Probing and manipulating photon wavefunctions

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Number squeezing in BEC

PRL 95, 260403 (2005)

Quantum teleportation and quantum memory


Manipulating photon wavefunction

PRA 71, 04160(R) (2005)

PRL 101, 120501 (2008)

Nat. Phys. 5, 95 (2009)

PRL 104, 223601 (2010)

PRA 80, 031803(R) (2009)
Quantum information science and photon manipulation

- Quantum teleportation, quantum cryptography, ... etc.
  → polarization-entangled states

- Quantum imaging, entanglement concentration, ... etc.
  → spatial shape of momentum-entangled states

- Long-distance quantum communication, clock synchronization, ... etc.
  → spectral shape of frequency-entangled states

- .......
Outline

- Single photon and time-energy entangled photons (biphoton)
- Measurement of short entangled photons
- Transmission of a single photon through noisy environment
- Summary
- Outlook
Single photon and time-energy entangled photons (biphoton)
Single photon

50/50 Beam splitter

Coincidence (AB)

single photon
0

A

B

time
Single photon

A

50/50 Beam splitter

B

Single photon

spectrum

time

spectral function

ω
Time-energy entangled photons (biphoton)

If photon 1 and photon 2 are time-energy entangled,

\[
\begin{align*}
\text{Photon 1:} & \quad \{ E_1, t_1 \} \\
\text{Photon 2:} & \quad \{ E_2, t_2 \}
\end{align*}
\]

\[\Delta E \Delta t \geq \hbar\]

\[\Delta (E_1 + E_2) \Delta (t_1 - t_2) \to 0\]

Measurements of \( E_1 + E_2 \) and \( t_1 - t_2 \) are not limited by the Heisenberg uncertainty principle.

This distinguishes entangled photons from photons that are correlated but not entangled.
Generation of time-energy entangled photons (biphotons)

The most common way to generate biphotons is by a process called spontaneous parametric down conversion in a nonlinear optical crystal.

The biphoton is described by a biphoton wavefunction $\varphi(t_1, t_2)$

Coincidence $\sim |\varphi(t_1, t_2)|^2$

$$T_C = \frac{L}{v_1} - \frac{L}{v_2} = \frac{L \Delta v}{v_1 v_2}$$

$0 \rightarrow T_C \rightarrow t_2 - t_1$
Measurement of short photons?

- Temporal length of biphoton ~ 1 ps
- Resolution of single photon detectors ~ 1 ns
- Photons are generated from a LiNdO₃ nonlinear crystal.

1.5 ns  Not 1 ps!
Generation of time-energy entangled photons with four-wave mixing and slow light

\[ \omega_p + \omega_c = \omega_s + \omega_i \]

\[ v_{as} = \frac{c}{10^4} \]

\[ v_s = c \]
Direct measurement of photon wavepacket $|\varphi(t_1, t_2)|^2$
Direct measurement of photon wavepacket $|\varphi(t_1, t_2)|^2$

$1 \mu s \times c = 300 \text{ m}$!
Measurement of short entangled photons
Measurement of short entangled photons?

For a short entangled photon wavepacket $G(\tau) = |\varphi(t_1, t_2)|^2$, measurement by slow detectors only gives $\int_0^\infty G(\tau) \, d\tau$ but not $G(\tau)$.

Let's use the following trick:

$$\int_0^\infty G(\tau) \, d\tau \rightarrow \int_0^\infty G(\tau) \cos(\omega \tau) \, d\tau$$

Now we have the Fourier transform of $G(\tau)$.

We just need to take the inverse Fourier transform and obtain $G(\tau)$!

But, how do we add $\cos(\omega \tau)$ in our measurement?
Amplitude modulation of entangled photons!

\[
\int_{0}^{T_c} G(\tau) \cos(\omega t) \cos(\omega(t + \tau)) dt = G(\tau) \cos(2\omega \tau) + \text{constant}
\]
Amplitude modulation of entangled photons!

\[ G(\tau) \]

\[ G(\tau) \cos(2\omega \tau) \]
Amplitude modulation of entangled photons!

\[ G(\omega) = \int_{0}^{\infty} G(\tau) \cos(2\omega \tau) \, d\tau \]
Measurement of “short” entangled photons with “slow” detectors

\[ G(\omega) = \int_{0}^{\infty} G(\tau) \cos(2\omega \tau) \, d\tau \]

\[ G(\tau) = \int_{0}^{\infty} G(\omega) \cos(2\omega \tau) \, d\omega \]
Transmission of a single photon through noisy environment
Transmission of single photons through noisy environment?
Telecommunication through noisy environment
Spread spectrum technology

Phase Modulation

Phase Demodulation

noise
Spread spectrum technology at single photon level

signal photons: 3 MHz $\rightarrow$ 10 GHz (30/s)

SPCM

EO Phase Modulator

MOT

EO Phase Modulator

$\omega_c$

$\omega_s$

$\omega_a$

$\omega_p$

Trigger for heralded single photon generation

Random sequence of 0 and $\pi$ phases.

Photon wavepacket

Electrical Cable

Pseudorandom Bit Sequence Generator
Spread spectrum technology at single photon level

signal photons: 3 MHz → 10 GHz → 3 MHz
(30/s)

noise photons: ~3 MHz → 10 GHz
(40000/s)

Trigger for heralded single photon generation

EO Phase Modulator

EO Phase Modulator

Pseudorandom Bit Sequence Generator

Narrowband Noise (laser)

Electrical Delay

Filter

SPCM

SPCM
Spread spectrum technology at single photon level

Without SS technology  
Without SS technology + noise photons  
With SS technology + noise photons

Signal photon rate = 30/s  
Noise photon rate = 40000/s
Summary

- Long biphoton → heralded long single photon
- Amplitude modulation of time-energy entangled photons
  → Measurement of short entangled photons
- Phase modulation of single photons
  → Transmission of single photons through noisy environment
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