A Robust Atom-Photon Entanglement Source for Quantum Repeaters

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(Dated: February 8, 2022)

We demonstrate a novel way to efficiently and very robust create an entanglement between an atomic and a photonic qubit. A single laser beam is used to excite one atomic ensemble and two different spatial modes of scattered Raman fields are collected to generate the atom-photon entanglement. With the help of build-in quantum memory, the entanglement still exists after 20.5 \(\mu\)s storage time which is further proved by the violation of CHSH type Bell’s inequality. Our entanglement procedure is the building block for a novel robust quantum repeater architecture [Zhao et al, Phys. Rev. Lett. 98, 240502 (2007)]. Our approach can be easily extended to generate high dimensional atom-photon entanglements.

PACS numbers: 03.67.Hk, 32.80.Pj, 42.50.Dv

Quantum communication provides an absolutely secure approach to transfer information by means of quantum cryptography or faithful teleportation of unknown quantum states. Unfortunately, the photon transmission loss and the decoherence scale exponentially with the length of the communication channel. This makes it extremely hard to deliver quantum information over long distance effectively. A quantum repeater protocol\textsuperscript{[3]} combining the entanglement swapping, purification and quantum memory provides a remarkable way to establish high-quality long-distance quantum networks, and makes the communicating resources increase only polynomially with transmission distance.

Following a scheme proposed by Duan, Lukin, Cirac, and Zoller (DLCZ[2], in recent years, significant experimental advances have been achieved towards the implementation of the quantum repeater protocol by using the atomic ensemble and linear optics[3-9]. However, the DLCZ protocol has an inherent drawback which is severe enough to make a long distance quantum communication extremely difficult\textsuperscript{[10,11]}. The phase fluctuation caused by path length instability over long distance is very hard to overcome. Recently, a more robust quantum repeater architecture was proposed to bypass the phase fluctuation over long distance\textsuperscript{[10,11]}. This architecture is based on the two-photon Hong-Ou-Mandel-type interference which is insensitive to the relative phase between two photons. Several experiments have proven that the path length fluctuations only need to be kept on the scale of the photon’s coherent length, from hundreds of micrometer\textsuperscript{[12]} to tens of meters\textsuperscript{[13,14,15]}. In our original protocol\textsuperscript{[10,11]}, two laser beams with fixed relative phase are needed to excite two atomic ensembles in order to generate the atom-photon entanglement for the local communication node. Only the path length between two ensembles in the local node need to be stabilized to sub-wavelength scale. Some recent works close to the requirements of our protocol have provided the techniques to generate atom-photon entanglement with spin excitation of magnetic sublevels\textsuperscript{[16,17]} or dual-species atomic ensemble to prevent for the propagating phase difference\textsuperscript{[18]}. But for each of these there remain problems like balancing the excitation between the ensembles or the complexity and efficiency of frequency mixing, which make it hard to implement the full protocol over long distance.

In this Letter, we present a new approach to effectively generate the entanglement between the atomic qubit and photonic qubit based on atomic ensemble in a local magneto-optical trap (MOT). This atom-photon entanglement can serve as a segment of the improved protocol\textsuperscript{[10]}. Contrast to the previous experiments\textsuperscript{[3,5,16,17,18]}, only one atomic ensemble is used to be excited by only one write beam with single frequency. Two spontaneous Raman scattered fields (anti-Stokes fields) in different spatial modes are combined on a polarizing beam splitter and serve as the photonic qubit. The collective spin excitations in the atomic ensemble corresponding to the two anti-Stokes fields represent the atomic qubit. This new scheme makes the local phase stabilization simple. With a single write beam excitation, only the phase difference between the two selected modes is relevant and can easily be stabilized by the local build-in Mach-Zehnder interferometer\textsuperscript{[19]}. Besides, high dimensional entanglement and hyper-entangled state can be easily realized by extend the approach to select more spatial mode of the collective excitation.

