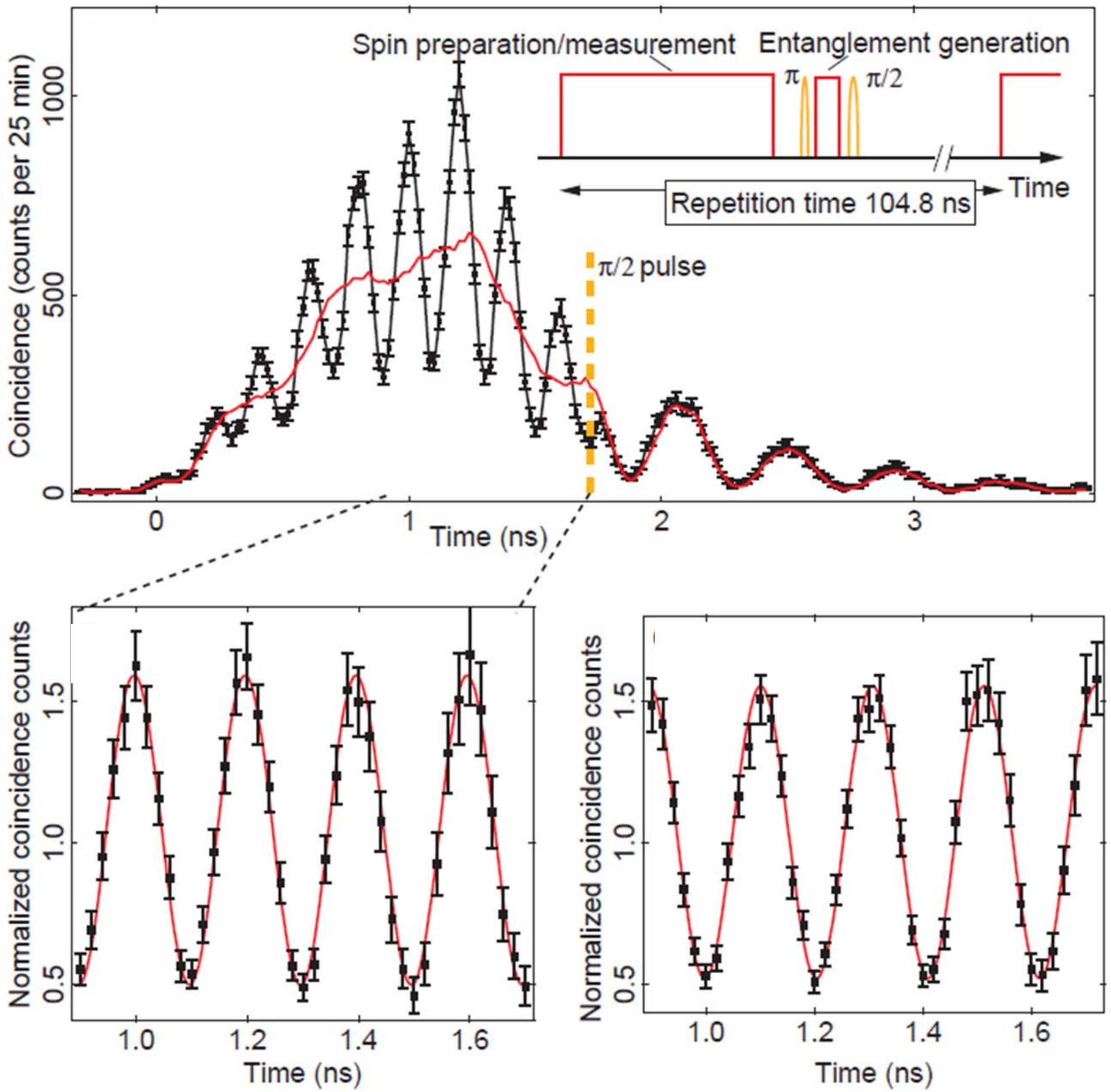
⇒ Photon generation events at different times correspond to a measurement of the photonic wave-function in different basis.

