Quantum Switching of Entangled Photons based on Rydberg Blockade Effect

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The long-range Rydberg interaction endows a medium with large optical non-linearity, thus resulting in strong photon-photon interaction that are essential quantum circuits and networks. Our efforts aim at the ultimate mission of single quantum particles controlling an entire entangled system, which is a benchmark and long-term goal in quantum information science. In particular, we demonstrated coherent optical switching of entangled photons in the system of cold atomic gases under a Rydberg electromagnetically induced transparency configuration. With the presence of Rydberg blockade effect, the gate field makes the atoms non-transparent thereby blocking the single photon emitted from another atomic ensemble. In contrast to the trivial case without the gate field, the gate field excites \( N \sim 1 \text{–} 2 \) atoms per average blockade sphere, and hence more than 50% of the entangled photons are blocked, thereby achieving effective entanglement switching. This switching of the photonic entanglement depends on the principal quantum number and the photon number of the gate field. Our experimental progress hints at quantum information processing through the interaction between Rydberg atoms and entangled photon pairs.

In analogy to classical electronic counterparts, quantum switches are regarded as basic building blocks for quantum circuits and networks [1–3]. Switching states in the full-quantum regime where single particles control a quantum qubit or entanglement from another system may enable further applications in quantum information fields, such as in quantum computing [4], distributed quantum information processing [5] and metrology [6]. Many efforts have gone towards constructing a prototype; examples include a coupled micro-resonator with a single atom [7], trapped cold atoms in a microscopic hollow fibre [8], coupled cold atoms in a cavity operating in the strong coupling regime [9], strongly coupled quantum dots–cavity [10], and single dye molecules [11].

However, all the related experiments on switching were demonstrated with weak coherent field, thus there are no reports on switching of entangled photons. The strong interaction offered by highly excited Rydberg atoms shifts the surrounding atoms dramatically and suppresses all further excitation in the neighbour. This interaction between cold atoms gives rise to the excitation blockade [12–18], many-body entanglement [19–22], spatial correlations [23–25], strong optical non-linearities [26–32], plasma formation [33], photon-photon gate [34]. Recent works on building a single-photon transistor [35–37] exhibit the strong interaction between Rydberg atoms and entangled photons [4], such as building a Toffoli gate [38] and quantum computation [39–42] with Rydberg ensembles, and switching a distributed quantum node.

Here, we demonstrate an experiment of quantum switching entangled photonic pairs within two atomic ensembles. The entangled photons are prepared in a two-dimensional atomic cloud and inputted into another three-dimensional atomic ensemble for switching. Because the non-linearity offered by the Rydberg long-range interaction is larger, the Rydberg electromagnetically induced transparency (Rydberg-EIT) medium [26, 43] becomes opaque and single photons are absorbed and finally blocked. The measured coincidence counts with and without a gate field show an obvious switching of the entangled state. The fidelity of the entangled state is 85.3% ± 1.5% and 80.4% ± 2.3% in the absence and presence of a gate field, respectively, with a switch contrast larger than 50% thus beating the cloning limit [44], showing an effective switching operation. By increasing the principal quantum number \( n \), switching become strong and the required photon number of the gate field decreases.

The sample media are optically thick atomic ensembles of Rubidium 85 (\(^{85}\text{Rb}\)) trapped in two-dimensional (2-D) and three-dimensional (3-D) MOTs, labelled MOT 1 and MOT 2. Schematics of the energy levels, time sequence, and experimental setup are shown in figure 1(a)–(c). A 2-D \(^{85}\text{Rb}\) atomic ensemble is first prepared in MOT 1 and then cooled down to about 100 \( \mu \)K via the optical molasses technique; the atomic cloud has dimensions of \( 10 \times 2 \times 2 \) mm\(^3\). In this atomic ensemble, we prepare photon pairs by spontaneous four-wave mixing (SFWM). The energy levels involved here correspond to the double-A system. The two pump fields couple the atomic transition \( 5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 3) \) with a detuning of \(-110 \times 2\pi\) MHz and the atomic transi-
configuration corresponding to the \(^{85}\text{Rb}\) states of \(5S_{1/2}(F = 2)\) \(|\uparrow\rangle\), \(5P_{3/2}(F' = 3)\) \(|\downarrow\rangle\), \(5S_{1/2}(F = 3)\) \(|\uparrow\rangle\), and \(5P_{1/2}(F' = 3)\) \(|\downarrow\rangle\), respectively, and the pump fields of P1 and P2 and their respective signal fields S1 and S2; the other energy diagram is of the ladder-type Rydberg-EIT with ground state \(5S_{1/2}(F = 3)\) \(|\downarrow\rangle\), excited state \(5P_{3/2}(F' = 4)\) \(|\uparrow\rangle\), and highly-excited state \(\mid nD_{3/2}\rangle\) \(|\uparrow\rangle\). Labels: P-pump, S-signal. (b) Time sequence for the preparation and switching of entanglement. \(\Delta T\) represents the experimental window. (c) Schematic overview of the experimental setup, comprising two magneto-optic traps (MOT) systems, in which MOT 1 and MOT 2 are used to generate and switch the photonic entanglement, respectively. Labels: PBS-polarizing beam splitter, DM-dichroic mirror, \(\lambda/2\)-half-wave plate, \(\lambda/4\)-quarter-wave plate, IF-interference filter, D-single photon detector, BD-beam displacer, AOM-acousto-optic modulator. (d) Rydberg-EIT transmission spectra recorded with and without the gate field; both the input signal and the gate fields are weak coherent fields; the principal quantum number is \(n = 50\). The solid lines are fitted using equation 1 in Methods.

