Non-classical correlation between a single photon and the collective spin excited state of a cold atomic ensemble

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We experimentally establish a non-classical correlation between a single Stokes photon and the collective spin excited state of a cold atomic ensemble by using a spontaneous Raman scattering process. The correlation between them can be proved by transferring the spin excited state of the atomic ensemble into an anti-Stokes photon and checking the Cauchy-Schwarz inequality between the Stokes and the anti-Stokes photons. The non-classical correlation can be kept for at least 300 ns.

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Quantum network is a fast growing branch of the quantum information field. It usually consists of quantum nodes connected with quantum channels. Quantum information can be exchanged through the channels by sending photons from a node to another, or through quantum entanglement shared among the nodes. One of the key points for quantum network is the ability to distribute quantum resource over a long distance. A possible solution for extending the transmission range is using quantum repeater. Recently, Duan, Lukin, Cirac, and Zoller (DLCZ) proposed a very nice protocol for the implementation of quantum repeaters with atomic ensembles and linear optics[1]. The scheme has several advantages in the entanglement generation, connection, and applications. Therefore, since it was proposed in 2001, experimental demonstrations of the basic ingredients of this technique have become a fast-paced field of investigation[2−12]. The basic primitive integral to DLCZ scheme is the realization of the non-classical correlation between a single photon and the collective spin excited state of an atomic ensemble. Since the first experimental demonstration of this step was achieved in 2003[2], several groups have reported their progresses in this direction[3−7]. To date, the maximum time the non-classical correlation can be kept for is at the microsecond level in a cold atomic ensemble trapped in a magneto-optical trap (MOT)[8], and which can be extended to milliseconds if an optical trap is used[9]. Very recently, we have reported the experimental preparation of the non-classical correlated photon pairs using spontaneous four-wave mixing (SFWM) in a hot atomic ensemble[10]. Furthermore, we have experimentally proven that these two photons are in an entangled orbital angular momentum state[11]. We have also experimentally prepared a non-classical non-degenerated photon pair via SFWM using an off-axis configuration in a cold ^{85}Rb atomic ensemble[12]. In this experiment, continuous-wave (CW) lasers are used, and there is no directive proof to show the non-classical correlation between the single photon generated and the collective spin excited state of the atomic ensemble, and no proof to show that this correlation can be kept for a while either. Therefore, in this letter, we use pulsed lasers to establish the non-classical correlation between the single photon (Stokes photon) and the spin excited state of the cold atomic ensemble by using spontaneous Raman scattering. The correlation between them can be proved by transferring the spin excited state of the atomic ensemble into another photon (anti-Stokes photon) and checking the Cauchy-Schwarz inequality between these two photons. In our experiment, a time-resolved second-order correlated function between the non-degenerated Stokes and anti-Stokes photons at different delayed time is measured. The experimental result shows that the Cauchy-Schwarz inequality is certainly violated, which clearly demonstrates the non-classical characteristic of the correlation between the Stokes and the anti-Stokes photons generated by the write and read pulses, and therefore shows that there is the non-classical correlation between the Stokes photon and the collective excited state of the atomic ensemble. The measured result clearly shows that the correlation can be kept for at least 300 ns.

In the experiment, ^{85}Rb atoms are loaded into a 10-port, stainless-steel vacuum chamber. We use sponta-

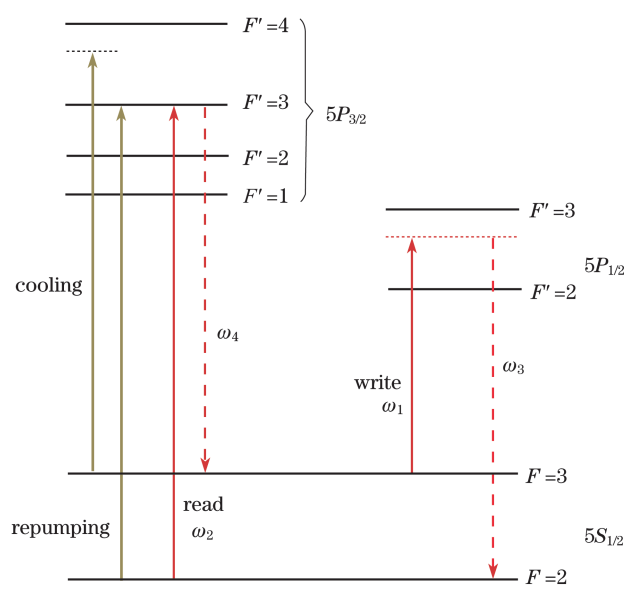

Fig. 1. Energy level diagram of ^{85}Rb.