Measurement of quantum correlations



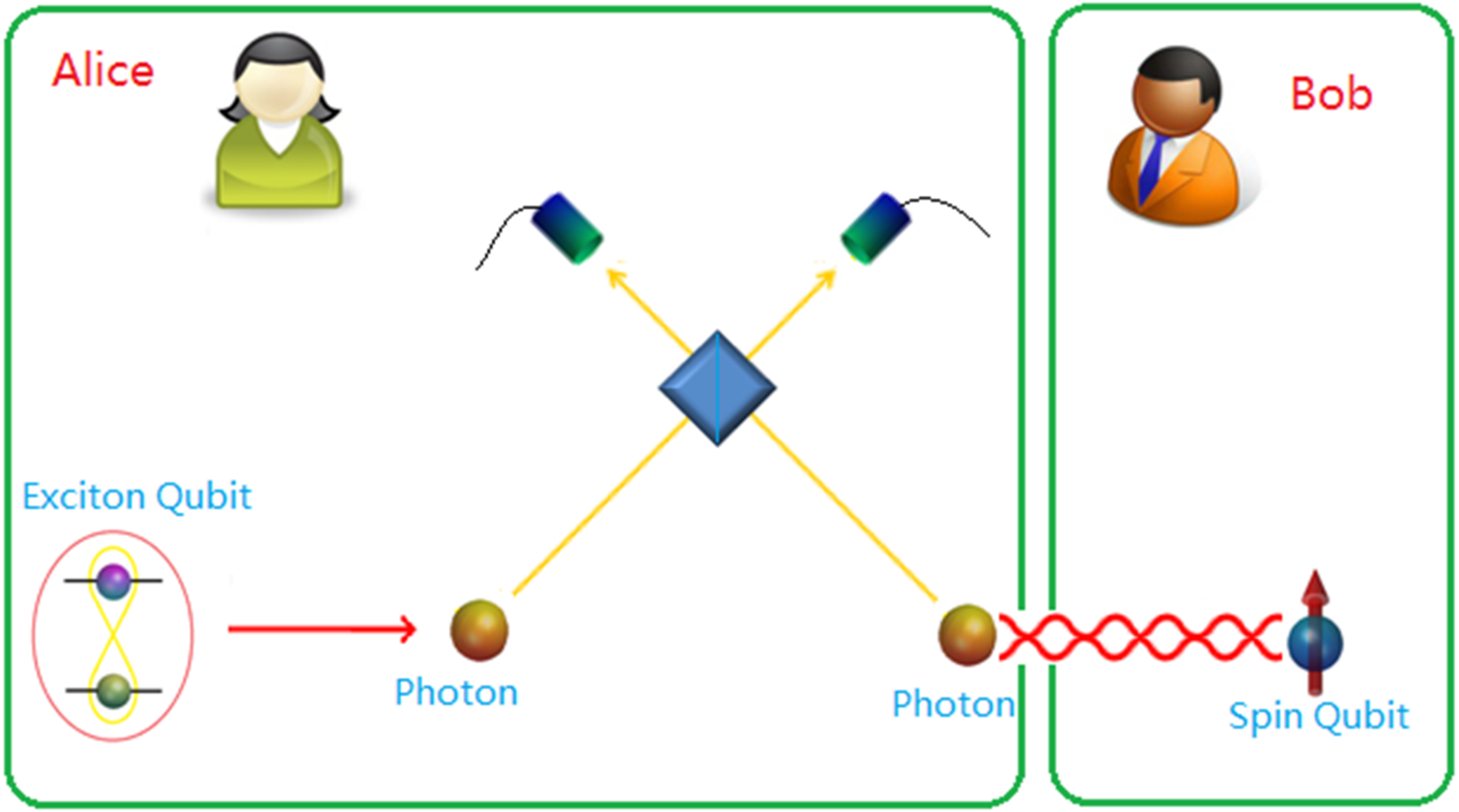
- An additional π/2 or 3π/2-pulse (dashed curve) is applied to measure the spin in |↑> ± |↓>.
- The data in b & c shows the coincidence measurement when π/2-pulse is applied.
- The data in d & e shows the coincidence measurement when 3 π/2-pulse is applied.
- F2=0.46 ± 0.04 in the rotated basis measurement;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

Improved spin-photon entanglement



- Fidelity limited primarily by the detector jitter
- The oscillation period before (after) the π/2 pulse is given by electron (hole) Zeeman energy.

