Quantum Storage of Orbital Angular Momentum Entanglement in an Atomic Ensemble

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(Received 22 October 2014; published 4 February 2015)

Constructing a quantum memory for a photonic entanglement is vital for realizing quantum communication and network. Because of the inherent infinite dimension of orbital angular momentum (OAM), the photon's OAM has the potential for encoding a photon in a high-dimensional space, enabling the realization of high channel capacity communication. Photons entangled in orthogonal polarizations or optical paths had been stored in a different system, but there have been no reports on the storage of a photon pair entangled in OAM space. Here, we report the first experimental realization of storing an entangled OAM state through the Raman protocol in a cold atomic ensemble. We reconstruct the density matrix of an OAM entangled state with a fidelity of 90.3% $\pm$ 0.8% and obtain the Clauser-Horne-Shimony-Holt inequality parameter S of 2.41 $\pm$ 0.06 after a programed storage time. All results clearly show the preservation of entanglement during the storage.

DOI: 10.1103/PhysRevLett.114.050502 PACS numbers: 03.67.Lx, 03.67.Hk, 42.50.Gy, 42.65.Hw

The establishment of a quantum network in the future needs a distribution of quantum entangled photons over channels between different nodes [1–4]. To overcome the exponential scaling of the error rate with the channel length, the concept of a quantum repeater is introduced [5], which combines entanglement swapping and quantum memory to efficiently extend the achievable distance of quantum communication. During the last years, important progress has been made towards the realization of an efficient and coherent quantum memory based on gas and solid atomic ensemble [6–10], photons encoded in a two-dimensional space spanned, for example, by orthogonal polarizations or different paths had been stored [11–16]. Moreover, many groups and researchers are active in storing light encoded using the spatial mode [such as orbital angular momentum (OAM)] in different physical systems [17–27]. Photons with OAM could be regarded as helices with left and right handedness twisted to varying degrees [28,29]. Because of the inherent infinite dimension of OAM space [30–32], a light encoded in OAM space could offer high channel capacity [33]. Therefore, the preparation of an OAM entangled state plays a vital role in quantum information and communication fields, and usually is realized by using the spontaneous parametric down-conversion in a crystal [34] or spontaneous Raman scattering (SRS) in an atomic ensemble [35,36] experimentally.

Building up a quantum network based on OAM involves coherent interaction [3] between OAM entangled photons and matter, so storing an entanglement of the OAM state is critical for establishing a quantum memory for photonic states encoded in OAM space. The present implemented memory protocols include electromagnetically induced transparency [37], Raman protocol [38], controlled reversible inhomogeneous broadening [39], atomic frequency combs [40], photon echo [41], optomechanical storage [42], and the off-resonant Faraday scheme [43]. Of which, the Raman protocol has some interesting features, such as the ability to store a broadband pulse towards high-speed quantum memories, the insensitivity to inhomogeneous broadening, etc. [44]. Walmsley's group experimentally realized the storage of a light near the single-photon level via Raman scheme recently [44,45]; however, it is a strongly attenuated laser, not a true single photon. References [24,25] report the storage of OAM states and images ingradient-echo memories, which are based on Raman absorption; still the light is a coherent light. So there has been no report on storing a true single photon carrying an image or OAM via Raman scheme. Furthermore, since Zeilinger's group observed the entangled properties of OAM [34] in 2001, there has not been any experimental progress for storing entangled OAM states via any protocol in any physical memory system. Experimentally realizing storage of the OAM entanglement is a big challenge.

Here we report the first experimental realization of a quantum memory for an OAM entanglement. We establish the OAM entanglement between the anti-Stokes photon and the collective spin excited state of one cold atomic ensemble by SRS first [35,36]. Then we send this anti-Stokes photon to and store it via Raman scheme in another cold atomic ensemble acting as the quantum memory. This way, an OAM entanglement is established between two atomic ensembles. We could demonstrate this OAM entanglement by mapping the spin excited states in two ensembles to two photons and checking their entanglement. We prove the entanglement existed in a space consisting of $m = \pm 1\hbar$. We reconstruct the density matrix of the OAM entangled photon pair with a fidelity of 90.3% $\pm$ 0.8% and obtain the Clauser-Horne-Shimony-Holt (CHSH) inequality parameter of $S = 2.41 \pm 0.06$ after a programed storage time. All results clearly show the preservation of the entanglement in our memory. The work includes two significant areas of progress: (i) the first experimental realization of storing an entangled OAM state and (ii) the first experimental evidence of a true single-photon-carrying OAM stored via Raman scheme.

