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Letter

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Experimental realization of high-fidelity quantum logic gate between photons

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Quantum logic gates with fidelity above fault-tolerant threshold are building blocks for scalable quantum technologies^{1,2}. Compared to other types of qubits, photon is one of a kind due to its unparalleled advantages in long-distance quantum information exchange³⁻⁵. As a result, high-fidelity photonic quantum operations are not only indispensable for photonic quantum computation⁶⁻⁸ but also critical for quantum network^{2,9}. However, two-qubit photonic quantum logic gate with fidelity comparable to that of leading physical systems, i.e. 99.7% for superconducting circuits¹⁰ and 99.9% for trapped ions¹¹, has not been achieved. A major limitation is the imperfection of single photons¹². Here, we overcome this limitation by using high-quality single photons generated from Rydberg atoms as qubits for the interference-based gate protocol, and achieve a gate fidelity up to 99.84(3)%. Our work paves the way for scalable photonic quantum applications¹³⁻¹⁵ based on near-optimal single-photon qubits and photon-photon gates.

Single photon plays a central role in the profound quantum technologies^{12,14}. Photon-photon quantum operations based on interference and projective measurement¹⁶⁻¹⁹ enable efficient photonic quantum computing in both the quantum circuit model, e.g., Knill-Laflamme-Milburn scheme⁶, and the cluster-state model²⁰, in which the resource overhead can be significantly reduced⁷. Furthermore, single photon is the key to mediate interactions between remote nodes in large-scale quantum network architectures such as quantum communication³⁻⁵, distributed quantum computing²¹ and metrology²².

Scalable quantum architectures such as photonic quantum computers⁶⁻⁸ and all-optical quantum repeaters^{2,9} impose stringent requirements on the fidelity of photonic quantum operations, and consequently on the quality of the single-photon source¹². For example, to implement cluster-state quantum computing and all-optical quantum repeaters, the minimum requirements on single-photon source are $g^{(2)}(0) < 10^{-3}$ and the indistinguishability higher than 99%¹². To date, these demanding requirements have not been simultaneously achieved by the state-of-the-art single-photon sources. The imperfections in purity and indistinguishability also set a ceiling on the fidelity of photon-photon quantum logic gates¹².

Recently, significant experimental progress has been made in single-photon sources based on cold Rydberg

atoms²³⁻²⁶. The strong interactions between Rydberg atoms lead to excitation blockade²⁷ and hence the efficient preparation of single Rydberg excitation, which can be converted into high-quality single photon on demand²⁸ through matter-light quantum state transfer.

Here we demonstrate a photon-photon quantum logic gate with a truth table fidelity up to 99.84(3)% by performing the interference-based controlled-NOT (CNOT) gate protocol with single photons generated from Rydberg atoms. The high fidelity is made possible by our near-optimal single-photon source with $g^{(2)}(0) = 4.5(8) \times 10^{-4}$ and an indistinguishability of 99.94(8)%. As illustrated in Fig. 1a, an ensemble of cold ⁸⁷Rb atoms is prepared in an optical dipole trap and can be coupled from the ground state $|g\rangle$ to a high-lying Rydberg state $|r\rangle$ using two-photon transition with a 780 nm laser field Ω_{780}^e and a 479 nm laser field Ω_{479}^e via an intermediate state $|e\rangle$. The waists of the Rydberg excitation and the dipole trap beams are chosen such that the entire excitation region is within the Rydberg blockade radius. As a result, multiple Rydberg excitations are suppressed and the entire atomic ensemble involving N atoms can be promoted from the ground state $|G\rangle = \prod_{i=1}^N |g_i\rangle$ to the single collective excitation state $|R\rangle = \sum_{i=1}^N |g_1\rangle \dots |r_i\rangle \dots |g_N\rangle / \sqrt{N}$ by a π pulse. To generate single photons on demand, a read-out field Ω_{479}^i resonant with the $|e\rangle \leftrightarrow |r\rangle$ transition is applied. Assisted by the enhanced atom-light cooperativity, the read-out field efficiently converts the Rydberg excitation into a single photon with well-defined spatial mode.