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

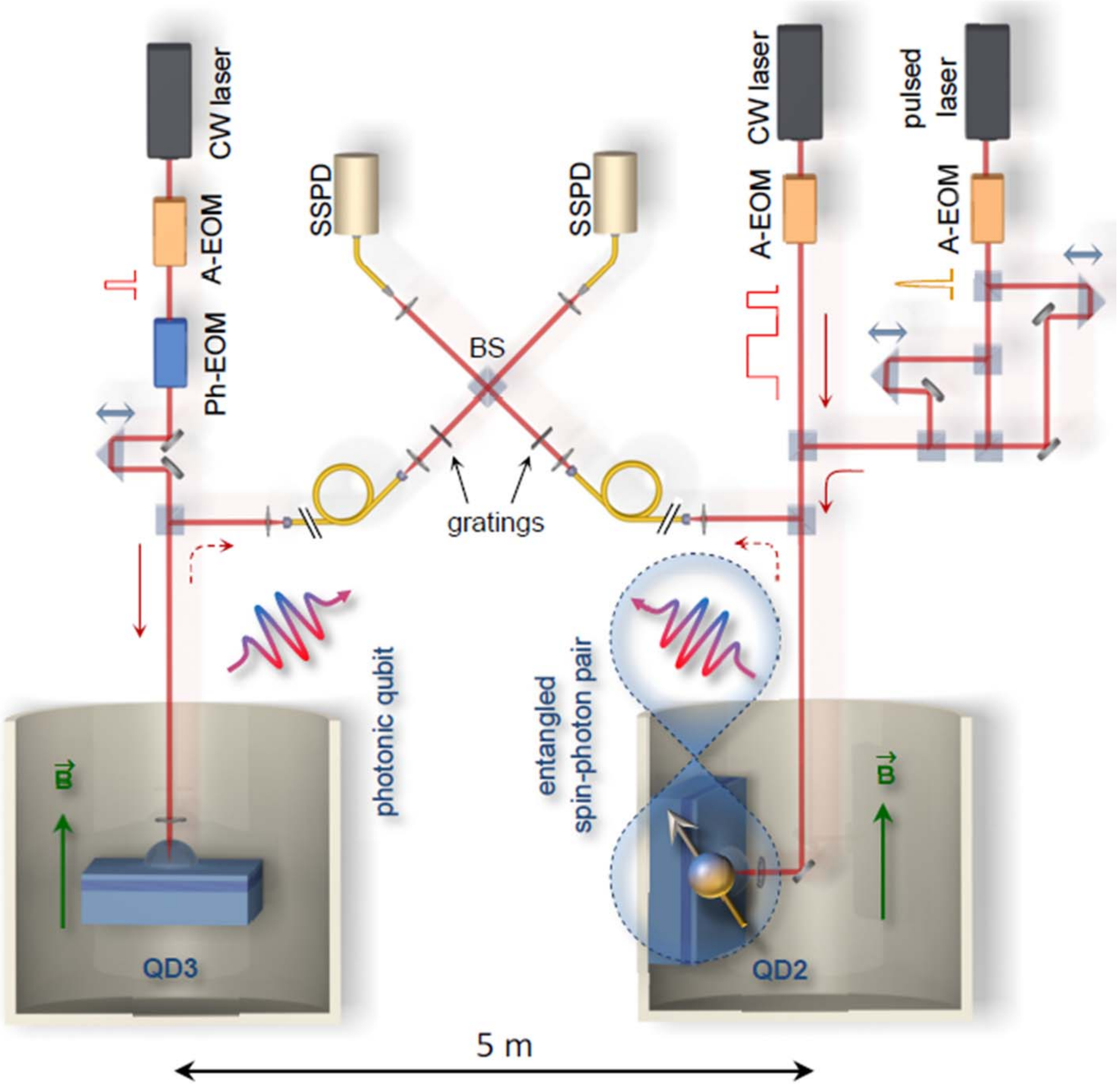


$$|\psi_p >= \alpha|\omega_b >_A + \beta|\omega_r >_A$$

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

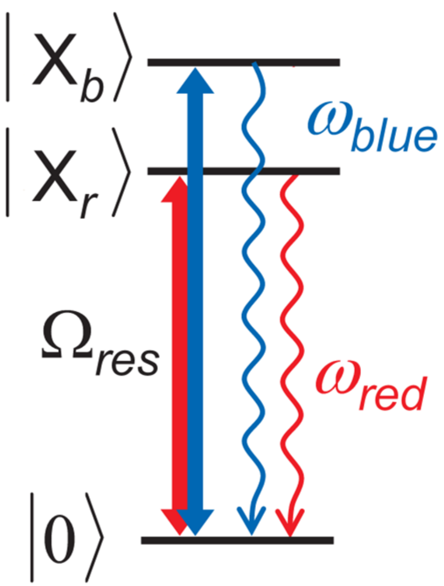
Output: $|\psi_e >= \alpha|\downarrow> + \beta|\uparrow>$