The layout of our experiment is depicted by Fig. 1. Pump 1 is applied first for generating an anti-Stokes photon at 795 nm called signal 1 by a noncollinear SRS process in an optically thick rubidium (Rb) ensemble, which is trapped in a two-dimensional magneto-optical trap (MOT1) [46]. By using a series of mirrors and lenses (a 4-f imaging system was consisted), the signal 1 photon is delivered into the second MOT2 for subsequent storage. A coupling pulse laser with orthogonal polarization to signal 1 is used to store the signal 1 via Raman scheme (see Supplemental Material [47]). After the signal 1 photon is retrieved from MOT2, the pump 2 laser is switched on for converting the collective spin excited state of the atomic ensemble in MOT 1 to a Stokes photon at 780 nm, called signal 2.

First, we establish the nonclassical correlation in time domain between atomic ensembles in MOT1 and MOT2 by storing the signal 1 photon in MOT2. The delayed time between pump 1 and pump 2 pulses is programed to be 260 ns, and both spatial light modulator (SLMs) act as mirrors. Before pump 2 is applied, we add a coupling laser to store the signal 1 photon via Raman scheme in MOT2 for a while. This way, we build up the nonclassical correlation between two MOTs. We could demonstrate this nonclassical correlation in the time domain by mapping the spin excited states in two ensembles to two photons and checking their correlation. After we retrieve the signal 1 photon in MOT2, we use the pump 2 laser to map the collective spin excited state of the atomic ensemble in MOT 1 to signal 2 photons. We measure the cross-correlation function $g_{s1,s2}(\tau)$ against the storage time; the results are shown in Fig. 2. We first prove the existence of a nonclassical correlation between these two photons by demonstrating a strong violation of the Cauchy-Schwarz inequality [6] (see Supplemental Material [47]). Furthermore, we demonstrate the single-photon property of the signal 1 photon by performing the Hanbury-Brown–Twiss (HBT) [6] experiment on the trigger photon. Experimentally, we obtain a heralded auto-correlation parameter $g_{s1;s1/s2}(t)$ value of 0.074 ± 0.0012 before storage and 0.29 ± 0.02 after 150 ns-long storage, confirming clearly that the single-photon nature is preserved during storage. Details are presented in the Supplemental Material [47].

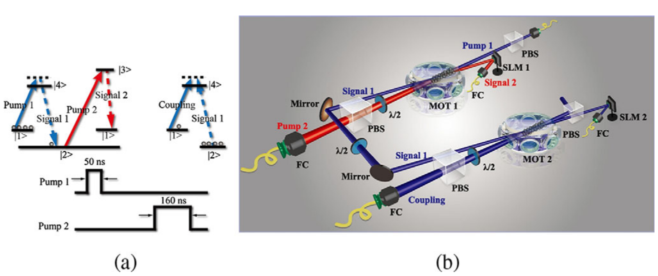

FIG. 1 (color online). Simplified energy level diagram of the SRS (a) and setup depicting the storage of entanglement of the OAM state (b). MOT: magneto-optical trap; FC: fiber coupler; SLM: spatial light modulator; PBS: polarization beam splitter; $\lambda/2$: half-wave plate. See Supplemental Material for detail [47].

Next, we move to the main part of this work: establishing an OAM entanglement in two atomic ensembles by storing the signal 1 photon in MOT2. In the following experiments, the SLMs act as spatial postselection tools instead of mirrors. We build up the OAM entanglement between the anti-Stokes photon and the collective spin excited state of the atomic ensemble in MOT1 by SRS first; this entanglement is specified by the formula of $|\psi\rangle = \sum_{m=-\infty}^{m=\infty} c_m |m\rangle_{s1} \otimes |-m\rangle_{a2}$ [35,36], and is a high-dimensional entangled state. Subscripts $s1$ and $a2$ label the signal 1 photon and the atomic ensemble in MOT1, respectively, $|c_m|^2$ is the excitation probability, and $|m\rangle$ is the OAM eigenmode with quanta of m. The initial state of the system has zero linear and angular momentum. Because of the fact that the SRS process conserves momentum, the resulting joint state of the anti-Stokes photon and the atomic spin