The basic setup of our experiment is shown in Fig.\textsuperscript{[1]} A cold \(^{87}\text{Rb}\) atomic cloud with temperature about 100 \(\mu\)K in the MOT is used as the medium to generate and store the information of the quantum excitation. The two hyperfine ground states \(|5S_{1/2}, F=2\rangle=|a\rangle\) and \(|5S_{1/2}, F=1\rangle=|b\rangle\) and the excited state \(|5P_{1/2}, F=2\rangle=|e\rangle\) form a \(\Lambda\)-type system. After loading the MOT, the atoms are first pumped to initial state \(|a\rangle\). A single weak 75 ns write beam illuminates the atom cloud with beam waist...
defines the spatial mode of the atomic ensemble and the propagating direction of the write beam. This also
neous Raman scattering are collected at $AS_R$.

The relevant energy levels of the $^{87}$Rb atom cloud to generate the spin excitation. The spontaneous
$\chi(m)$ is the excitation probability of one collective spin in ensemble $m$ ($m = L, R$), and $\sqrt{\chi(m)}|\chi AS b_m\rangle_m$ denote the $i$-fold excitation of the anti-Stokes light field and the collective spin in atomic ensemble.

When the write beam excites the atomic ensemble and an anti-Stokes photon is generated, it also transfers the
momentum to the collective spin excitation in the atomic ensemble. To fulfill the momentum conservation, the overall $k$-vector of the collective excitation after the spontaneous Raman scattering is $\vec{k}_{\text{atom}} = \vec{k}_W - \vec{k}_{AS}$, where $\vec{k}_{AS}$ and $\vec{k}_W$ are the wave vector of the anti-Stokes field and write beam, respectively. If no other external field interrupts the atomic state, during the storage time $\tau$, the momentum of the collective excitation is kept. When the read pulse is applied on the atomic ensemble to retrieve the collective excitation back into a correlated Stokes field, the momentum of the collective excitation is transferred back to the Stokes field. The wave vector of the Stokes field becomes $\vec{k}_S = \vec{k}_R + \vec{k}_{\text{atom}}$, where $\vec{k}_R$ represents the wave vector of the read beam. Then after the retrieve process, the wave vector of the correlated Stokes field fulfill the mode-matching condition:

$$\vec{k}_S = \vec{k}_R + \vec{k}_W - \vec{k}_{AS}. \quad (2)$$

Under the counter-propagating condition of read and write beams (shown in Fig. 1), the anti-Stokes and mode-matched Stokes fields are also counter-propagating ($\vec{k}_S \approx -\vec{k}_{AS}$).

To characterize the light field, we measure the cross correlation $g^{(2)}_{AS,S}$, which marks the degree of quantum correlation, between the anti-Stokes and the Stokes fields. As two anti-Stokes fields $AS_L$ and $AS_R$ are detected at two different spatial modes, two corresponding Stokes fields $S_L$ and $S_R$ can be detected during the retrieve process. For the mode-matched fields $S_L$ and $AS_L$ ($S_R$ and $AS_R$), the cross correlation $g^{(2)}_{AS,S} \gg 1$ when $\chi \ll 1$, which means good quantum correlation between these fields. But for the unmatched fields $S_L$ and $AS_R$ ($S_R$ and $AS_L$), no quantum correlation is observed ($g^{(2)}_{AS,S} \sim 1$), which means there’s no cross talk between these two different modes. The viability of our new approach is guaranteed by this condition.

For the further part of our experiments, we adjust the two modes $L$ and $R$ to be equal ($\chi_L = \chi_R = \chi$), select orthogonal polarization of the two anti-Stokes fields, combine them on a beam polarizing beam splitter PBS1 and send into a polarization analyzer, as illustrated in Fig. 1. Neglecting the vacuum state and high order excitations, the entangled states between the photonic and atomic qubit can be described as:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle |L\rangle + e^{i\phi_1}|V\rangle |R\rangle) \quad (3)$$

where $|H\rangle/|V\rangle$ denotes horizontal/vertical polarizations of the single anti-Stokes photon and $|L\rangle/|R\rangle$ denotes single collective spin excitation in ensemble $L/R$. $\phi_1$ is the propagating phase difference between the two anti-Stokes fields before they overlap at PBS1. Physically, the atom-photon entangled state is equivalent to the maximally polarization entangled state generated by spontaneous parametric down-conversion.
Stokes fields under neglected. The visibility $\chi_{HWP}$ of cross correlation between the anti-Stokes and Stokes fields \[17\] of the coincidence rate between anti-Stokes and Stokes photons for various value of excitation back into Stokes fields. In our experiment, the total phase $\phi$ between two Stokes fields before they overlap at the PBS counter-propagating with the write beam is applied after a controllable time $\tau$ to convert the atomic collective excitation back into Stokes fields.