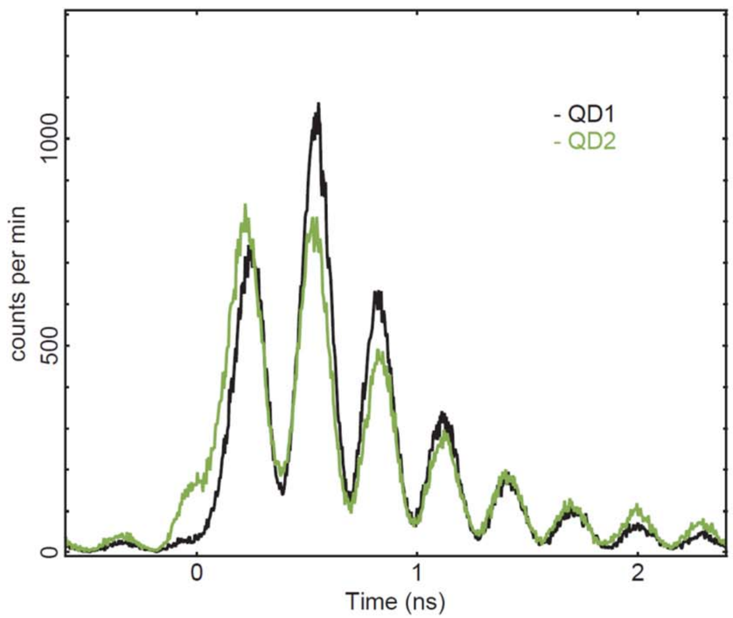
Experimental teleportation scheme

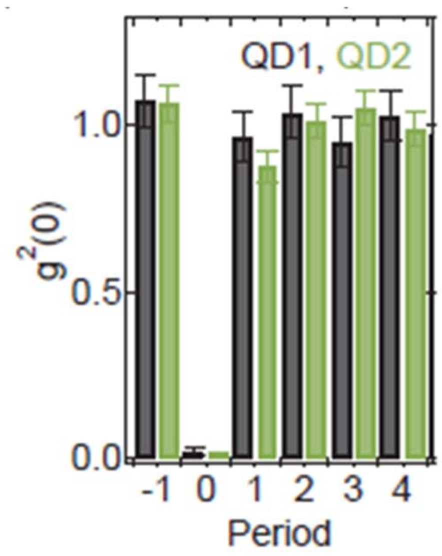


Generation of a single-photon color-qubit from a QD exciton

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

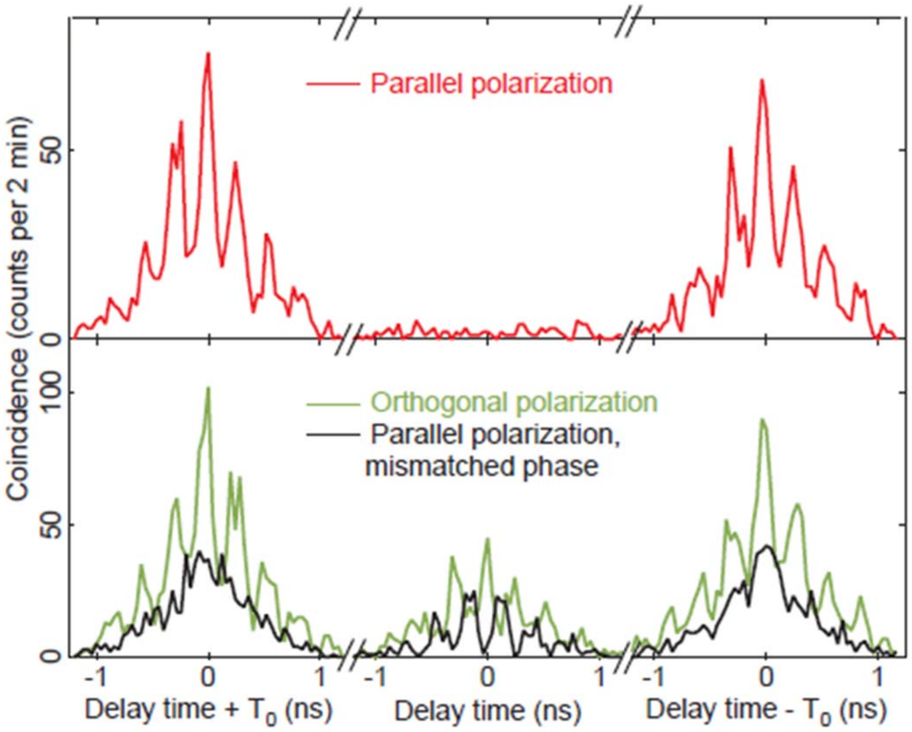


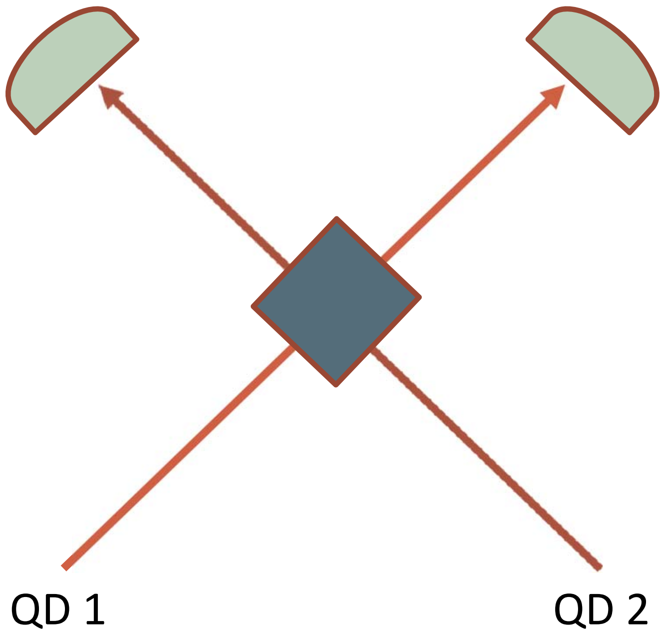




By controlling the pulse-shape, detuning and polarization of the