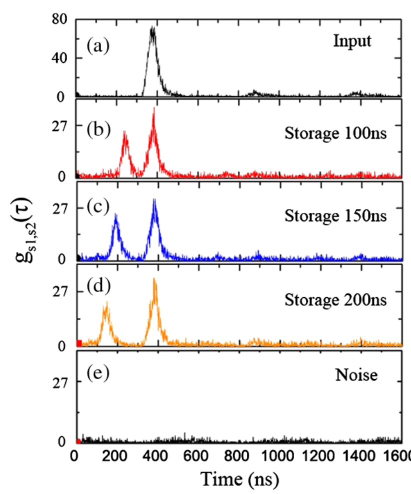

FIG. 2 (color online). The measurement of the cross-correlated function $g_{s1,s2}(\tau)$ in the process of storage. (a) Cross-correlated function $g_{s1,s2}(\tau)$ between signal 1 and signal 2 photons with a delayed time of 260 ns between pump 1 and pump 2. (b),(c), (d) The time-correlated function $g_{s1,s2}(\tau)$ between signal 2 photon and the retrieval signal 1 photon with storage time of 100, 150, and 200 ns, respectively. (e) The collected noise without the input signal, which is mainly from the scattering light of the coupling laser. Signal 1 acts as the trigger photon, and signal 2 acts as the stop signal. The spatial modes of both signal 1 and signal 2 are Gaussian. All data are raw, without noise correction.

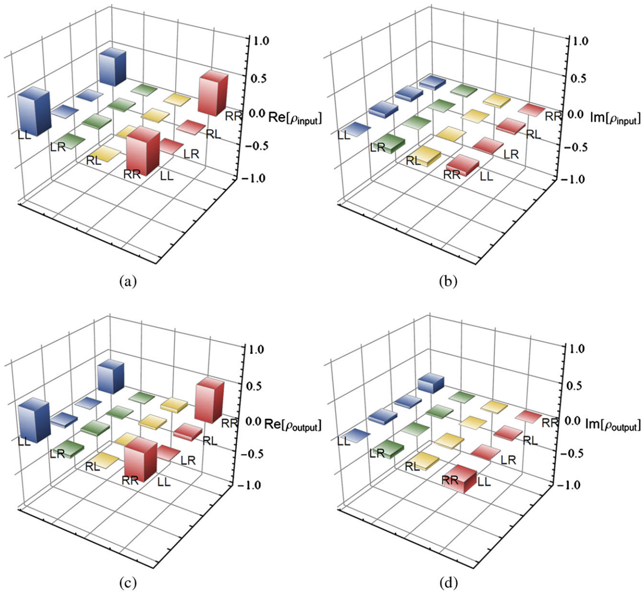

FIG. 3 (color online). The real (a), (c) and imaginary (b), (d) parts of the reconstructed density matrix of the state before and after storage, respectively. The background noise has been subtracted, which was estimated by repeating the experiment without input signal 1 photon to MOT2. The measurement time for data is 500 s in (a) and (b) and 1000 s in (c) and (d).

