Single and paired photons from many entangled atoms

Jonathan Simon
James K. Thompson
Vladan Vuletic

Haruka Tanji
Huanqian Loh

Massachusetts Institute of Technology
MIT-Harvard Center for Ultracold Atoms
Outline

• Why single (and paired) photons?
• Conditional single-photon generation: how it works.
• Experimental results:
  – Conversion of stored quantized spin gratings into single photons;
  – Narrowband identical photon generation (Hong-Ou-Mandel test);
  – Hong-Ou-Mandel effect with delayed photons: entanglement;
  – Interferometry with photon pairs;
  – Recovery efficiency and Fock state generation.
Why single photons?

- Proposed applications in quantum information processing and quantum communication:
  - Atoms have very long storage time for quantum states (quantum bits), but are difficult to transport.
  - Photons are ideal carriers of quantum information, but are difficult to store.
  - Coherent mapping between atomic and photonic qubits is an important building block for quantum information processing.
Why single photons?

• Proposed applications in quantum information processing and quantum communication:
  • Single-photon sources would enable quantum repeaters to extend entanglement and quantum communication over distances longer than the absorption length of optical fibers.

Why single photons?

- **States of definite photon number** $n$ (Fock states) are fundamental states in quantum mechanical description of light.
- Fock states are **highly non-classical**. Applications in sub-shot noise interferometry and precision measurements.
- Single-photon state $n=1$ is the simplest Fock state, can serve as building block.
Classical communication

classical signal

communication channel
(optical fiber)

eavesdropper
Secure quantum communication

Single-photon pulses
communication channel
Receiver can determine that signal has been corrupted

eavesdropper

Single-photon states necessary
Poissonian photon source: coherent state

Laser beam \( \langle p \rangle \gg 1 \) \rightarrow \text{attenuator} \rightarrow \langle p \rangle \ll 1 \rightarrow \text{weak laser beam}

Poissonian source:
Attenuated laser pulse with low average photon number \( \langle p \rangle \ll 1 \):
\( p_0 \approx 1 \quad p_1 \approx \langle p \rangle \quad p_2 \approx \langle p \rangle^2/2 \)

Two-photon events can be suppressed by attenuating beam.
Is it possible to suppress zero-photon events as well?
**Desired single-photon source**

**single-photon emitter**  →  **single-photon detector**

**Desired single-photon source:**

\[ p_0 \approx 0 \quad p_1 \approx 1 \quad p_2 \approx 0 \]

How to overcome inherent randomness in photon generation?
Use *single particle* or *single excitation*.

How to achieve directional emission?
Use *collective excitation*. 
Single three-level ($\lambda$) atom emits single photon.

Photon emission on demand.

Directionality problem: resonator.
Single-photon sources with resonators

- Single quantum dots with integrated resonator structures. (Stanford).

Suppression of two-photon events relative to Poissonian distribution by factor 50.

Broadband photons, collection efficiency to be improved.

Single-photon sources with resonators

- Single atoms strongly coupled to a macroscopic resonator produce single photons (Caltech, Max-Planck Institute).
- Requires strong coupling regime (probability of emission into resonator must exceed emission into $4\pi$).


Single-photon sources with resonators

• Single atoms strongly coupled to a resonator can emit single narrowband photons into a well-defined direction, but there are severe technical problems:

  Resonator finesse
  \( F = 400,000 \);

  Control of atomic position with resolution below optical wavelength;

  Confinement of atom;

  Mirror losses.
Avoiding the strong-coupling regime

- Use many atoms instead to achieve directional emission.


How can we make sample emit into a small solid angle?
How can we make many (10⁶) atoms emit exactly one photon?
Single-photon generation by many atoms: Semiclassical picture
A Poissonian generator of photon pairs can serve as a deterministic single photon source if a photon can be stored.

Random generation of write photon at $t_0 - \tau$

Store read photon for time $\tau$

Deterministic generation of read photon at $t_0$
Conditional single-photon emission by many atoms
Random generation of “write” photon

write pump

write photon

|r⟩

|b⟩
Conditional generation of “read” photon

\[ |b\rangle \rightarrow \text{read pump} \rightarrow |r\rangle \rightarrow \text{read photon} \]
Two-atom transfer can be suppressed by reducing transfer probability.