resonant laser, we could generate a single-color photon or a two-color photonic qubit

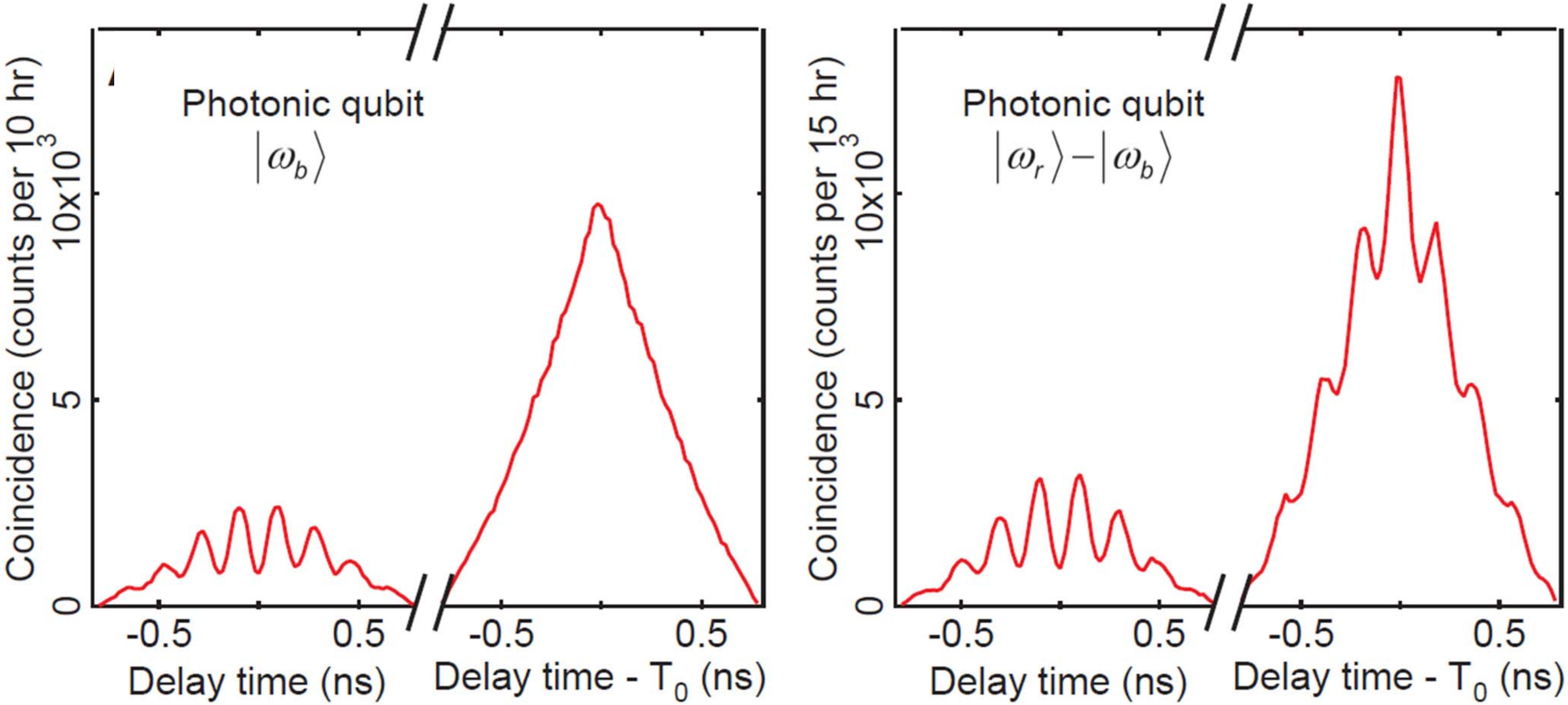
Interference of photonic qubits (superposition of blue & red photons) coming from two neutral quantum dots





- For identical incident photons no coincidence detection (i.e. no counts around t = 0)
- 80% visibility in intereference of two photonic (color) qubits