wave have zero total angular momentum, which enforces the OAM correlations between them. After we stored the signal 1 photon in the atomic ensemble in MOT2, an OAM entangled state between two atomic ensembles was established. We could demonstrate this OAM entanglement by mapping the spin excited states in two ensembles to two photons and checking their entanglement. But in order to simplify the experiment, we shorten the measurement time; here we only demonstrate the storage of the OAM entanglement postselected in a two-dimensional subspace ($|m\rangle$ and $|-m\rangle$ basis); thus, the photonic entanglement state becomes $|\Psi\rangle = (|m\rangle|m\rangle + |-m\rangle|-m\rangle)/2^{1/2}$. In order to characterize the obtained state, two-qubit state tomography [51] was performed to reconstruct the density matrix of state. We set the delayed time of the applied pump 2 to be 260 ns. Before pump 2 was applied, the OAM entanglement between the signal 1 photon and the ensemble in MOT1 was established, which could be verified by mapping the OAM of the ensemble in MOT1 to signal 2 photon, and checking OAM entanglement between signal 1 and signal 2 photons. By projecting signal 1 and signal 2 photons on basis vectors of $|L\rangle$, $|R\rangle$, $(|L\rangle - i|R\rangle)/2^{1/2}$, $(|L\rangle + |R\rangle)/2^{1/2}$ (where $|L\rangle$ and $|R\rangle$ were states corresponding to a well-defined OAM of $1\hbar$ and $-1\hbar$, respectively; see the Supplemental Material [47]) by using two SLMs, we obtain the corresponding 16 coincidence rates, then use them to reconstruct the density matrix of the state. Figures 3(a) and 3(b) are the corresponding real and imaginary parts of the reconstructed density matrix. By using the formula of $F_1 = \mathrm{Tr}(\sqrt{\sqrt{\rho_{\mathrm{input}}}\rho_{\mathrm{ideal}}\sqrt{\rho_{\mathrm{input}}}})^2$, we calculate the fidelity of the reconstructed density matrix by comparing it with the ideal density matrix, which is of $91.0\% \pm 1.8\%$. Where ρ_{ideal} was the density matrix corresponding to the ideal OAM entangled state of $|\Psi\rangle = (|L\rangle|L\rangle + |R\rangle|R\rangle)/2^{1/2}$, ρ_{input} is the reconstructed density matrix. Next, we send the signal 1 photon to MOT2 for subsequent storage via Raman scheme. After a programed storage time of 150 ns, the signal 1 is retrieved by switching on the coupling light again. Then we apply the pump 2 to map the spin excited state of the ensemble in MOT1 to the signal 2 photon. We measure the time-correlated function between the signal 2 photon and the retrieved signal 1 photon, and reconstruct the density matrix according to the measured coincidence rates. The real or imaginary part of the reconstructed density matrix of the OAM entanglement is shown by Figs. 3(c) and 3(d). The fidelity of the density matrix calculated is $84.6\% \pm 2.6\%$ by comparing it with the ideal density matrix ρ_{ideal}, and is $90.3\% \pm 0.8\%$ compared with the reconstructed density matrix ρ_{input} before storage by using the formula of $F_2 = \mathrm{Tr}(\sqrt{\sqrt{\rho_{\mathrm{output}}}\rho_{\mathrm{input}}\sqrt{\rho_{\mathrm{output}}}})^2$, where ρ_{output} is the reconstructed density matrix after storage.

We further characterize the degree of entanglement after storage through checking the CHSH inequality [52–54]. For our experiment, the CHSH parameter S is referenced by Ref. [55] as

$$S = E(\theta_A, \theta_B) - E(\theta_A, \theta'_B) + E(\theta'_A, \theta_B) + E(\theta'_A, \theta'_B). \quad (1)$$

θ_A, θ_B are the angles of the phase distributions on the surfaces of SLMs which are defined in Fig. S2(b) of the Supplemental Material [47]. $E(\theta_A, \theta_B)$ can be calculated from the coincidence rates at particular orientations,

$$E(\theta_A, \theta_B) = \frac{C(\theta_A, \theta_B) + C(\theta_A + \frac{\pi}{2}, \theta_B + \frac{\pi}{2}) - C(\theta_A + \frac{\pi}{2}, \theta_B) - C(\theta_A, \theta_B + \frac{\pi}{2})}{C(\theta_A, \theta_B) + C(\theta_A + \frac{\pi}{2}, \theta_B + \frac{\pi}{2}) + C(\theta_A + \frac{\pi}{2}, \theta_B) + C(\theta_A, \theta_B + \frac{\pi}{2})}.$$

We select $\theta_A = 0$, $\theta_B = \pi/8$, $\theta_{A'} = \pi/4$, $\theta_{B'} = 3\pi/8$. The calculated S is of $S = 2.48 \pm 0.04$ before storage and $S = 2.41 \pm 0.06$ after storage with background subtraction ($S = 2.16 \pm 0.04$ before storage and $S = 2.10 \pm 0.06$ after storage without any background subtraction). The inequality is violated when the values of S are greater than 2 and the violation of inequality means that there exists the entanglement between photons after storage.

Moreover, we check the two-photon interference. If the visibility of the two-photon interference is $>70.7\%$ [56], then the CHSH inequality would be violated, proving the entanglement existed between two photons. We fix the phase angle of SLM 1 to be $\theta_A = 0°$ or 45°, respectively, and measured the coincidence rate at different angles of θ_B of the SLM 2. The storage time is set to 150 ns. The experimental results are shown by Fig. 4—visibility is $85.2\% \pm 3.0\%$ ($71.8\% \pm 3.3\%$) at $\theta_A = 0°$ and $86.8\% \pm 3.3\%$ ($72.9\% \pm 3.0\%$) at $\theta_A = 45°$ with (without) noise corrections; both are larger than 70.7%, which clearly proves the preservation of the OAM entanglement in storage again.

