Cavity-Enhanced Atom-Photon Entanglement with Subsecond Lifetime

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A cold atomic ensemble suits well for optical quantum memories, and its entanglement with a single photon forms the building block for quantum networks that give promise for many revolutionary applications. Efficiency and lifetime are among the most important figures of merit for a memory. In this Letter, we report the realization of entanglement between an atomic ensemble and a single photon with subsecond lifetime and high efficiency. We engineer dual control modes in a ring cavity to create entanglement and make use of three-dimensional optical lattice to prolong memory lifetime. The memory efficiency is 38% for 0.1 s storage. We verify the atom-photon entanglement after 1 s storage by testing the Bell inequality with a result of $S = 2.36 \pm 0.14$.

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A quantum network [1,2] of long-lived quantum memories [3–6] gives the promise for a series of revolutionary applications [2], such as large-scale quantum communication via quantum repeaters [7], cooperative operation of atomic clocks [8], and distributed quantum sensing. The building block for quantum networks is a pair of hybrid entanglement between a single photon and a quantum memory [1,5], with the memory being efficient and long lived [9–11]. Entangling remote quantum memories is further mediated via photons through entanglement swapping [12–14]. Larger networks can be further constructed via concatenating entanglement swapping of the memories [7,15]. Hybrid memory-photon entanglement has been created in many physical systems, such as trapped ions [16], single neutral atoms [17,18], atomic ensembles [10], rare earth ions [19,20], NV centers [21], and quantum dots [21]. Within all demonstrations so far, Dudin *et al.* achieved a memory-photon entanglement [22] with the longest lifetime. While the memory efficiency in Ref. [22] was merely 7% at 0.1 s, which hinders further scalable extensions.

Atomic ensembles [10,23,24] are an excellent candidate for quantum networks, since single photons can interact with the atoms strongly via collective enhancement. Extensive studies [10,25–40] have been performed so far for improving the memory performances. Motional dephasing can be tackled with optical lattice [31,41] and spin-wave engineering [25,29,30,42]. High efficiency can be achieved by engineering either a huge optical depth [35–37,40] or a low-finesse cavity with moderate optical depths [25,27,31,43]. In a previous work [31], we have taken a joint approach with optical lattice and a ring cavity to achieve efficient and long-lived storage simultaneously. Nevertheless, we merely demonstrated nonclassical correlation of DLCZ storage [23]. In this Letter, we report the realization of atom-photon entanglement with long lifetime and high retrieval efficiency. We make use of a scheme with dual control modes to create entanglement between a single photon's polarization and the momentum vector of a collective atomic excitation. Moreover, we optimize compensation of differential light shifts of the optical lattice, and get a $1/e$ memory lifetime of 458(19) ms for qubit storage. The initial retrieval efficiency measured is 58% and drops to 38% at 0.1 s, which is 5.4 times higher than the result [22] by Dudin *et al.* Finally we test the atom-photon entanglement after 1 s storage via violation of the Bell inequality by 2.57 standard deviations ($S = 2.36 \pm 0.14$).

Our experimental setup is shown in Fig. 1. An ensemble of ^{87}Rb atoms is first prepared via magneto-optical trapping and further transferred into a three-dimensional optical lattice. Atoms in the lattice have a population lifetime of 2–3 s, thus providing a solid basis for long-lived storage. Nevertheless, minor differential light shifts between the two energy levels used for storage will dephase a collective atomic excitation, resulting in a typical lifetime of several milliseconds [41]. In our experiment, they are compensated via tuning the magnetic field and making the lattice beams circularly polarized [31]. In this way, the vector part of the differential light shift cancels the scalar part [44]. A ring cavity with a finesse of 43.4/44.3 (for H/V polarized light) is placed around the atoms to enhance the atom-light interaction. More details on our lattice and cavity setup can be found in our previous publication [31].