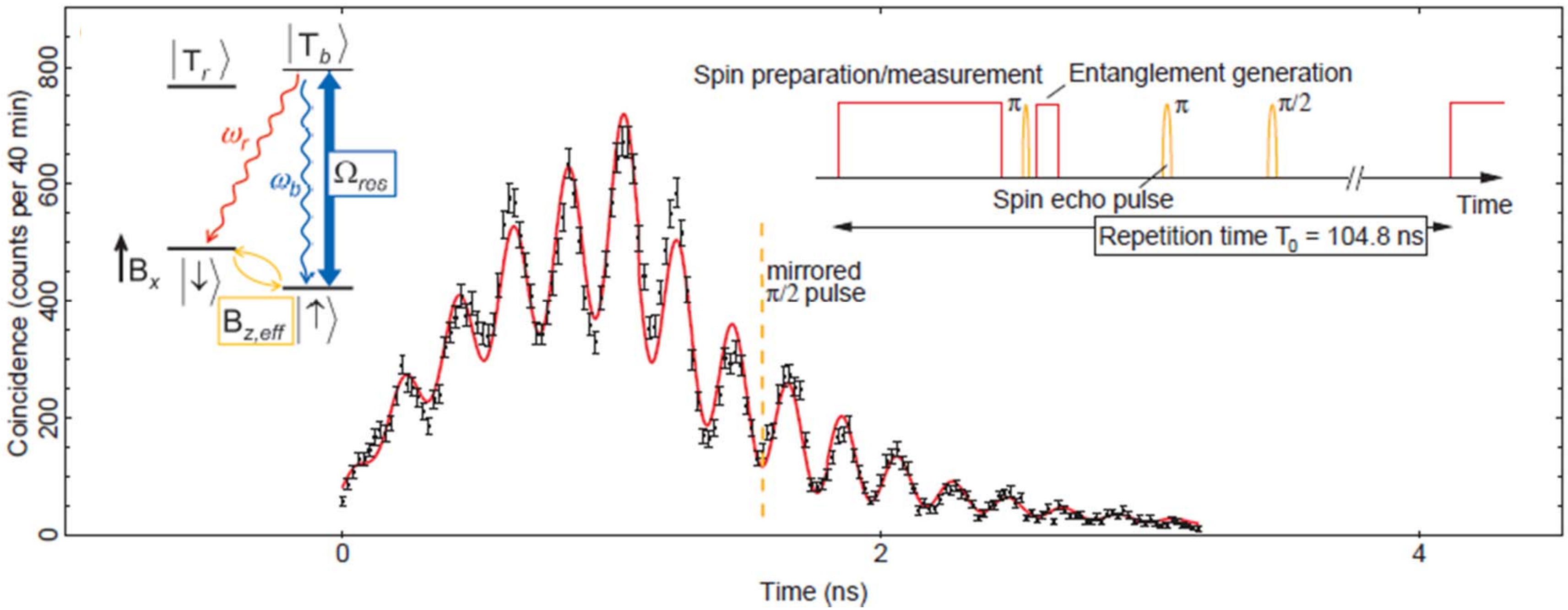
Interference of one photon coming from a neutral QD with a photon from a single-electron-charged QD