We first recorded the EIT spectra for a coherent field [marked in red in figure 1(d)]. For demonstrating photonic switching, we need a second coherent pulse acting as a gate field; this field is resonant with the atomic transition \(5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 4)\). If we add the gate field, the medium become non-transparent because of the remarkable optical nonlinearity of the excited Rydberg atoms with a \(C_{6}\) here, \(n\) type atomic configuration, consisting of a ground state \(|\downarrow\rangle\), an excited state \(|\uparrow\rangle\), and a highly-excited state \(|\uparrow\rangle\). Labels: P-pump, S-signal.

![Figure 1](image1.png)

![Figure 2](image2.png)
To demonstrate the Rydberg-EIT for single photons, a connection is required between the two physical systems under the quantum regime, including a matching procedure of frequency and bandwidth between the signal-2 photon and the absorption window of the atomic ensemble in MOT 2. This can be realized by changing the frequency and Rabi frequency $\Omega_{p2}$ of the field of pump 2, see Methods for more details. For the optimized case $\Omega_{p2} \sim 1 \times 2\pi$ MHz, the bandwidth of the signal-2 photon is at $\sim 5 \times 2\pi$ MHz, and the absorption window for the atomic ensemble in MOT 2 is $\sim 13 \times 2\pi$ MHz. Thus, the signal-2 photon falls completely within the Rydberg EIT window.

The central phenomenon behind the operation of a single-photon switch at the Rydberg platform is the strong nonlinearity. The long-range Rydberg interaction endows the medium with a large optical nonlinearity. The resulting dipole blockade effect makes the medium non-transparent in the Rydberg-EIT configuration [26]. We use this nonlinearity to demonstrate switching. Before demonstrating the switching of the entangled photons, we show switching for a single photon. The single photon used here is from signal 2 and is switched by applying a gate field. The results are shown in figure 2(a) and (b); the former shows the coincidence counts of photon pairs when the atoms in MOT 2 are absent (red) and present (blue), whereas the latter shows the results under Rydberg-EIT without (red) and with (blue) gate field. Obviously, coincidence counts decrease when the gate field is applied as the signal-2 photon is absorbed significantly compared with the no-gate situation. We define a switch contrast to characterize switching,

$$C_{\text{switch}} = \frac{CC_{\text{EIT}} - CC_{\text{gate}}}{CC_{\text{EIT}}},$$

where $CC_{\text{EIT}}$ and $CC_{\text{gate}}$ represent the coincidence counts between the signal-1 and signal-2 photons without and with gate field. From the data [figure 2(a) and (b)], we obtain a switch contrast of $C_{\text{switch}} = 77.6\% \pm 3.1\%$. The little peak in the rising edge comes from the high-frequency components of the single photons, which fall out the absorption window of the atoms, [marked in blue color in figure 2(a)]. In our experiment, the absorption window of atoms in MOT 2 is about $\sim 2\pi \times 13$ MHz. Although the wave-packet of the signal-2 photon may be turned by decreasing the field power of pump 2 [46], there is always a high-frequency component in the wave-packet of the signal-2 photon, resulting in an optical precursor of single photons [47].

In our experiment, the switch effect is obviously decreased against with the bandwidth of signal 2 photon, which is given in figure. 5(d). Due to the narrow transparency window in the spectrum of Rydberg-EIT, the optical response on two-photon resonance is strongly effected by the level shifts induced by Rydberg dipole-dipole interaction and the linewidths of the input lasers. This external field noise can be resolved by reducing the linewidths of the input fields [48], in which high-fidelity Rydberg atomic qubit is achieved by narrow linewidths lasers input. In the case of Rydberg-EIT, the bandwidth of signal 2 photon is optimized at $\sim 5 \times 2\pi$ MHz, and we can observe the obvious blockade effect in Rydberg-EIT window.