neous Raman scattering via an off-axis configuration to prepare the non-classical correlation between the Stokes photon and the collective spin excited state of the atoms. The energy level structure of ^{85}Rb and the frequency arrangement of the lasers are shown in Fig. 1. The property of atomic absorption resulting from the interaction between coherent light and N-type four-level system is investigated in Ref. [13]. In our experiment, the write laser is +35 MHz detuned from the $5S_{1/2}(F=3) \rightarrow 5P_{1/2}(F'=3)$ transition of ^{85}Rb, and the read laser is resonant with the $5S_{1/2}(F=2) \rightarrow 5P_{3/2}(F'=3)$ transition. The two lasers used in the experiment are from two external-cavity diode lasers (ECDLs, DL100, Toptica). They are modulated into pulses by acousto-optic modulators. The pulse widths of the write and read lasers are about 230 ns and 2 μs, respectively. The first 100 ns of the read is used for retrieving the photon from the spin excited state of the atoms and the following 1900 ns is used to repump the atoms back to the initial state. These two lasers are counter propagated and orthogonally linear polarized. The diameters of the write and read lasers are about 0.4 mm and they are weakly focused to pass through the atomic cloud. In our experiment, the Stokes and anti-Stokes photon pair at an angle of about 2° to the laser direction is collected in order to reduce the very strong noise introduced by the lasers and simplify the filtering system. During one experimental period, the trapping and repumping lasers are cut off after the atoms are loaded into MOT for 9 ms. In order to pump the atoms to the level $F=3$, the repumping laser is shuttered off about 100 μs later than the trapping laser. The experiment is performed in a 1-ms window. The sequences of the experiment are shown in Fig. 2. The 0.9-ms experiment window is divided into about 200 trials, and the period of each trial is about 4.2 μs. In each trial, the write laser is turned on firstly, and after a programmable delay, the read pulse is applied. All sequences are controlled by using a programming card (NI PCI-6602). The Stokes and anti-Stokes photons collected by single mode fibers are input to two single photon detectors (PerkinElmer SPCM-AQR-15-FC). For a start event from the write pulse, within the interval $t_j^{(1)} \pm T/2$ at the jth trial of the experiment, where T=230 ns, we record the anti-Stokes photon from the read pulse within successive $t_k^{(2)} = t_k^{(1)} + \Delta T \pm T'/2$, where ΔT is the programmed delay between the write and read pulses, $k = j+1, j+2, \cdots, j+7$, and $T' =$ 100 ns. Over many repetitions of the experiment, we acquire time-resolved coincidences between the Stokes and anti-Stokes photons, both within the same trial and for subsequent trials $k \neq j$. The outputs of the detectors are sent to a coincidence circuit for coincidence counting, which mainly consists of a counting card (FAST ComTec P7888-2) with 4-ns bin width and totally 8192 bins and a computer.

Figure 3 shows an example of the data accumulated in this manner for coincidence between the Stokes and anti-Stokes photons, with successive peaks separated by the time between trials of about 4.2 μs. Note that there is an excess of coincidence counts in the initial peak for joint detections from the same trial as compared to the detections from different trials. The programmed time delay between the lead edges of the write pulse and the read pulse is about 250 ns.

In order to check the correlation between the Stokes photon and the collective spin excited state of the atoms, we check whether Cauchy-Schwarz inequality is violated or not, where the classical fields are constrained by this inequality. The Cauchy-Schwarz inequality is defined as $|\tilde{g}_{1,2}(\delta t)|^2 \leq \tilde{g}_{1,1}\tilde{g}_{2,2}$, where $\tilde{g}_{1,1} = \frac{N_{1,1}}{M_{1,1}}$, $\tilde{g}_{2,2} = \frac{N_{2,2}}{M_{2,2}}$, and $\tilde{g}_{1,2}(\delta t) = \frac{N_{1,2}}{M_{1,2}}$; $N_{1,1}$ is the total number of coincidences obtained by summing over time bins for detection with the same trial for autocorrelation between the Stokes photons, $N_{2,2}$ denotes the one between the anti-Stokes photons, and $N_{1,2}$ is the number for cross-correlation between the Stokes photon and the anti-Stokes photon, respectively; $M_{1,1}$, $M_{2,2}$, and $M_{1,2}$ are the average numbers of coincidences obtained by summing over time bins with successive trials for autocorrelation and cross-correlation, respectively. From our experimental data, we find $\tilde{g}_{1,2}(\delta t) = 2.3295$. Because $N_{1,1}$ and $N_{2,2}$ are much smaller than $N_{1,2}$, and it will take a very long time to measure $\tilde{g}_{1,1}$ and $\tilde{g}_{2,2}$, we give up measuring them directly. $\tilde{g}_{1,1} = \tilde{g}_{2,2}$=2 is expected for DLCZ protocol

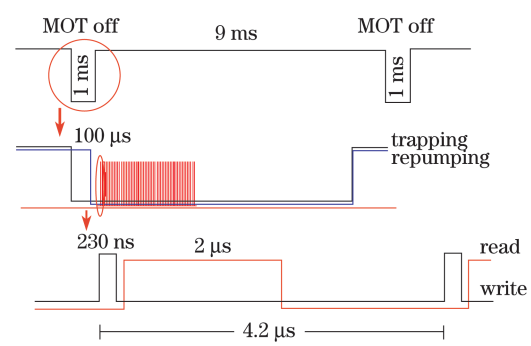

Fig. 2. Timing sequence for data acquisition.