After combine the two Stokes fields on PBS$_2$ (see Fig. 1), the superposition state of anti-Stokes and Stokes fields is the following maximally polarization entangled state

$$\Psi_{AS,S} = \frac{1}{\sqrt{2}}|H\rangle_{AS}|V\rangle_S + e^{i(\phi_1 + \phi_2)}|V\rangle_{AS}|H\rangle_S,$$  \hspace{1cm} (4)

where $\phi_2$ represent the propagating phase difference between two Stokes fields before they overlap at the PBS$_2$. In our experiment, the total phase $\phi_1 + \phi_2$ is actively stabilized via the build in Mach-Zehnder interferometer and fixed to zero $[19]$. To investigate the scaling of entanglement with the excitation probability $\chi$, we measure the visibility $V$ of the interference fringes of the coincidence rate between anti-Stokes and Stokes photons for various value of $\chi$ with fixed memory time $\tau = 500$ ns. The half waveplate HWP$_1$ (see Fig. 1) is set to $+22.5^\circ$ to measure the anti-Stokes fields under $|H\rangle + |V\rangle$ base and rotate HWP$_2$ to measure the Stokes fields under different bases. As $\chi$ increases, the high order term in Eqn. (4) can not be neglected. The visibility $V$ can be expressed as the function of cross correlation between the anti-Stokes and Stokes fields $[17]$

$$V = \frac{g_{AS,S}^{(2)} - 1}{g_{AS,S}^{(2)} + 1}.$$  \hspace{1cm} (5)

Ideally, the relationship of the excitation rate $\chi$ and cross correlation $g_{AS,S}^{(2)}$ is $g_{AS,S}^{(2)} = 1 + 1/\chi$. Considering the total detected efficiency of the anti-Stokes field $\eta_{AS}$, we have the detection rate of the anti-Stokes photon $p_{AS} = \eta_{AS}\chi$, where $\eta_{AS}$ is the detect efficiency of the anti-Stokes channel. At the small excitation rate limit ($\chi \ll 1$), the visibility can be expressed as

$$V = 1 - 2p_{AS}/\eta_{AS}.$$  \hspace{1cm} (6)

In our experiment, $\eta_{AS} \sim 8\%$. Figure 2 shows the measured visibility $V$ varying with $p_{AS}$. As the intensity of the write beam is tuned to make the excitation rate $\chi$ decrease, which corresponds to decrease of $p_{AS}$, the visibility $V$ increases as does the degree of entanglement. The solid line is the linear fit for the experiment data. At $p_{AS} \rightarrow 0$, $V$ is near 0.95. This imperfection is mainly caused by the overlap of the two anti-Stokes fields $AS_L$ and $AS_R$, the noise of the detector and the phase fluctuation in the interferometer. As the detection rate $p_{AS}$ increases, the probability of high order excitations increases faster than that of the single excitation. Then the correlation $g_{AS}^{(2)}$ decreases, as well as the visibility. At $p_{AS} < 1.3 \times 10^{-2}$, $V$ is larger than $1/\sqrt{2}$ which marks the bound of violation of the Clauser-Horne-Shimony-Holt (CHSH) type Bell’s inequality $[17,21]$. To further study the storage ability of the atomic ensemble quantum memory, we characterize the temporal decay of entanglement with storage time $\tau$. Here we measure the decay of the $S$ parameter, sum of the correlation function in CHSH type Bell’s inequality, where $S \leq 2$ for any local realistic theory with

$$S = |E(\theta_1, \theta_2) - E(\theta_1', \theta_2') - E(\theta_1', \theta_2) - E(\theta_1, \theta_2')|.$$  \hspace{1cm} (7)