Suppressed as \( p^2 \) if transfer probability \( p \ll 1 \).

But: if \( p \ll 1 \) then large probability for zero-atom transfer.
Zero-atom transfer can be reduced conditionally

|\text{write}|
|\text{pump}|

If no write photon detected, restore original situation and repeat experiment (Duan, Lukin, Cirac, Zoller). Kuzmich, Kimble, Heidelberg groups.
Repeat experiment until successful

Detection of write photon prepares single-photon source (to be read out at a desired later time).
Triggered (conditional) single-photon generation from single pumped atom

Why many atoms?
How to create directional source:

• A single dipole antenna emits dipole pattern.

• An array of dipole antennas can emit in a specific direction.
Collective emission enables directional source

Any atom could have emitted, we cannot know which one.

Sample is in an superposition of states (entangled state):

Addition of quantum mechanical amplitudes with correct phases:

Single-photon emission writes polarization grating with a single quantized excitation into many-atom system.
Collective emission enables directional source

Emitted single write photon writes phased array of dipole antennas (holographic grating) into atomic sample.
Holographic grating with quantized excitations

Emitted single write photon writes phased array of dipole antennas (holographic grating) into atomic sample.

Grating contains only one excitation (one quantum of atomic spin).

Pump beam Bragg-scatters off the grating into the detector: directional emission.
Holographic grating with quantized excitations

Emitted single write photon writes phased array of dipole antennas (holographic grating) into atomic sample.

Grating contains only one excitation (one quantum of atomic spin).

Pump beam Bragg-scatters off the grating into the detector: directional emission.

Grating disappears after single photon has been emitted: no further Bragg-scattered photons.
Experimental results:
Near-simultaneous pair generation
Setup photon pair generation

Diagram illustrating the setup for generating photon pairs. The diagram includes components such as the laser-cooled Cs Ensemble, π-pump, repumper, λ/4 Plate, Polarizing Beam Splitter, Single Mode Optical Fiber, and Single Photon Detectors. The right side of the diagram depicts energy levels with transitions labeled as write photon, read photon, and d and pump transitions.
Two-photon correlation functions

\[ g_{\text{wr}}(\tau) = \frac{\langle n_r(\tau) n_w(0) \rangle_T}{\langle n_w \rangle_T \langle n_r \rangle_T} \]

The two-photon correlation function is the number of coincidences, normalized to the expected number for a Poissonian source.
Correlation functions for classical sources

The two-photon correlation function is the number of coincidences, normalized to the expected number for a Poissonian source.

Classical autocorrelation functions have $g_{aa} \geq 1$:

- $g_{rr} = 1$ (Poissonian or laser);
- $g_{rr} = 2$ (Classical field);
- $g_{rr} > 2$ (intensity noise);
- $g_{rr} < 1$ sub-poissonian photon source;
- $g_{rr} = 0$ ideal single-photon source.
Near-simultaneous photon generation: four-wave mixing at the twin-photon level

\[ \Delta \]

- \( \sigma_+ \) read photon (fast)
- \( \sigma_- \) write photon (slow)

Write pump

Read pump

[Diagram of photon generation process with time scale]
The waveform of the read photon

Write photon observed here

Photon coincidence 60 times as likely as for Poissonian source.

Resonator linewidth $\kappa/2\pi = 10$ MHz

Fit parameters:
- Optical depth $N\eta = 6.5$
- Pump strength $\Omega/2\pi = 17$ MHz
Quality of the conditional single-photon source

g_{rr|w} conditioned on w detection. Perfect single-photon source corresponds to $g_{rr|w} = 0$.

We observe $g_{rr|w} = 0.04(2)$
Are the write and read photon identical?

