Experimental demonstration of a BDCZ quantum repeater node

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Quantum communication is a method that offers efficient and secure ways for the exchange of information in a network. Large-scale quantum communication (of the order of 100 km) has been achieved; however, serious problems occur beyond this distance scale, mainly due to inevitable photon loss in the transmission channel. Quantum communication eventually fails when the probability of a dark count in the photon detectors becomes comparable to the probability that a photon is correctly detected. To overcome this problem, Briegel, Dür, Cirac and Zoller (BDCZ) introduced the concept of quantum repeaters, combining entanglement swapping and quantum memory to efficiently extend the achievable distances. Although entanglement swapping has been experimentally demonstrated, the implementation of BDCZ quantum repeaters has proved challenging owing to the difficulty of integrating a quantum memory. Here we realize entanglement swapping with storage and retrieval of light, a building block of the BDCZ quantum repeater. We follow a scheme that incorporates the strategy of BDCZ with atomic quantum memories. Two atomic ensembles, each originally entangled with a single emitted photon, are projected into an entangled state by performing a joint Bell state measurement on the two single photons after they have passed through a 300-m fibre-based communication channel. The entanglement is stored in the atomic ensembles and later verified by converting the atomic excitations into photons. Our method is intrinsically phase insensitive and establishes the essential element needed to realize quantum repeaters with stationary atomic qubits as quantum memories and flying photonic qubits as quantum messengers.

Although the BDCZ protocol attracted much interest as a solution to extend the communication length, the absence of quantum memory has hindered the implementation of quantum repeaters. In 2001, Duan, Lukin, Cirac and Zoller (DLCZ) proposed an alternative quantum repeater scheme where linear optics and atomic ensembles are used to incorporate entanglement connection and quantum memory into a single unit. Motivated by the DLCZ protocol, number-state entanglement between two atomic ensembles has been observed. Most recently, a functional quantum node based on asynchronous preparation of number-state entanglement for two pairs of atomic ensembles – the basic element of the DLCZ protocol – has also been demonstrated.

However, two serious drawbacks make the DLCZ-type functional quantum nodes unlikely to be a realistic solution for long-distance quantum communication. First, the required long-term sub-wavelength stability of the path difference between two arms of a large scale single-photon interferometer spanning the whole communication channel is very difficult to achieve, even with the latest and most sophisticated technology for coherent optical phase transfer. Second, the swapping of number-state entanglement using a single-photon interferometer leads to the growth of a vacuum component in the generated state, and to the rapid growth of errors due to multiple emissions from individual ensembles.

A novel solution is to combine the atomic quantum memory in DLCZ and the strategy of BDCZ. Since in this scheme two-photon interference is used to generate long-distance entanglement, the stability requirement for the path differences is determined by the coherence length of the photons and is consequently 7 orders of magnitude looser than in the DLCZ protocol. Moreover, the vacuum component can be suppressed and is no longer a dominant term after a few entanglement connections. Following this scheme, we demonstrated the implementation of a quantum repeater node, involving entanglement swapping with the function of storage and retrieval of light. A high precision of local operations has been achieved that surpasses the theoretical threshold required for the realization of robust quantum repeaters for long-distance quantum communication.

In our experiment, to demonstrate entanglement swapping with storage and retrieval of light, we follow three steps: implementing two atom-photon entanglement sources, sending the flying qubits (the photons) to an intermediate station for a BSM, and verifying the entanglement between the stationary qubits. In our experiment, to demonstrate entanglement swapping with storage and retrieval of light, we follow three steps: implementing two atom-photon entanglement sources, sending the flying qubits (the photons) to an intermediate station for a BSM, and verifying the entanglement between the stationary qubits. In our experiment, to demonstrate entanglement swapping with storage and retrieval of light, we follow three steps: implementing two atom-photon entanglement sources, sending the flying qubits (the photons) to an intermediate station for a BSM, and verifying the entanglement between the stationary qubits.