To demonstrate photonic entanglement switching, we

Figure 3. Switching with different bases: (a)–(d) are the coincidence counts without gate field (red bar) and with gate field (blue bar) under different signal-1 states of $|H\rangle$, $|V\rangle$, $|H\rangle - i|V\rangle$, and $|H\rangle + |V\rangle$. (e) and (f) are the recorded two-photon interference patterns with signal-2 states of $|H\rangle$ and $|H\rangle + |V\rangle$ without gate field (red) and with gate field (blue). Their interference visibilities are 87.0% ± 0.8% ((e), red), 82.9% ± 0.7% ((e), blue), 72.0% ± 1.1% ((f), red), and 57.1% ± 2.6% ((f), blue). The solid lines are fitted curves to the measured data. Both these coincidence counts were recorded over a 1000-s interval. Error bars are ±1 standard deviation.

atoms [31] [marked in blue in figure 1(d)].
created passive-locking interference using techniques described in Ref. [49–52]. In this configuration, two beam displacers are used to combine the signal photons with the left and right optical paths coherently. The form of the entanglement is

\[ |\psi\rangle = (|H_s⟩|V_s⟩ + e^{i\phi} |V_s⟩|H_s⟩)/\sqrt{2} \]  

with \( \phi \), the relative phase between the left and right optical paths, set to zero in our experiment; \( |H_{s1,s2}\rangle \) and \( |V_{s1,s2}\rangle \) represent the horizontal and vertical polarized states of the signal photons. To demonstrate photonic entanglement switching in principle, we only block the signal-2 photons. In this situation, we use a 50-m fibre to introduce a time delay in the path of the signal-1 photons. This guarantees the entanglement does not collapsed before switching has finished.

We changed the basis \( \phi_2 \) of the signal-2 photon and recorded the coincidence counts under different signal-1 states \( \phi_1 \) of \( |H⟩, |V⟩, |H⟩ - i|V⟩, \) and \( |H⟩ + |V⟩ \). To obtain the difference with and without the gate field, we recorded these coincidence counts under these situations [figure 3(a)–(d)]. The coincidence counts without (red)/with (blue) the gate field are obviously different. We obtain switch contrasts \( C_{SW_1}^{HV} = 81.0\% \), \( C_{SW_1}^{HV} = 64.3\% \), \( C_{SW_1}^{RR} = 52.2\% \), and \( C_{SW_1}^{DD} = 79.9\% \) under the four situations \( \phi_1 = |V⟩, \phi_2 = |H⟩; \phi_1 = |V⟩, \phi_2 = |H⟩ + i|V⟩, \phi_1 = |V⟩, \phi_2 = |H⟩ - i|V⟩, \) and \( \phi_1 = |V⟩, \phi_2 = |H⟩ + |V⟩ \). The two sets of data we obtained both exceed 50% suggesting a very promising application in which the cloning limit 50% between classical and quantum regime is required. In addition, we measured two-photon interference without and with the gate field under the signal-2 basis of \( |H⟩ \) and \( |H⟩ + |V⟩ \) [figure 3(e) and (f)]. We also have reconstructed the density matrices of the entanglement without and with the gate-field switch, and calculated the state fidelity, which are 85.3% ± 1.5% and 80.4% ± 2.3%, respectively (see Methods).

In our case, our system saturates if we further increase the photon number of the gate field. Because the gate field and the coupling field excite atoms from the ground state to Rydberg state in MOT 2 through two-photon transition, this process would deplete the atoms after a certain duration. Hence, in the experiment of switching entanglement, we set the experimental window to 25 \( \mu \)s with an average of \( \sim 1.7 \) Rydberg atoms per blockade sphere. The average number of Rydberg atoms per blockade sphere is estimated by considering the atomic density, the gate field intensity and the atomic volume covered the signal 2 field.

The nonlinearity of Rydberg atoms not only depends on the Rydberg atom number, which determines the interaction distance, but also is strongly affected by the dipole interaction strength. Thus, we change the principal quantum number \( n \) to change the interaction to measure both the Rydberg-EIT transmission contrast and switch contrast. The results (figure 4) show that the Rydberg-EIT contrast decreases with increasing \( n \); this is because the transition amplitude for \( |e⟩ \rightarrow |nD⟩ \) decreases. In contrast, because the dipole interaction strength increases, switching of the signal-2 photon is obvious from a comparison of two situations, \( n = 60 \) (\( r_b = 1.2 \mu m \)) and \( n = 40 \) (\( r_b = 5.9 \mu m \)). The switch contrast is larger than 50 when \( n > 45 \), beating the quantum cloning limit [44], revealing an effective quantum blocking operation. Although the gate field has hundreds of photons because of the relatively large size of the atomic cloud in our experiment, the average \( \sim 2.1 \) atoms per blockade sphere shows that switching the entanglement is realizable with a single gate-field photon when trapping atoms into the blockade radius and increasing the principal quantum number \( n \).