Here $E(\theta_1, \theta_2)$ is the correlation function, where $\theta_1$ and $\theta_2$ (and $\theta_1'$ and $\theta_2'$) are the measured polarization bases of

\begin{figure}[h]
\begin{center}
\includegraphics[width=0.5\textwidth]{figure2.png}
\end{center}
\caption{Visibility of the interference fringes $V$ between Anti-Stokes fields and Stokes fields various with the changing of the detected rate of anti-Stokes field $p_{AS}$. The solid line is the fit corresponding to Eq (4). The dashed line shows the bound of $1/\sqrt{2}$ which mark the limit to violate the CHSH-type Bell’s inequality.}
\end{figure}

\begin{figure}[h]
\begin{center}
\includegraphics[width=0.5\textwidth]{figure3.png}
\end{center}
\caption{Decay of the $S$ parameter in the Bell’s inequality measurement with the storage time $\tau$. The dashed line shows the classical bound of $S = 2$.}
\end{figure}
the anti-Stokes field and Stokes field. During the measurement, the HWP$_1$ and HWP$_2$ are set to different angles to make the bases settings at $(0^\circ, 22.5^\circ)$, $(0^\circ, -22.5^\circ)$, $(45^\circ, 22.5^\circ)$ and $(45^\circ, -22.5^\circ)$, respectively. The excitation rate $\chi$ was fixed to get $p_{AS} = 2 \times 10^{-3}$, and the result of measurement is shown in Fig. 3. At the storage time of 500 ns, $S = 2.60 \pm 0.03$, which violates Bell’s inequality by 20 standard deviations. As the storage time increases, the $S$ parameter decreases, indicating the decoherence of the entanglement. At storage time $\tau = 20.5 \mu$s, we still get $S = 2.17 \pm 0.07$, which means the character of quantum entanglement is still well preserved. The decay of $S$ parameter with increasing storage time $\tau$ is caused by the residual magnetic field which inhomogeneously broadens the ground state magnetic sublevels. This process can be observed from the decay of the retrieve efficiency and the cross correlation between anti-Stokes and Stokes fields.

Shown in Fig. 4 the retrieve efficiency and the cross correlation between anti-Stokes and Stokes field all decreases with increasing the storage time $\tau$. At $\tau = 500$ ns, the overall retrieve efficiency (including the transmission loss and the detector efficiency) is $12.2 \pm 0.4\%$ and the cross correlation $g_{AS,S}^{(2)} = 38 \pm 1$. At $\tau = 20.5$ $\mu$s, the retrieve efficiency and cross correlation decrease to $2.2 \pm 0.1\%$ and $g_{AS,S}^{(2)} = 9.8 \pm 0.7$, respectively. These values are still sufficient to violate the CHSH-type Bell’s inequality. When $\tau$ is longer than 24$\mu$s, $g_{AS,S}^{(2)} < 6$ makes it insufficient to violate the Bell’s inequality.

In conclusion, we have generated a robust atom-photon entanglement with a novel approach. A single write beam and a single atomic ensemble are used to generate the collective spin excitations. Two spatial modes of collective excitations are defined by the collection modes of anti-Stokes fields. The conservation of momentum during the atom-photon interaction prevent for the cross talk between different excited spatial modes. The visibility of the entanglement and violation of the CHSH type Bell’s inequality are measured to prove the atom-photon entanglement between anti-Stokes photon and collective excitation in atomic ensemble. Also with the help of the build-in quantum memory, the violation of the Bell’s inequality still exists after 20.5 $\mu$s, corresponding to the time of light propagating 4 km in an optical fiber. That means we have successfully achieved a memory build-in atom-photon entanglement source which can work as a node of the long-distance quantum communication networks. Further more, if the atomic ensemble is confined in the optical trap and ”clock states” is implemented, the memory time could be extended to longer than 1 ms. Moreover, if more anti-Stokes modes are selected at different angles corresponding to the write beam, this approach can be easily extended to generate high order entanglement, which could be very useful in the complex quantum cryptography and quantum computation.

This work was supported by the Deutsche Forschungsgemeinschaft (DFG), the Alexander von Humboldt Foundation, the Marie Curie Excellence Grant of the EU, the Deutsche Telekom Stiftung and the CAS.

![Graph](image)

**FIG. 4:** The decay of retrieve efficiency and cross correlation $g_{AS}^{(2)}$ with the storage time $\tau$. The anti-Stokes detection rate is fixed at $p_{AS} = 2 \times 10^{-3}$. The square dots show the decay process of the retrieve efficiency of the Stokes fields, round dots show the decay of the cross correlation $g_{AS,S}^{(2)}$ between anti-Stokes field and Stokes field.

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