Unlike previous atom-photon entanglement sources realized with trapped ions, single atoms in a cavity, or two spatially separated atomic ensembles, we use
two collective excitations in different spatial modes of a single atomic ensemble to implement the atom-photon entanglement [21]. In contrast to the method in which two separated spatial regions in one atomic cloud are covered by their own read and write beams [14], here the two excitation modes share the same write and read beams, which offers high-quality entanglement and long-term stability.

The basic principle is shown in Fig. 1 (see Methods). Alice and Bob each have a cold atomic ensemble consisting of about $10^8$ $^{87}$Rb loaded by magneto-optical traps (MOTs). At each site atoms are first prepared in the initial state $|a⟩$, followed by a weak write pulse. Two anti-Stokes fields $A_{SL}$ and $A_{SR}$ induced by the write beam via spontaneous Raman scattering are collected at $\pm 3^\circ$ relative to the propagating direction of the write beam. This defines two spatial modes of excitation in the atomic ensembles ($L$ and $R$), which constitute our memory qubit.

The two anti-Stokes fields in modes $L$ and $R$ are adjusted to have equal excitation probability and orthogonal polarizations. The two fields are then overlapped at a polarizing beam splitter PBS2 and coupled into a single-mode fiber. Neglecting the vacuum state and higher order excitations, the entangled state between the atomic and photonic qubits can be described effectively as,

$$|\Psi⟩_{at-ph} = \frac{1}{\sqrt{2}} (|H⟩|R⟩ + e^{i\phi_1}|V⟩|L⟩)$$

where $|H⟩/|V⟩$ denotes horizontal/vertical polarization of the single anti-Stokes photon and $|L⟩/|R⟩$ denotes single collective excitation in ensemble $L/R$, $\phi_1$ is the propagating phase difference between the two anti-Stokes fields before they overlap at PBS2. Physically, the atom-photon entangled state (1) is equivalent to the maximally polarization-entangled state generated by spontaneous parametric down-conversion [22].

In this way, one can implement two separate and remote atom-photon entanglement sources at Alice (I) and Bob’s (II) sites respectively. To make the higher order excitations negligible, a low excitation probability ($\chi_m \sim 0.01$) is chosen. Due to the imperfect coupling of light modes, the transmission loss, and the inefficiency of single photon detectors, the overall detection efficiency of an emerging anti-Stokes photon ($\eta_{AS}$) is around 25%. To check the quality of atom-photon entanglement, a read
pulse (see Methods) is applied after a controllable time-delay $\delta t_s$ to convert the atomic collective excitation back into a Stokes field. Ideally, the retrieve efficiency of the Stokes fields should reach unity. However, various imperfections such as low optical depth of the atomic ensembles and mode mismatching between the write and read pulses lead to a 35% retrieve efficiency. Together with the non-ideal collection and detection efficiency ($\sim40\%$) of single photon detectors, the overall detection efficiency of the Stokes photon is around 15%. After combining the two retrieved Stokes fields on PBS1 (see Fig. 1), the anti-Stokes and Stokes fields are in the following maximally polarization-entangled state

$$|\Psi_{AS,S}\rangle = \frac{1}{\sqrt{2}} \left( |H\rangle_{AS} |H\rangle_S + e^{i(\phi_1+\phi_2)} |V\rangle_{AS} |V\rangle_S \right),$$

where $\phi_2$ represents the propagating phase difference between two Stokes fields before they overlap at PBS1. In our experiment, the total phase $\phi_1 + \phi_2$ is actively stabilized via the built-in Mach-Zehnder interferometer and fixed to zero (see the online supplementary information).

With a time-delay $\delta t_s = 1\ \mu s$, the measured polarization correlations of the Stokes and anti-Stokes photons show a strong violation of a CHSH-type Bell’s inequality, with a visibility of 92%, confirming the high quality of our atom-photon entanglement sources. Further measurement shows our atom-photon entanglement still survives up to a storage time of $\delta t_s = 20\ \mu s$ (see the online supplementary information).