To implement the CNOT gate¹⁶⁻¹⁹, two single photons are consecutively generated from the Rydberg atoms and used as the control and target photonic qubits in a free-space photon-photon interferometer. As shown in Fig. 1b, the non-classical correlations between the control and target qubits can be established via the two-photon quantum interference at a partial polarization beam splitter (PPBS), which has 1/3 reflectivity for horizontally polarized photons and is totally reflective for vertically polarized photons. When the control qubit is in the vertically polarized state, encoded as $|0\rangle_C$, two photons do not interfere so the target qubit remains unchanged. In contrast, with the control qubit in the horizontally polarized state, encoded as $|1\rangle_C$, the horizontally polarized component of the target qubit acquires a π -phase shift as a result of the unbalanced two-photon quantum interference, while the vertically polarized component is unaffected. By encoding the diagonally and

FIG. 1. **Illustration of the experimental protocol.** **a**, An ensemble of cold ^{87}Rb atoms is confined in a 1012 nm dipole trap. The counter-propagating 780 nm and 479 nm excitation beams are combined on a dichroic mirror (DM) and tightly focused onto the ensemble, with waists of $6\mu\text{m}$ and $30\mu\text{m}$, respectively. Atoms are initialized in the ground state $|g\rangle$ and excited to a high-lying Rydberg state $|r\rangle$ with a single-photon detuning of $\Delta/2\pi = -200\text{ MHz}$. After the excitation, a 479 nm read-out light resonant with $|r\rangle \leftrightarrow |e\rangle$ transition converts the single collective excitation state $|R\rangle$ into a single photon which is coupled into a single-mode fiber. The insert shows the atomic levels involved in the excitation and read-out processes: ground state $|g\rangle = |5S_{1/2}, F=2, m_F=2\rangle$, intermediate state $|e\rangle = |5P_{3/2}, F=3, m_F=3\rangle$, and Rydberg state $|r\rangle = |90S_{1/2}, J=1/2, m_J=1/2\rangle$. **b**, Two single photons are sequentially generated with an interval of $5\mu\text{s}$, and their temporal wave packets are well overlapped at the interferometer using a polarization switching electro-optic modulator (EOM) and a 1 km delay fiber. Before the two-photon interference at the first PPBS, two half-wave plates (HWPs) are employed to prepare the input state of the control and target qubits. Two more PPBSs and HWPs are used after the interference to complete the CNOT gate operation. The output state is measured by a polarization-sensitive detection setup consisting of HWPs, polarization beam splitters (PBSs) and SPCMs ($c_{0,1}$ and $t_{0,1}$).

anti-diagonally polarized states as $|0\rangle_T$ and $|1\rangle_T$, the target qubit is flipped when the control qubit is in $|1\rangle_C$. Therefore, the implemented input-output relation is

$$\begin{aligned} |00\rangle &\rightarrow |00\rangle, & |01\rangle &\rightarrow |01\rangle, \\ |10\rangle &\rightarrow |11\rangle, & |11\rangle &\rightarrow |10\rangle, \end{aligned}$$

which defines a CNOT gate operation.

The fidelity of the photon-photon quantum logic gate critically relies on the purity and indistinguishability of the Rydberg single-photon source. Ideally, Rydberg states with higher principal quantum number n feature stronger interactions and better multi-excitation suppression. However, detrimental effects such as long-lived Rydberg contaminants, ambient electric fields induced level shifts and density-dependent dephasing also worsen with higher n . To balance the pros and cons, Rydberg state with $n=90$ is employed in our experiment for the generation of high-quality single photons. The purity of our Rydberg single-photon source is characterized with a Hanbury Brown-Twiss experiment, in which the photons are coupled into a 50:50 fiber beam splitter followed by two single-photon counting modules (SPCMs). Fig-

FIG. 2. **High-quality Rydberg single-photon source.** **a**, Second-order intensity correlation function $g^{(2)}(\tau)$ as a function of delay τ . The duration of each experimental cycle is $2.5\mu\text{s}$. The insert shows $g^{(2)}(0)$ at zero delay. **b**, The visibility of HOM interference $V(t)$ as a function of two-photon temporal mismatch t . The error bars represent the 1σ standard deviation from photoelectric counting events.

ure 2a shows the measured second-order intensity correlation function $g^{(2)}(\tau)$ as a function of delay τ . As a result of the Rydberg excitation blockade, strong suppression of

FIG. 3. **High-fidelity photon-photon gate.** **a,b**, Truth tables of the CNOT gate in the computational ZZ basis (**a**) and the complementary XX basis (**b**). The ideal input-output relation in the ZZ basis is $|00\rangle \rightarrow |00\rangle$, $|01\rangle \rightarrow |01\rangle$, $|10\rangle \rightarrow |11\rangle$ and $|11\rangle \rightarrow |10\rangle$. Similarly, the ideal input-output relation in the XX basis is $|++\rangle \rightarrow |++\rangle$, $|+-\rangle \rightarrow |--\rangle$, $|-+\rangle \rightarrow |--\rangle$ and $---\rangle \rightarrow |--\rangle$, with the definitions of $|\pm\rangle_C = (|0\rangle_C \pm |1\rangle_C)/\sqrt{2}$ for control qubit and $|\pm\rangle_T = (|0\rangle_T \pm |1\rangle_T)/\sqrt{2}$ for target qubit. The measured probabilities are shown on a logarithmic scale. **c,d**, Real (**c**) and imaginary (**d**) parts of the reconstructed density matrix ρ for the created entangled state.