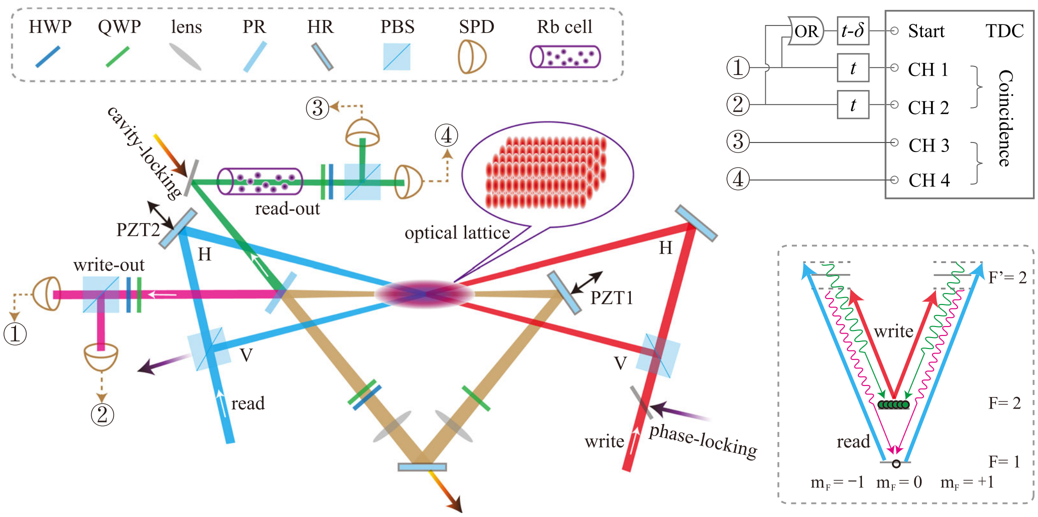

FIG. 1. Schematic experimental setup and atomic energy levels. The ^{87}Rb atoms are trapped in a 3D optical lattice formed by interfering four circularly polarized 1064 nm laser beams. The lattice beams are not shown in the picture for the sake of simplicity, and more details about the optical lattice can be found in our former publication [31]. The phase difference between two write-read paths is locked by a PID control loop. Angles between the write-out signal and the two write beams are 2.5° and −4.2°, respectively. A three-mirror cavity is placed around the atomic ensemble to increase the retrieval efficiency with whose beam waist matching the write(read)-out signal. The cavity has a beam waist radius of ~60 μm, a finesse of 43.4/44.3 for H/V polarized light, and a free spectral range of 484 MHz. The cavity is also locked by a PID control loop. PZT1 (piezoelectric ceramic transducer) is used to lock the cavity by displacing a HR mirror, and PZT2 is used to lock the W-R interferometer. Write-out and read-out photons are analyzed in polarization, and detected with single-photon detectors (SPD). We use a pumped Rb vapor cell to filter leakage from the read beam to the read-out channel. Some other parameters and symbols are listed as following. Cavity-locking beam: 796 nm, 0.5 μW. Phase-locking beam: 796 nm, 0.5 μW. Write beam: red detuned −30 MHz, 2 μW. Read beam: blue detuned +36 MHz, 320 μW. Beam radii of the write and read lasers are both 300 μm. Polarizing beam splitter (PBS), half-wave plate (HWP), quarter-wave plate (QWP). partially reflecting (PR) mirror with reflectivity of 90.4(2)%, highly reflecting (HR) mirror. Lens: focal length 250 mm. δ: electronic delay around several μs.

To create entanglement in our setup, a popular scheme using dual internal states [45] is not suitable since it hinders long-lived storage via being magnetic-field sensitive [46,47]. While another popular scheme using dual spacial modes [48] is not suitable either since it requires duplicating the cavity setup which will make the whole system over complicated. Here, instead of collecting two spatial modes for the single photons as in Ref. [48] to create entanglement, we harness dual spatial modes both for the read and write beams, which involves merely minor modifications of our previous setup with optical lattice and a ring cavity [31].