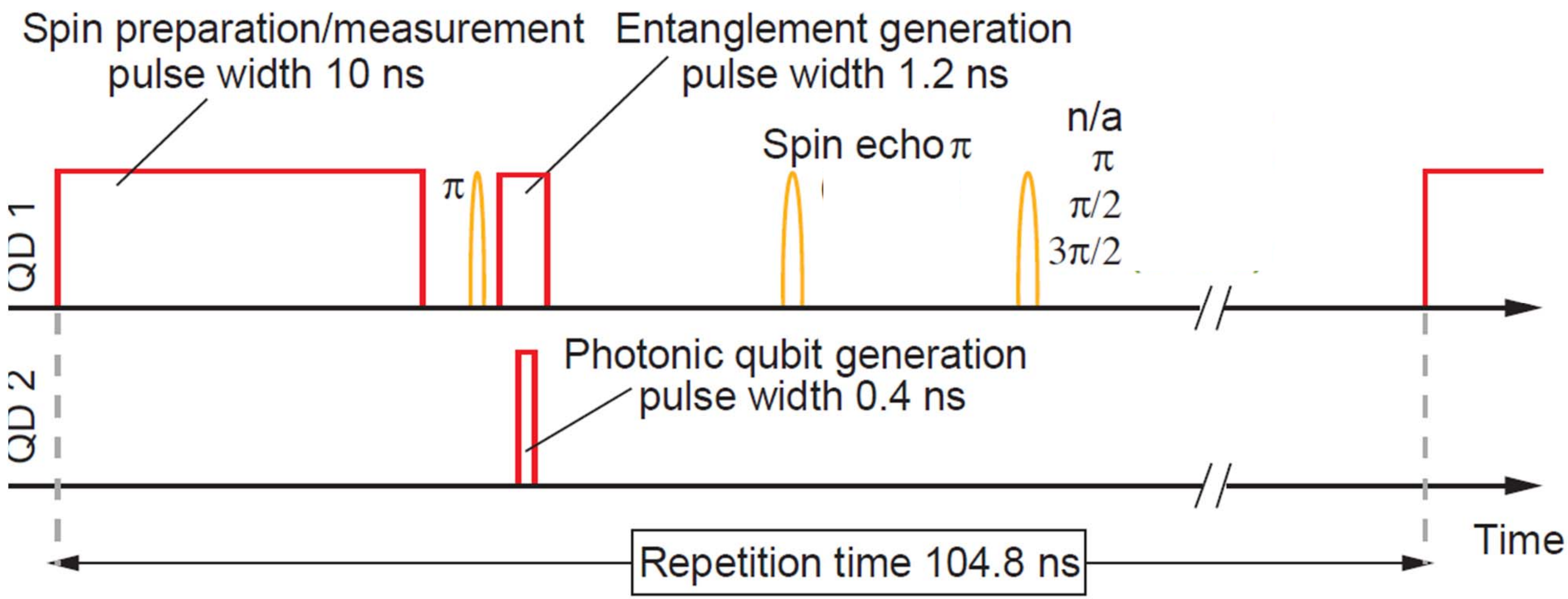
- Coincidences from the same-period are ideally ¼ of the other peaks, when the spin state is discarded.
- It is these coincidences that herald teleportation.

Spin-photon entanglement with spin-echo

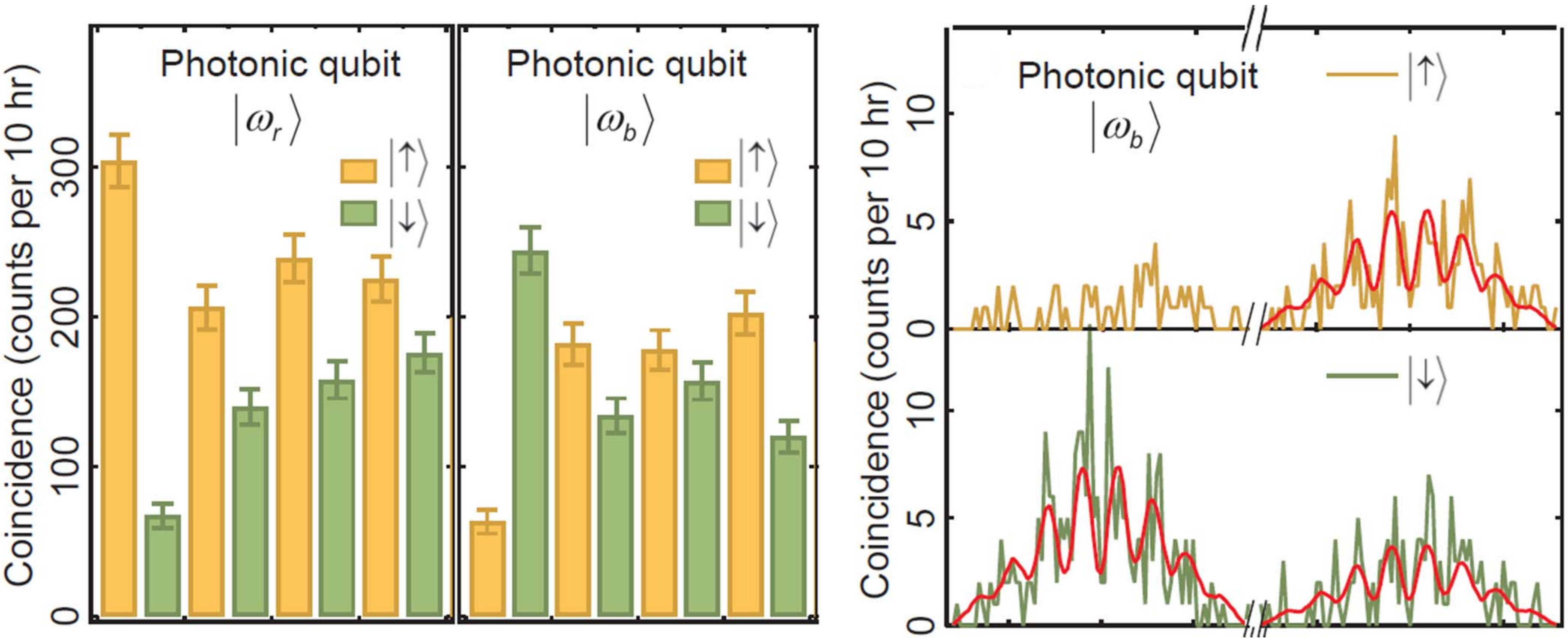
- To ensure that spin is detected after a coincidence event heralds successful teleportation, we need to prolong the spin-coherence
- Quantum correlations between the QD spin and the emitted single-photon after an echo time of 13 ns