We now describe the entanglement generation between atomic ensembles I and II via entanglement swapping. As shown in Fig. 1, photon 2 from Alice and photon 3 from Bob are both sent through a 3 m optical fiber to an intermediate station for a joint BSM. In the experiment, we chose to analyze the projection onto the Bell state $|\Phi^{+}\rangle_{2,3} = \frac{1}{\sqrt{2}}(|H\rangle_2 |H\rangle_3 + |V\rangle_2 |V\rangle_3)$, which is achieved by overlapping photons 2 and 3 onto a polarizing beam splitter (PBSm) and performing a proper polarization decomposition in the output modes and a subsequent coincidence detection. Conditioned on detecting a $|\Phi^{+}\rangle_{2,3}$ state at the intermediate station, the two remote atomic ensembles is projected onto an identical entangled state $|\phi^{+}\rangle_{1,II} = \frac{1}{\sqrt{2}}(|R\rangle_1 |R\rangle_{II} + |L\rangle_1 |L\rangle_{II})$. It is worth to note that double excitations in either atomic ensemble I or II will cause false events in the BSM, which reduce the success probability of entanglement swapping by a factor of 2. Experimentally, the false events can be eliminated at the stage of entanglement verification by the four-fold coincidence measurement of photons 1, 2, 3 and 4. Note that, the detection time of photons 1 and 4 is later than that of photons 2 and 3 by an interval $\delta t_s$, the storage time in quantum memories. More importantly, such false events do not affect the applications of our experimental method in quantum repeaters, since the generation of entanglement will be deterministic after a second step of connecting two such nodes, where double excitations are excluded automatically.

The established entanglement between atomic ensembles I and II can be verified by converting the atomic spins into an entangled photon pair 1 and 4, which are in the state $|\Phi^{+}\rangle_{1,4}$. Here we measure the $S$ parameter in a CHSH-type Bell’s inequality,

$$S = |E(\theta_1, \theta_4) - E(\theta_1, \theta'_4) - E(\theta'_1, \theta_4) + E(\theta'_1, \theta'_4)|,$$

where $E(\theta_1, \theta_4)$ is the correlation function and $\theta_1$ and $\theta'_1$ (and $\theta_4$ and $\theta'_4$) are the measured polarization bases of photon 1 (4). In the measurement, the polarization settings

![Graph](image-url)

**Fig. 2:** Correlation functions of a CHSH-type Bell’s inequality with the storage time $\delta t_s = 500\ \text{ns}$. Error bars represent statistical errors, which are $\pm 1$ standard deviation.

![Graph](image-url)

**Fig. 3:** Visibility as a function of the storage time with 6 m fiber connection. Black dots are for the visibility and the dashed line shows the threshold for the violation of the CHSH-type Bell’s inequality. Error bars represent statistical errors, which are $\pm 1$ standard deviation.
remote memory qubits, we measure the interference via the violation of Bell’s inequality by 3 standard deviations. Transition functions (shown in Fig. 2) result in higher than the threshold 1/2. Up to a storage time of 4.5 ns, the measured correlation functions shown in Fig. 3, with |φ⟩\rangle⟨|φ⟩⟩, (0°, 22.5°), (45°, 22.5°) and (45°, -22.5°), respectively.

At a storage time δt = 500 ns, the measured correlation functions (shown in Fig. 2) result in S = 2.26 ± 0.07, which violates Bell’s inequality by 3 standard deviations. To observe the lifetime of the entanglement between two remote memory qubits, we measure the interference visibility of photons 1 and 4 as a function of the storage time by choosing the polarization basis of +/− (shown in Fig. 3 with |+⟩ = 1/√2(|H⟩ + |V⟩) and |−⟩ = 1/√2(|H⟩ − |V⟩) ). Up to a storage time of 4.5 μs, the visibility is still higher than the threshold 1/√2, sufficient for the violation of Bell’s inequality. From the visibilities of the atom-photon and atom-atom entanglements, the precision of local operations at the BSM station is estimated to be better than 97% (see the online supplementary information). We emphasize that this precision achieved here surpasses the threshold of 95% for local operations of independent photons necessary for future entanglement purification and connections [6], and therefore fits the requirement for a scalable quantum network.