The energy levels employed are shown in the inset of Fig. 1. Atoms are first optically pumped to the initial state $5S_{1/2}:|F=2, m_F=0\rangle$. Then we apply a write pulse with linear polarization to induce spontaneous Raman scattering. With a very small probability we will detect a scattered single photons in one spatial mode. The polarization of the scattered photon is orthogonal to the polarization of the write pulse, due to the specific dipole matrix elements involved. As shown in Fig. 1, a write pulse is split into two spatial modes, with one mode from top right with horizontal (H) polarization, and the other from bottom right with vertical (V) polarization. The top right mode will create a V photon along with a collective atomic excitation of $|\downarrow\rangle$, while the bottom right mode will create a H photon along with a collective atomic excitation of $|\uparrow\rangle$. Thus superposition of the two cases will create an entangled state of

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_w|\uparrow\rangle_a + e^{-i\phi_w}|V\rangle_w|\downarrow\rangle_a), \tag{1}$$

where the subscript w denotes the write-out photon, a denotes the atomic ensemble, and ϕ_w is the phase difference between two write pulses at the location of the atoms. The write process is repeated until a write-out photon is detected, giving a production rate of ~800 Hz for the atom-photon entanglement without considering the atom loading time (see Supplemental Material [49] for detailed time sequences). Afterwards, we store the atomic qubit for a programmable duration t, and detect the atomic qubit by applying the read pulse. Similar to the write process, a read pulse is split into two spatial modes, one mode from the top left with H polarization will convert the atomic state $|\downarrow\rangle_a$ to a read-out photon with V polarization, while the other mode from the bottom left with V polarization will convert $|\uparrow\rangle_a$ to a read-out photon with H polarization. Thus, equivalently, the atom-photon entanglement $|\Psi\rangle$ is converted to a photon-pair entanglement of

$$|\Psi\rangle_t = \frac{1}{\sqrt{2}}(|H\rangle_w|V\rangle_r + e^{-i(\phi_w+\phi_r)}|V\rangle_w|H\rangle_r), \quad (2)$$

where the subscript r denotes the read-out photon, and ϕ_r is the phase difference between two read pulses at the location of the atoms. In our experiment, both ϕ_w and ϕ_r drifts slightly as a function of time, thus we actively stabilize the sum of ϕ_w and ϕ_r to 0 via inserting a phase-locking beam (796 nm). The ring cavity is engineered to be resonant both for the write-out photon and the read-out photon. The cavity is actively stabilized by inserting the cavity-locking beam (796 nm) in the read-out mode. To minimize the influence on the quantum memory, we merely stabilize the write-read interferometer and the ring cavity during the atom loading phase. Birefringence of optical elements in the ring cavity is compensated with several low-loss wave plates [27]. Detector signals are registered with a time-to-digital converter (TDC). We count number of single-channel events and coincidences, from which we can calculate retrieval efficiency, polarization correlations, etc.

We note that in the case of free space [28,53] the above scheme of dual control modes is imperfect since the two atomic states $|\uparrow\rangle_a$ and $|\downarrow\rangle_a$ can be retrieved by either one of the two read modes, thus leading to a reduced retrieval efficiency by one-half. In our setup, the ring cavity enhances retrieval into the cavity mode, and retrieval into other directions will be suppressed. Thus ideally the collective excitation $|\uparrow\rangle_a$ will only be retrieved by the top left mode, and $|\downarrow\rangle_a$ will only be retrieved by the bottom left mode.

Therefore we first measure the retrieval efficiencies and compare the cases with one or two control modes, by varying the lattice trap power. We get the retrieval efficiencies via measuring the detection probabilities of a read-out photon conditioned on the detection of a write-out photon and applying loss calibration. The comparison of intrinsic retrieval efficiencies [27,31] measured with dual control modes or a single control mode is shown in Fig. 2(a). By increasing the trap power, we capture more atoms from the magneto-optical trap and prepare an atomic ensemble with a larger optical depth. Therefore, we see the retrieval efficiency increases as a function of trap power. To explicitly compare the two cases, we also plot the double-mode efficiency as a function of single-mode efficiency, shown in Fig. 2(b). It is clear to see that, for smaller lattice trap power, the ratio of double-mode efficiency over single-mode efficiency is around 0.5. While for larger trap power, the ratio starts to rise significantly above 0.5, which is a clear signature of benefit from cavity enhancement. Extended discussions on the relation between single-mode and double-mode efficiencies are given in the Supplemental Material [49].

To achieve long-lived storage, it is crucial to minimize the part of free moving atoms [31]. In our experiment, this is achieved via dynamical loading of the optical lattice.