In summary, we have demonstrated the optical switching of photonic entanglement based on strong photon-photon interaction within two atomic ensembles. The emitted signal-2 photon correlated with the signal-1 photon is blocked by another gate field under the Rydberg-EIT configuration. Switching effect depends on the principal quantum number, the bandwidth of the emitted single photons, and the average photon number of the gate field. We have successfully realized optical switching of entangled photons, with more than 50% of pairs being blocked. These results on switching the photonic entanglement using the strong photon-photon interaction hold promises in constructing quantum networks between Rydberg atoms and entangled photons.
MATERIALS AND METHODS

Experimental time sequence. The repetition rate of our experiment is 200 Hz, and the MOT trapping time is 4.71 ms. Moreover, the experimental window is 290 ps. The fields of pumps 1 and 2 are controlled by two AOMs, and therefore the frequencies of signals 1 and 2 photons can be tuned. The optical depth in MOT 1 is about 20. Two lenses L1 and L2, each with a focal length of 300 mm, are used to couple the signal fields into the atomic ensemble in MOT 1. The fields of pumps 1 and 2 are collinear, and hence their respective signal fields are collinear. The vector matching condition $k_{p1} - k_{S1} = k_{p2} - k_{S2}$ is satisfied in the spontaneous four-wave mixing process, as the methods are the same as in our previous work [53]. The two signal photons are collected into their respective single-mode fibers and are detected by two single photon detectors (avalanche diode, PerkinElmer SPCM-AQR-16-FC, 60% efficiency, maximum dark count rate of 25/s). The two detectors are gated by an arbitrary function generator. The detected signals from the two detectors are then sent to a time-correlated single photon counting system (TimeHarp 260) to measure their time-correlated function.

Frequency matching between signal 2 and atoms in MOT 2. Connecting two different physical systems requires matching the frequency windows. For this point, the emitted signal-2 photon from MOT 1 may not be matched with the working window of Rydberg EIT in MOT 2. The detuning of the signal-2 photon is performed by changing the frequency of the pump-2 field, which is controlled by an AOM. The pump 2 field passes through the AOM, the frequency being tuned from $-12 \sim 17 \times 2\pi$ MHz. There is another AOM added in the optical path of the signal-2 photon (see figure 1), which afterwards has frequency $+120 \times 2\pi$ MHz. By this method, the frequency of the signal-2 photon can be tuned from the atomic transition $5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 3)$ to the atomic transition $5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 4)$. Because the signal-2 photon falls into the atomic transition window $5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 4)$ in MOT 2, then by changing the frequency of the emitted signal-2 photon, we measure its transmission spectra (figure 5). To check this process, we added a coupling field, which is resonant with the atomic transition $5P_{3/2}(F' = 3) \rightarrow 50D_{5/2}$, to demonstrate the Rydberg EIT. Under the plane-wave approximation, the EIT transmission has the form $e^{-2i\frac{w_{s2}}{c}(1+\chi/2)\frac{2\pi}{\gamma_{eg}}}L$, where $L$ is the length of the atomic medium, $w_{s2}$ the frequency of the signal 2 photon, $c$ the speed of light in a vacuum, and $\chi$ denotes the linear susceptibility (complex) defined as [54]

$$\chi = \frac{\alpha_0}{k_0} \frac{4(\Delta w_{s2} + i\gamma_{eg})\gamma_{eg}}{\Omega_c^2 - 4(\Delta w_{s2} + i\gamma_{eg})(\Delta w_{s2} + i\gamma_{eg})} \tag{3}$$

where $\alpha_0 = OD/L$ is the absorption coefficient when the coupling field is not present, $OD$ is the optical depth of atomic ensemble. $k_0$ is the wave vector. $\Delta w_{s2}$ is the detuning of the signal-2 photon. $\gamma_{eg}$, $\gamma_{rg}$ are the corresponding decay rates of atomic transition $|e\rangle \rightarrow |g\rangle$ and $|nD\rangle \rightarrow |g\rangle$. $\Omega_c$ represents the Rabi frequency of coupling field. We use this equation 3 to simulate the results given in figure 5(a) and (b).