Δ

σ\(_-\) write photon (slow)

Write pump

σ\(_+\) read photon

Fast (resonant and collective)

Read pump
Hong-Ou-Mandel effect for identical photons

non-polarizing beamsplitter

Identical photons always emerge together.

polarizing beamsplitter

\[ \sigma_-(\tau) \sigma_+(0) = (h-iv)(h+iv) = hh + vv + i(hv-vh) \]

disappears if \( \tau = 0 \) and photons identical
Hong-Ou-Mandel dip for identical photons

Cross correlation function $g_{rl}, g_{hv}$

Arrival time difference $\tau$ [\(\mu\text{s}\)]

- $\sigma_+\sigma_-$ analysis
- $hv$ analysis
Group correlation function, Hong-Ou-Mandel dip, photon bandwidth and Bell parameter

Two-photon interferometry below the shot-noise limit

Correlations oscillate twice as fast as single-photon signal
Two-photon interferometer for simultaneously arriving photons

The graph shows the function $g_{wr}(0)$ for 30 ns bins as a function of interferometer phase difference (degrees).
Hong-Ou-Mandel dip for delayed photons?

\[
\sigma_-(\tau) \sigma_+(0) = (h-iv)(h+iv) = hh + vv + i(hv-vh)
\]

\[
\sigma_+(\tau) \sigma_-(0) = (h-iv)(h+iv) = hh + vv - i(hv-vh)
\]

\[
\sigma_-\sigma_+ + \sigma_+\sigma_- = hh + vv
\]

Even if the photons arrive at different times.
Entangled photon pair generation

\[ \Delta \]

\[ m = -3 \quad m = -2 \quad \ldots \quad m = 2 \quad m = 3 \]
Two-photon interferometer for photons passing the interferometer separately
Can we make a single-photon Fock state?

Storage and readout of quantized spin grating
Setup with reduced Doppler effect

Adjustable delay between write and read processes
Read efficiency vs. write photon number $n_w$

Why not 100%?

Single Excitation Retrieval Efficiency = .87
Recovery efficiency at short times

Doppler decoherence, recovery 91% at zero time

$t_0 = 260\,\text{ns}$
Recovery efficiency with two time constants for standing wave geometry

\[ \tau_1 = 140 \text{ ns} \]
\[ \tau_2 = 23 \mu\text{s} \]
Recovery efficiency vs. optical depth

- Dephasing of collective state during read process due to differential light shifts
- Competition between collective and free-space scattering
Experimental results with samples in free space

- **Lukin group**: write/read correlations with many photons
  van der Wal *et al*., *Science* **301**, 196 (2003);
  storage and retrieval of a single photon, Eisaman *et al*., *Nature* **438**, 837 (2005);

- **Kimble group**: first strongly non-classical light in single-photon regime,
  Kuzmich *et al*., *Nature* **423**, 731 (2003);

- **Kuzmich group**: probabilistic entanglement, storage and retrieval of a single photon,
  Chaneliere *et al*., *Nature* **438**, 833 (2005);
  enhancement of single-photon generation using feedback,

- **Harris group**: pair generation with large rate, Balic *et al*., *PRL* **94**, 183601 (2005).
Summary

• Generation of single-excitation quantized spin gratings by detection of one photon
• Storage time of spin grating 20 μs due to thermal motion (Doppler effect)
• Conversion of spin grating into photon with 80% efficiency (intracavity), 65% outside resonator
• High-brightness source of indentical photons (10³ times brighter than best parametric downconverter)

• Future work:
  – Storage of quantum bits (milliseconds to seconds) in optical lattice
  – Two, three and four-photon generation on demand
Correlation functions and ratio

Ratio \( G = \frac{(g_{wr})^2}{(g_{ww} \cdot g_{rr})} \)

\( G > 1 \) indicates non-classical light

Cross correlation \( g_{wr} \)

Autocorrelations \( g_{ww}, g_{rr} \)
Waveforms of write and read photons

- Single write photon
- Unconditional read photon
- Conditional read photon

$\Delta t_0 = 20 \text{ ns} \ < 2/\Gamma$
Secure quantum communication: no cloning of quantum states

Eavesdropper cannot copy quantum state without changing it

Receiver can determine that signal has been corrupted
Recovery efficiency of the read photon

Observation of the write photon defines $t=0$. 

- Uncorrelated rate
- Correlated rate

56(7)\% recovery

Photon number into detector

Photon number into resonator

bin size $T$ [$\mu$s]