Quantum memory for long-distance and multiphoton entanglement

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The possibility of generating single photons at room temperature might solve the scalability problem associated with quantum communication and computing.

Quantum information science is an intriguing example where purely fundamental and even philosophical research has led to new technologies. Indeed, quantum physics, which explains the atomic behavior underpinning these innovations, provides qualitatively new and powerful concepts of communication and information processing. In this small world, single photons (particles of light) are the most promising messengers because they can be easily manipulated. Like a coin tossed into the air that could be either heads or tails until it lands, a photon can exist in a superposition of two or more states. We say that the photon has simultaneously horizontal and vertical polarization. When the superposition is extended to more than one particle, it is called entanglement. Before measurement, neither of the photons has a definite polarization, and the result of a single measurement on either of them is always completely random. As soon as the polarization of one of the photons is determined, however, its distant entangled ‘twin’ acquires a well-defined polarization.\(^1\) These quantum phenomena, which Albert Einstein called ‘spooky action at a distance,’ have the potential to enable absolutely secure cryptography and very powerful computers.

The bigger and more complex the entangled systems become, the more surprising and more rich the quantum phenomena appear. Three and four entangled particles already give rise to more powerful communication protocols and even to some elementary blocks of future computers, including the new concept of one-way quantum computing using highly-entangled cluster states.\(^2\) A cluster state can be seen as a superposition of all possible answers of the computation’s outcome, similar to novel-Jorge Luis Borges’ library of all possible books. Simple measurements on the state will then create the right outcome with certainty. So far, however, all experiments have been limited to few-photon entangled states due to the unavailability of controlled and efficient single-photon sources.\(^3\)

Single-photon generation using quantum memory

The current state-of-the-art technology for producing single photons is so-called spontaneous parametric down-conversion (SPDC) (see Figures 1 and 2). But SPDC has the disadvantage of emitting randomly entangled photon pairs, which reduces exponentially the emission rate of several photon pairs at the same time, as required to generate multiphoton cluster states. One way around this limitation is to use different sources together with quantum memory, which makes it possible to store

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*Figure 1. Schematic of noncollinear type II parametric down-conversion using a β-barium borate (β-BBO) crystal. Extraordinary \(|V\rangle\) photons of a certain wavelength emerge on the upper cone, ordinary \(|H\rangle\) on the lower cone. The intersections are unpolarized with a fixed relative phase (φ) and display polarization entanglement after proper compensation of the birefringent delay incurred in the down-conversion crystal. \(e^{i\phi}\): Euler description of the relative phase.*
Figure 2. Schematic drawing of the setup for generating four-photon cluster states without quantum memory. A UV laser passes through the β-BBO crystal, is reflected at the pump mirror Δ1, and passes through the crystal again. The coherent overlap of all modes, a1–a2 and b1–b2, at the two polarizing beamsplitters (PBS) allows for the generation of four-photon cluster states.4 EPR-Pair: Entangled photon pair. Comp.: Compensator. Pol.: Polarizer. D_A3, D_A4, D_B3, D_B4: Detectors. a3, a4, b3, b4: Paths of the photons after the PBS.

an atomic excitation. Over the past few years, great progress has been made in this field from a number of different directions.5–11 The basic idea and setup of experiments dealing with atomic ensembles (very large numbers of atoms or atom gas) are based on the theoretical work of Duan, Lukin, Cirac, and Zoller12 and are illustrated in Figure 3.

To conditionally generate single photons (in other words, we know when we get them) the atomic ensemble is initially prepared in the ground state |g⟩ (the structure of a 87Rb atom in zero magnetic field can be pictured as a three-level atom with |g⟩ = |52S1/2, F = 1⟩, |s⟩ = |52S1/2, F = 2⟩, and |e⟩ = |52P1/2, F′ = 1⟩ and |52P1/2, F′ = 2⟩). Atomic spin excitations to the state |s⟩ are produced via spontaneous Raman scattering, induced by a laser beam referred to as the write laser. In this process, correlated pairs of frequency-shifted ‘Stokes’ photons and flipped atomic spins are created via Raman transitions into the state |s⟩. Energy and momentum conservation ensure that by detecting a Raman-scattered Stokes photon, the atomic ensemble is prepared in a state with exactly one flipped spin quantum in a well-defined spin-wave mode. Conditioned upon detecting a single Stokes photon, the stored single spin-wave quantum is later coherently converted into a single-photon anti-Stokes pulse using electromagnetically induced transparency (EIT) by applying a second near-resonant retrieve laser beam8,13 for converting the atomic excitation from state |s⟩ into a single anti-Stokes photon. Thus, the direction, bandwidth, and central frequency of the single-photon anti-Stokes pulse are determined by the direction, intensity, and frequency of the retrieve laser.

All laser beams and signal modes are aligned to be collinear to reduce the effects of Doppler shifts of frequencies at room temperature. The retrieve laser and the anti-Stokes field are counterpropagating in respect to the write laser and the Stokes field inside the magnetically shielded atomic ensemble. The single spatial mode, defined by the detection fibers and by the optics, has a diameter of 200µm at the center of the ensemble. An etalon (85Rb cell) is used to reflect (absorb) the fraction of the write (retrieve) laser intensity not filtered by the polarizing beamsplitters. The atomic ensemble is a 4.5cm-long isotopically pure 87Rb vapor cell with 7torr neon buffer gas (see Figure 4).

To quantify the properties of the single-photon source, the anti-Stokes photons are studied using a Hanbury–Brown–Twiss-type setup, which allows us to measure normalized second-order correlation functions, g(2), which are ideally g(2) = 0 for a pure single-photon state and g(2) = 1 for a coherent state.
Figure 5. Anti-Stokes fluctuations, conditioned on detection of a single Stokes photon, are characterized by the correlation function $g^{(2)}(\text{AS}\mid n_S = 1) = \langle \hat{n}_{\text{AS}1} \hat{n}_{\text{AS}2} \rangle / \langle \hat{n}_{\text{AS}1} \rangle \langle \hat{n}_{\text{AS}2} \rangle$, where $(\hat{n}_{\text{AS}1}, \hat{n}_{\text{AS}2})$ is the number operator for detector $(\text{AS}1, \text{AS}2)$. The dashed line represents the classical limit of $g^{(2)}(\text{AS}\mid n_S = 1) = 1$. Measurements are shown for three values of the Stokes channel transmission: $\eta_S = 0.08$ (red triangles), $\eta_S = 0.14$ (blue diamonds), and $\eta_S = 0.27$ (green squares). Solid lines represent a theoretical model for $\eta_S$ equal to 0.08, 0.14, and 0.27, respectively. For this data, source ensemble temperature $\approx 26^\circ$C.

Figure 5 shows a measurement of the photon-number fluctuations of the anti-Stokes field conditioned on detecting a single Stokes photon, as a function of the detection probability $p\eta_S$ in the Stokes channel, where $p$ is the probability that a Stokes photon is emitted and $\eta_S$ is the transmission probability between the source ensemble and the Stokes detectors. As $p$ becomes much smaller than unity, we observe substantial suppression of the conditional intensity fluctuations in the anti-Stokes pulses compared to the classical limit of unity.

Conclusion
Our results demonstrate that Raman scattering and the use of EIT in room-temperature atomic ensembles make it possible to generate states that are close to single photons. The fact that the demonstrated storage time of the quantum memory is on the order of several microseconds may mean that scalable single-photon sources are brought a step closer, and the implementation of large-scale quantum communication and computation may not be so far out of reach.

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References