Quantum teleportation pulse sequence

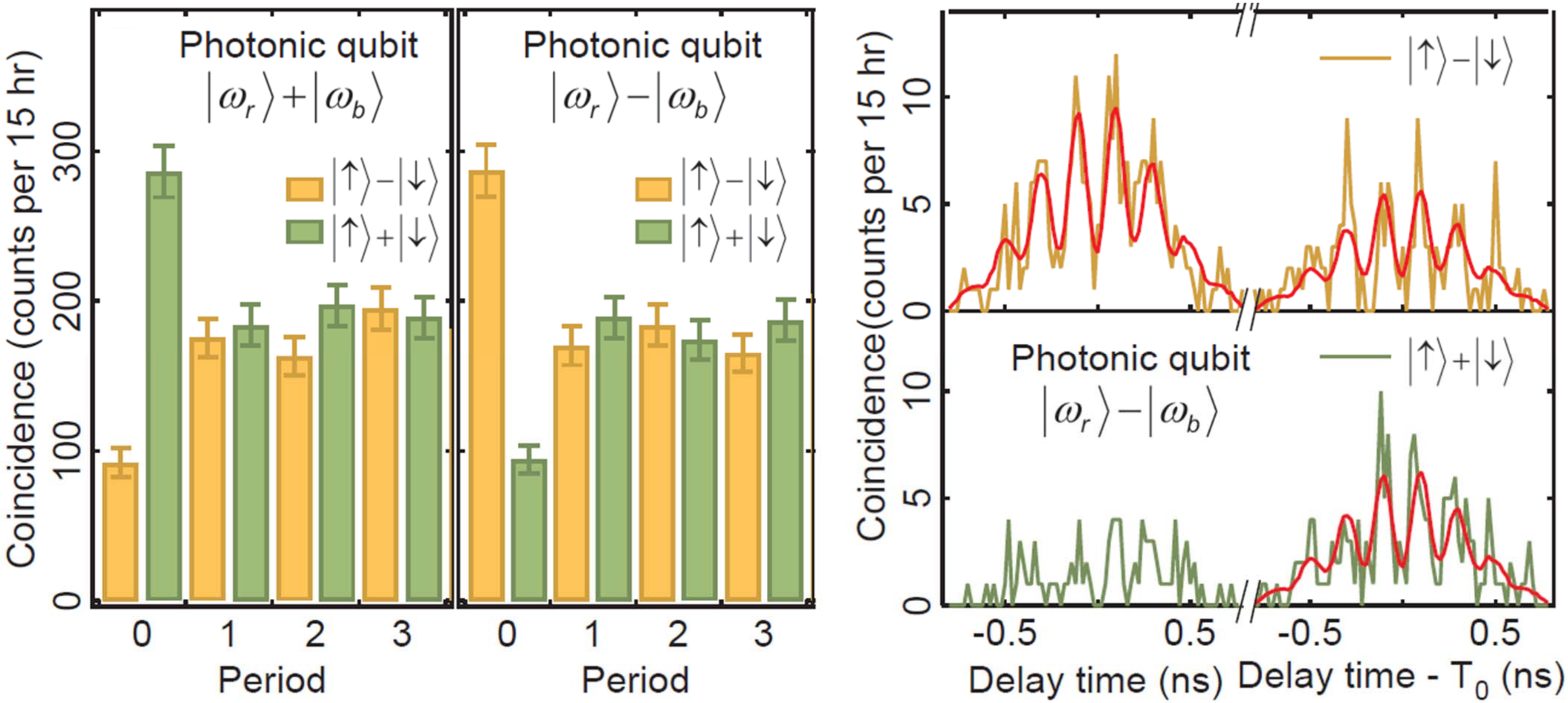


«Classical teleportation» (3-fold coincidences)



- For a photonic qubit in $|\omega_b\rangle$, detection of a coincidence ensures that the photon from the entangled pair was in $|\omega_r\rangle$ - which in turn fixes the spin to be in $|\uparrow\rangle$.

Quantum correlations in teleportation (3-fold coincidences)



Overall teleportation fidelity: 0.78 ± 0.03

Outlook

- Spin-Spin entanglement
- Understanding and suppressing the role of hyperfine interactions.

Thanks to

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