To demonstrate the robustness of our protocol in generation of quantum entanglement between two atomic ensembles over large distances, we change the length of the two connecting fibers from 3 m to 150 m. The anti-Stokes photon is delayed 730 ns and the connection length between Alice and Bob is 300 m. The entanglement swapping can be quantified by the fidelity of the measured state of the atomic ensembles. To determine the fidelity, we write the density matrix of |φ⟩\rangle⟨|φ⟩⟩ in terms of the Pauli matrices:

Here σx = |+⟩⟨+|−|−⟩−|−⟩⟨−|−⟩, σy = |⟩⟩⟨|−⟩−|−⟩⟨⟩⟩, and σz = |⟩⟩⟨|⟩−|⟩−⟩⟨⟩⟩, with |⟩⟩⟨|⟩ = (1/√2) (|H⟩ + i|V⟩) and |⟩⟩⟨|⟩ = (1/√2) (|H⟩ − i|V⟩) . After a storage time of 1230 ns (with a 730 ns delay being taken into account), the two retrieved photons 1 and 4 are sent to their own polarization analyzer. Three series of polarization settings are used and the measured local observables are shown in Fig. 4. The fidelity of final state ρ_exp on |φ⟩\rangle⟨|φ⟩⟩ is given by F = Tr(ρ_exp|φ⟩\rangle⟨|φ⟩⟩) = 0.83 ± 0.02, with 2.5 standard deviations beyond the threshold of 0.78 to violate the CHSH-type Bell’s inequality for Werner states, demonstrating the success of entanglement swapping. This fidelity is comparable to the average value achieved in the DLCZ-type functional quantum node [14].

In summary, we have successfully demonstrated high precision entanglement swapping with storage and retrieval of light, a building block for quantum repeaters. The extension of our work to longer chains will involve many quantum repeater nodes. To achieve this ambitious goal, several quantities—such as the lifetime and retrieve efficiency of the quantum memory, the fidelity and generation rate of the entanglement state—still need to be improved significantly. We suggest three ways forward. First, better compensation of the residual magnetic field and trapping the atoms in “clock states” [24] should improve the lifetime to ~1 s. Second, a high optical density of the atomic cloud, achieved by the help of traps or by coupling the atoms into an optical cavity [26], should increase the retrieve efficiency close to unity. These improvements of the quantum memory would greatly enhance the fidelity and generation rate of the entanglement. Last, by local generation of entangled pairs of atomic excitations together with the present technique of entanglement swapping, the entanglement distribution rate can be greatly improved [27]. Not only does our work enable immediate experimental investigations of various quantum information protocols, but—with the abovementioned future improvements— entanglement swapping with storage and retrieval of light would also open the way to long-distance quantum communication.

Methods

As shown in Fig. 1, Alice and Bob each have a cold atomic ensemble consisting of about 10^8 atoms of 87Rb with temperature ~100 μK. After 20 ns of loading atoms into their MOTs separated by ~60 cm, we switch off the laser beams and magnetic fields of the MOTs and start a 5-ms-long experiment cycle. At each site, atoms are first prepared in the initial |a⟩, followed by a (50 ns long, ~1 μs) weak write pulse, which has a beam waist of 240 μm and is 10 MHz red-detuned from the |a⟩ → |c⟩ transition. Two anti-Stokes fields AS_L and AS_R induced by the write beam via spontaneous Raman scattering are
collected at ±3° relative to the propagating direction of the write beam (70 μm waist, |e⟩ → |b⟩). The excitation probability (χ_m) of the collective modes m (m = L, R) is low (χ_m ≪ 1); thus the state of the atom-photon field can be expressed as [11]

|Ψ⟩_m = |0_A S 0_b⟩_m + √χ_m |1_A S 1_b⟩_m + O(χ_m),  \hspace{1cm} (5)

and |i_A S b⟩_m denote the i-fold excitation of the anti-Stokes field and the collective spin in the atomic ensemble. The read beam is counter-propagating and mode-matched with the write beam with a pulse length of 50 ns, a power of 60 μW and a frequency close to resonance of the |b⟩ → |e⟩ transition.

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