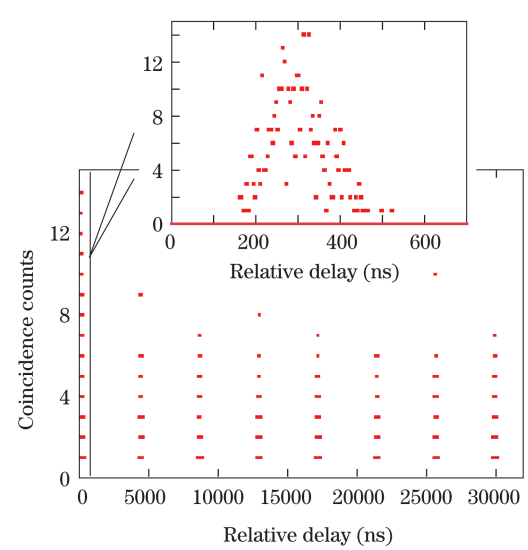

Fig. 3. Time-resolved coincidence between the Stokes photon and the anti-Stokes photon versus time delay. The first peak shows the coincidence counts with the same trial, and the other peaks show the coincidence counts between one trail and the successive trials. Inset is the zoom of the first peak.

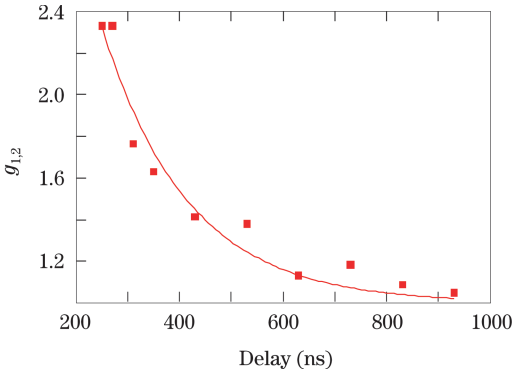

Fig. 4. $\tilde{g}_{1,2}(\delta t)$ versus the programmed delay time between the lead edges of the write and read pulses.

in the ideal case, but usually it is degraded by diverse sources of background counts. Due to the experimentally obtained $\tilde{g}_{1,2}(\delta t) = 2.3295 > 2$, the Cauchy-Schwarz inequality is certainly violated, which clearly demonstrates the non-classical characteristic of the correlation between the Stokes and anti-Stokes photons generated by the write and read pulses, and therefore shows that there is the non-classical correlation between the Stokes photon and the collective excited state of the atomic ensemble.

The same process with different programmed delays between write and read pulses are repeated. The measured $\tilde{g}_{1,2}(\delta t)$ versus the programmed delay time between the lead edges of the write and read pulses is displayed in Fig. 4. It can be seen that $\tilde{g}_{1,2}(\delta t)$ decreases exponentially with the delayed time.

The reasons why $\tilde{g}_{1,2}(\delta t)$ is not very large are given as follows. Firstly, it is due to the large background noise, for example, the reflected light from optical components. In our experiment, we do not use any filter to cut off the noise, so the accidental coincidence is quite large. Secondly, it comes from the low efficiency mode matching of the Stokes and anti-Stokes fields with detection system. Thirdly, it comes from the magnetic field of the trap. During the experiment, this field is always on, which reduces the coherence time and $\tilde{g}_{1,2}(\delta t)$ significantly[4]. In the experiment, the storage time of the collective spin excited state in the atomic ensemble is not very long, which is mainly caused by the off-axis configuration. This configuration will greatly simplify the filter system[8], but if a collinear configuration is used, a much longer storage time can be achieved.

In conclusion, we experimentally establish the non-classical correlation between the Stokes photon and the collective spin excited state of the cold atomic ensemble with the process of spontaneous Raman scattering. The correlation is proved by transferring the spin excited state into the anti-Stokes photon and checking the Cauchy-Schwarz inequality between the two photons. The experimental result shows that the Cauchy-Schwarz inequality is certainly violated, which clearly demonstrates the non-classical characteristic of the correlation between the Stokes and anti-Stokes photons generated by the write and read pulses, and therefore shows that there is a non-classical correlation between the Stokes photon and the collective excited state of the atomic ensemble. This non-classical correlation can be kept for at least 300 ns.

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