A solid-state quantum interface between stationary and flying qubits

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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

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

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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.

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

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

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

The diagram illustrates the setup, showing the start (voltage) pulse, stop pulse, single photon detectors, and the Time-to-amplitude converter.
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• Photon correlations from a weak pulsed laser (\( \langle n \rangle \sim 1 \)); detection of a photon does not change the likelihood of detecting a second.
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  \]

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

- The single photon pulses have to have the same spatio-temporal profile, center frequency, 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 \( \sim 5 \text{ GHz} \)

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 and red photons) coming from two quantum dots

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

⇒ Measurement of a spin qubit: \( |\psi\rangle = \alpha |\uparrow\rangle + \beta |\downarrow\rangle \)
Single-shot measurement of electron spin

- Prepare the electron spin in $|\uparrow\rangle$ or $|\downarrow\rangle$
- Apply a 0.8 $\mu$s resonant laser pulse on the trion transition corresponding to $|\downarrow\rangle$
- Single-shot measurement fidelity $\sim 80\%$ in 0.8 $\mu$s
- Fidelity is limited by spin pumping into $|\uparrow\rangle$ - long duration of excitation leads to initialization of the qubit.

![Graph showing photon counts.](c)

- $<n> = 1.27$
- $<n> = 0.05$
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 \(|\downarrow\rangle\) state or a V polarized blue photon to \(|\uparrow\rangle\) state, with equal probability.
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\[\Rightarrow \text{Spin-photon entanglement: potentially near-deterministic entanglement generation at } \sim 1 \text{ GHz rate}\]

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

Similar results by Yamamoto, Steel groups; earlier work by Monroe, Lukin
Procedure for spin-photon entanglement generation

Spin measurement/preparation

π

Entanglement generation

Rotation

Repetition period = 13 ns
Measurement of classical correlations

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

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

$F_1=0.87 \pm 0.05$ in the computational basis measurement.
Measurement of quantum correlations

- An additional $\pi/2$ or $3\pi/2$-pulse (dashed curve) is applied to measure the spin in $|\uparrow\rangle \pm |\downarrow\rangle$. 
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- An additional $\pi/2$ or $3\pi/2$-pulse (dashed curve) is applied to measure the spin in $|\uparrow> \pm |\downarrow>$.   

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

$\Rightarrow$ Coherent oscillations in conditional detection demonstrate quantum correlations between spin and photon.
Measurement of quantum correlations

- An additional $\pi/2$ or $3\pi/2$-pulse (dashed curve) is applied to measure the spin in $|\uparrow> \pm |\downarrow>$.  

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

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

- $F_2=0.46 \pm 0.04$ in the rotated basis measurement; overall fidelity $F = 0.67 \pm 0.05$
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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Next step: probabilistic entanglement of two distant spins
Entanglement of distant spins

- We need spins with long coherence time: hole spin

![Diagram showing entanglement and Ramsey measurements with optical transitions and counts over time.](image)
Entanglement of distant spins

- Erasing which-path information in single-photon scattering from distant spins, leads to entanglement upon detection.
Future: Integrated spin photonics
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