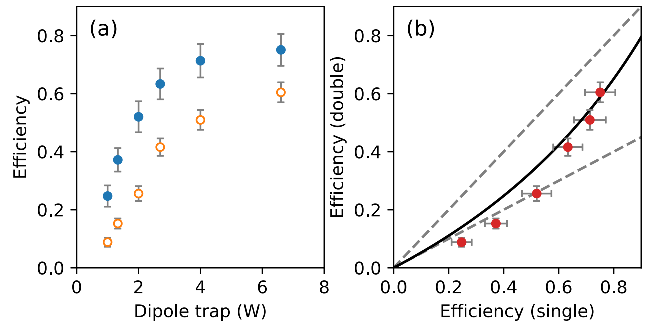

FIG. 2. Comparison of one and two control mode retrieval efficiencies. (a) Intrinsic retrieval efficiencies at different lattice trap powers. Blue circles indicate memory efficiencies with a single control mode, and orange open circles indicate memory efficiencies with double control modes. (b) Double-mode efficiencies plotted as a function of single-mode efficiencies. Slopes of two dashed lines are 0.5 and 1, respectively. A solid curve in black refers to the theoretical model, which is discussed in detail in the Supplemental Material [49].

In particular, when the unconfined atoms fall off the optical lattice region, we gradually increase the trap potential within 60 ms to reduce atoms which are not totally confined within single lattice sites. The trapping potential is increased from 70 to 90 μK. Besides, it is also very important to eliminate leakage of the control beams. We find that extinction ratio of ordinary acousto-optic modulators is not high enough. Therefore, we use mechanical shutters to block all of the laser beams excluding the lattice beams during storage. Moreover, for seconds regime storage, when we apply the read pulse, the cavity resonant point and write-read interferometer locking point may both drift away. To solve this problem, for storage time larger than 100 ms, we turn on the locking beams for 3 ms a few milliseconds before the read pulse to pull the cavity back to resonance and the interferometer to the right phase. Finally, we also optimize the magnetic field gradient and magnitude very carefully. We note that during lifetime optimization, we make use of classical electromagnetically induced transparency (EIT) storage instead, which saves us quite a lot of time.

Next we measure the temporal dependence of retrieval efficiency, with the result shown in Fig. 3(a). We use a double-exponential decay function $\eta(t) = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)$ to fit the results. For the case of single control mode, we get an initial retrieval efficiency of 0.77(4), and 1/e lifetime of 407(42) ms. For the case of dual control modes, we get an initial retrieval efficiency of 0.58(2), $1/e$ lifetime of 458(35) ms. In comparison with previous single-photon storage experiments [37,40] involving dual modes and a huge optical depth, the lifetime achieved is more than 4 orders of magnitude longer, albeit the memory efficiency is slightly lower. We attribute the limited lifetime to two reasons. One is the atomic loss from the optical lattice during storage. The other is imperfect magnetic