The strong dipole interaction couples the nearby Rydberg atoms so that the evolution of these atoms is fundamentally linked, thereby modifying the individual atomic energy levels and lifetimes [55]. As a result of the Rydberg dipole interactions, the behaviour of an ensemble of N-atoms cannot simply be described by summing the response of a single atom N times. When we apply a weak coherent gate field, the response of the atoms cannot be described by equation 3, which refers to a single body; if there are no Rydberg dipole interactions, the transmission of the N-atom system can be traced to a summation of N single-atom contributions. To describe the behaviour for Rydberg EIT with a gate field, we use a simplifying assumption $\gamma_{rg} \rightarrow |\xi \cdot \gamma_{rg}|$ where $\xi$ is the cooperative gain coefficient. The atomic decay rate
would then increase when the Rydberg atoms interact, and the response of each atom is modified significantly. Because of this process, the response of Rydberg atoms would exhibit non-transparency behaviour for single photons when $\xi$ is sufficiently large. Thus, we can control the single photon transmission behaviour of Rydberg EIT depending on whether nearby Rydberg atoms are excited. The Rydberg EIT effect with a gate field was measured [figure 5(c), red solid line] and the results fitted curve for $\xi = 6$.

**Bandwidth matching between signal 2 and atoms in MOT 2.** In this process, bandwidth mismatching between the signal-2 photon and the atomic ensemble in MOT 2 decreases the switch contrast. Because the high-frequency component of the signal-2 photon is unable to fall within the Rydberg EIT window, the reabsorption of the signal-2 photon weakens although the gate field is present; see figure 5 (d). The switch contrast decreases with increasing Rabi frequency $\Omega_{s2}$ of pump 2 field. The bandwidth of the signal-2 photon depends significantly on $\Omega_{s2}$ [46, 56], because the profile of the wave packet of the signal-2 photon changes through tuning the $\Lambda$-EIT transparent window. This result plotted in figure 5 (d) tells us that switching is better with a narrower bandwidth for the signal-2 photon. For the optimized case, the bandwidth of the signal-2 photon is measured to be $\sim 5 \times 2\pi$ MHz, and the absorption window for the atomic ensemble in MOT 2 is $\sim 13 \times 2\pi$ MHz. That is, the signal-2 photon can completely fall within the Rydberg EIT window.

**Threshold against excited Rydberg atoms.** Continuously exciting the atoms from ground state to Rydberg state would deplete the atoms in MOT 2 finally. Because highly-excited Rydberg atoms decay to other atomic levels via non-cycle transitions, we therefore changed the photon number of the gate field and the time duration to measure switch contrast. The results (figure 6) show switch contrast versus time duration with an average Rydberg atoms number per blockade sphere is $\sim 2.1$, and measured switch contrast versus photon number of the gate field setting the time duration at 25 $\mu$s. There is an obvious peak when the average Rydberg atoms number per blockade sphere is $\sim 1.7$. With increasing the photon number, the atoms are clearly depleted as evident in the weakened fluorescence image of the atoms.

**Quantum state tomography of photonic entanglement.**

We have also performed quantum state tomography [57] for the photonic entanglement to compare the entanglement properties before and after gate field switching. Signals 1 and 2 are polarization entangled, their entangled state being $|\psi\rangle = (|H\rangle_{S1}|V\rangle_{S2} + |V\rangle_{S1}|H\rangle_{S2})/\sqrt{2}$, here, $|H\rangle_{S1/S2}$ and $|V\rangle_{S1/S2}$ represent signals 1 and 2 carrying the horizontal and vertical component of the polarization. Using the polarizing beam splitter, half-wave plate, and quarter-wave plate, we projected the two photon states onto the four polarization states $|\phi_{1,2}\rangle$ $(|H\rangle, |V\rangle, (|H\rangle - i |V\rangle)/\sqrt{2}, (|H\rangle + |V\rangle)/\sqrt{2})$. We obtained then a set of 16 data points from which to reconstruct the density matrix. By comparing the ideal density matrix $\rho_{\text{ideal}}$ for these four states, and using $F = \text{Tr}(\sqrt{\sqrt{\rho_{\text{ideal}}}\rho\sqrt{\rho_{\text{ideal}}}})$, we found the fidelity for the input and output states to be $85.3\% \pm 1.5\%$ and $80.4\% \pm 2.3\%$, respectively. The fidelity is not clearly decreasing because switching is effective for any polarization state. The trend is consistent with single qubit switching demonstrated above. The error bars in our experiment are estimated by Poisson statistics using Monte Carlo simulations with the aid of Mathematica software.

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