The storage of a two-dimensional entanglement with higher OAM values $m/-m$ could be realized in principle; the storage efficiency decreases with the increase of value m [50], but the fidelity could still keep high. For the storage of a two-dimensional entanglement in different subspaces, the different storage efficiency for different OAM will result in low storage fidelity. The larger the OAM value difference is, the worse the fidelity is.

We want to mention that we can prove the storage of high-dimensional OAM entangled states ($d \geq 3$) by reconstructing the density matrix as was done in the two-dimensional case in principle, but we should consider the effects shown in the previous paragraph. Besides, there are some big challenges in the experimental realization: for example, how to achieve higher signal-to-noise ratio and how to stabilize the system over a long period. This is because we have to take more data in the case of storing a high-dimensional entanglement (for $d = 3$, 81 data are required [50]).

This memory could store a high-dimensional OAM entangled state ($d \geq 3$) in principle, the number of dimensions per photon can be simply estimated by the formula of $w(z) = \sqrt{m+1}w_0(z)$, where $w(z)$ is the beam waist of a light carrying OAM of m at the center of the atomic vapor in MOT2, and $w_0(z)$ is the beam waist of a Gaussian light. In our experiment, $w_0(z) \sim 100$ μm and the radius of the atomic vapor in MOT2 is ~1 mm, therefore $m \sim 100$; therefore, the maximal OAM dimension per photon that could be stored in our system was limited to be 200. This number is also limited by other factors, such as the Fresnel number and the optical depth of the atomic ensemble [57], the angle of the signal field, and the control field in MOT2, etc., which need further investigation. The fidelity of the measured OAM entangled state prepared in MOT1 was below 100%, one main reason was from the imperfect measurement: in the experiment, the distance between the SLM 1 and SLM 2 was 3 m. The mismatch between the positions of these two SLMs where signal photons should be entangled and the actual positions reduced the fidelity. One could soften this influence by enlarging the beam waist of the signal 1 and signal 2 photons. Another reason was from dephasing between two ground states induced by Earth's magnetic field.

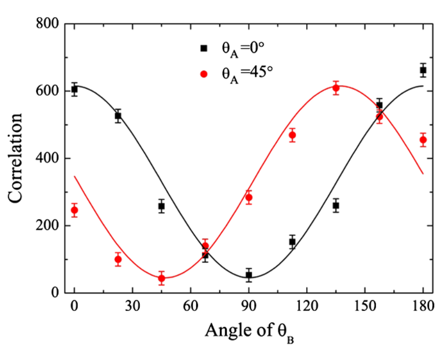

FIG. 4 (color online). The measured coincidence rate at $\theta_A = 0°$ and 45° with different θ_B. The red (blue) curve represents the correlated coincidence rate with the orientations of $\theta_A = 0$ (45°). The background noise has been subtracted. Error bar is ±1 standard deviation. The background noise was estimated by repeating the experiment without input signal 1 photon to MOT2. The measurement time for the data was 1000 s.

We report the first experimental realization of storing OAM entanglement via Raman scheme in an atomic ensemble. The fidelities of the reconstructed density matrices in a postselected two-dimensional subspace before and after storage are 91% and 84%, respectively, compared with the ideal density matrix. In addition, the violations of the CHSH inequality were experimentally demonstrated before and after storage. We also provide experimental evidence that an image memory at the single-photon level can be realized via Raman scheme. This work clearly demonstrates the workability of building up a high-dimensional quantum communication system in the future.

We thank Dr. Yun-Feng Huang and Dr. Jin-Shi Xu for helpful discussions. This work was supported by the National Fundamental Research Program of China (Grant No. 2011CBA00200), the National Natural Science Foundation of China (Grants No. 11174271, No. 61275115, and No. 61435011), the Youth Innovation Fund from USTC (Grant No. ZC 9850320804), and the Innovation Fund from CAS.

Note added.—During submission of this Letter, we note that a paper [58] also reports the storage of a true single photon in a hot atomic vapor via Raman scheme.

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