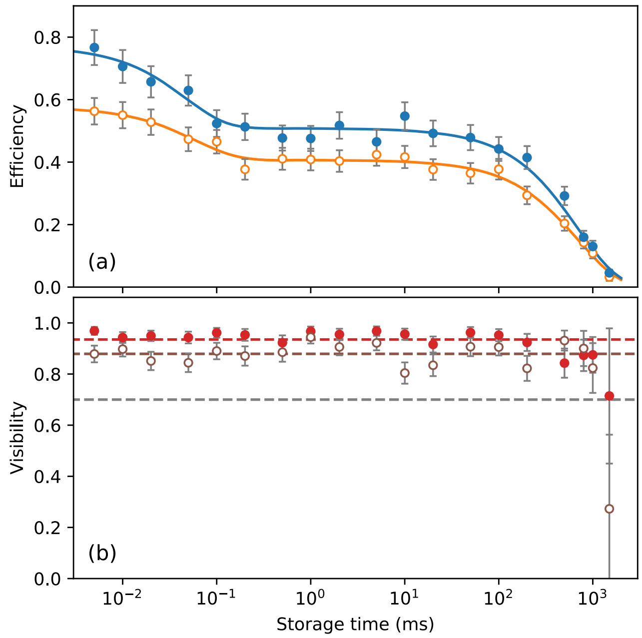

FIG. 3. Intrinsic retrieval efficiencies and entanglement visibilities versus storage time. (a) Blue circles represent efficiencies of a single-mode quantum memory at different storage time. We fit the data with the function $\eta(t) = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)$, resulting in $A_1 = 0.26 \pm 0.04$, $A_2 = 0.51 \pm 0.01$, $\tau_1 = 0.047 \pm 0.018$ ms, $\tau_2 = 697 \pm 32$ ms. Orange circles represent efficiencies of the dual-mode storage. With the same fit function, we get the result of $A_1 = 0.17 \pm 0.02$, $A_2 = 0.41 \pm 0.01$, $\tau_1 = 0.060 \pm 0.021$ ms, $\tau_2 = 703 \pm 31$ ms. (b) Red solid circles show the H/V (horizontal/vertical) visibilities of the entanglement and brown open circles show the D/A (diagonal/antidiagonal) visibilities. Red and brown dashed lines are the average values within 1 s. The gray dashed line is the threshold of 0.707 to violate the Bell inequality.

compensation of the differential light shifts. Since the angles among the lattice beams are not zero, therefore the degree of circular polarization A ($A = \pm 1$ for pure $\sigma^{\pm}$ light) [54] of the lattices after interference is not constant for the whole atomic ensemble. Another reason that may cause imperfect magnetic compensation is the hyperpolarizability [55].

After that, we test correlations of our atom-photon entanglement and its temporal dependence. Measurement is performed via measuring the polarization correlations between the write-out photon and the read-out photon both in the eigenbasis $|H\rangle/|V\rangle$ and in the superpositional basis $|D\rangle/|A\rangle$, where $|D\rangle = 1/\sqrt{2}(|H\rangle + |V\rangle)$ and $|A\rangle = 1/\sqrt{2}(|H\rangle - |V\rangle)$. The visibility V is defined as

$$V_{ab} = \left| \frac{n_{ab} + n_{ba} - n_{aa} - n_{bb}}{n_{ab} + n_{ba} + n_{aa} + n_{bb}} \right|, \tag{3}$$

where n_{ab} is the number of coincidences measured for a write-out photon in polarization $|a\rangle$ and a read-out photon in polarization $|b\rangle$. The temporal dependence for V_{HV} and V_{DA} is shown in Fig. 3(b). We find that V_{HV} and V_{DA} nearly stay as constant values for $t \lesssim 1$ s. For $t > 1$ s, the visibilities start to drop significantly due to the reduction of signal-to-noise ratio. We also note that V_{DA} is slightly smaller than V_{HV}, which is due to imperfect phase control of the interferometer. By selecting the points $t \lesssim 1$ s, we get an average value of 0.935 for V_{HV} and 0.879 for V_{DA}, which together enable us to estimate an entanglement fidelity as $F \simeq (1 + \bar{V}_{HV} + 2\bar{V}_{DA})/4 = 0.923$ [56].

TABLE I. Measurement of Bell inequality.

t	5 μs	200 ms	500 ms	1 s
S value	2.64(9)	2.59(11)	2.41(12)	2.36(14)

Finally, we verify the atom-photon entanglement directly via testing the Bell inequality [57,58]. We measure the S parameter for several different storage durations, with results shown in Table I. It is clear that all the S values measured are above the threshold of $S > 2$ to justify entanglement. Most notably, after storage of 1 s, we still get an S value of 2.36 ± 0.14, which violates Bell's inequality by 2.57 standard deviations. To the best of our knowledge, this is a Bell test with the longest storage duration. The delay is already enough to perform a Bell test with random basis selection by the free will of human beings.

In summary, we have realized a source of atom-photon entanglement with cavity enhancement and 3D-lattice confinement. We harness the momentum vector degree for a collective atomic excitation and the polarization degree for a single photon that is very robust for long-distance transmission in optical fibers. Together with quantum frequency conversion from near-infrared to telecom, our entanglement will become a building block to construct heralded entanglement between two remote quantum nodes [59]. The achieved long-lived storage and efficient retrieval will enable scalable extension to multiple nodes and longer distance via photonic entanglement swapping [10].

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