two-photon events at zero delay is observed. In order to achieve low $g^{(2)}(0)$, efforts are spent on suppressing the background detection events to SPCM dark-count level (see Supplementary Section II). The measured value for the second-order intensity correlation function at zero delay is $g^{(2)}(0) = 4.5(8) \times 10^{-4}$, which indicates excellent single-photon purity.

The scalability of interference-based quantum photonic protocols strongly depends on the indistinguishability of single photons, since distinguishable photons severely deteriorate the operation fidelity. To investigate the indistinguishability, two-photon interference visibility is measured by a Hong-Ou-Mandel (HOM) experiment. The HOM setup is designed to minimize the visibility reduction due to mismatch of photon wave packets, polarization and beam-splitting imperfections, and background detection events (see Supplementary Section III). Figure 2b displays the interference visibility $V(t)$ as a function of two-photon temporal mismatch t . Due to the quantum interference between two single photons, we observe a non-classical suppression of coincidences at zero temporal mismatch with a high visibility of $V(0) = 99.87(8)\%$. Besides photon indistinguishability, $V(0)$ is also affected by background detection events and single-photon impurity characterized by non-zero $g^{(2)}(0)$. By analyzing these contributions, we extract an indistinguishability of 99.94(8)% (see Supplementary Section III).

Having a single-photon source with near-optimal purity and indistinguishability at hand, we proceed to the implementation and characterization of the photonic CNOT gate by inputting different control-target qubits combinations to the gate and measuring the corresponding output states. The truth tables of the CNOT

gate are shown in Fig. 3a,b, where the measured probabilities for different input-output combinations are displayed on a logarithmic scale. The measured fidelities of the CNOT gate in the computational ZZ basis and the complementary XX basis are $F_{\text{CNOT}}^{\text{ZZ}} = 99.84(3)\%$ and $F_{\text{CNOT}}^{\text{XX}} = 99.81(3)\%$, which is defined as the probability of detecting the desired output states averaged over input states (see Supplementary Section IV). To the best of our knowledge, the photon-photon quantum logic gate demonstrated here has the highest fidelity reported until now.

The most remarkable feature of a two-photon quantum logic gate is its ability to establish entanglement between two initially uncorrelated photons. With a product state of $(|0\rangle - |1\rangle)|1\rangle/\sqrt{2}$ as input, the CNOT gate ideally generates a maximally entangled Bell state $|\Psi^-\rangle = (|01\rangle - |10\rangle)/\sqrt{2}$. To characterize the entangling-gate fidelity, quantum state tomography is performed on the output state and the reconstructed density matrix ρ is shown in Fig. 3c,d. The measured state fidelity $F_{\Psi^-} = \langle \Psi^- | \rho | \Psi^- \rangle = 99.69(4)\%$ is in good agreement with our analysis (see Supplementary Section V), and demonstrates the preparation of high-fidelity entangled photon pairs.

To further verify the entanglement, we demonstrate the violation of Bell's inequality with the output state by evaluating the correlation function $E(\theta_c, \theta_t)$ given by

$$\frac{C_{01}(\theta_c, \theta_t) + C_{10}(\theta_c, \theta_t) - C_{00}(\theta_c, \theta_t) - C_{11}(\theta_c, \theta_t)}{C_{01}(\theta_c, \theta_t) + C_{10}(\theta_c, \theta_t) + C_{00}(\theta_c, \theta_t) + C_{11}(\theta_c, \theta_t)}, \quad (1)$$

where θ_c (θ_t) is the polarization angle for the measurement of the control (target) output state, and C_{ij} is the coincidence rate between SPCMs $c_{i=0,1}$ and $t_{j=0,1}$ in Fig. 1b. Correlation function $E(\theta_c, \theta_t)$ with high fringe

FIG. 4. **Entanglement created by the quantum logic gate.** Measured correlation function $E(\theta_c, \theta_t)$ as a function of θ_c with $\theta_t = 0$ (diamonds) and $\theta_t = \pi/4$ (circles). Solid curves are sinusoidal fits with 0.99(1) visibility. The error bars represent the 1σ standard deviation from photoelectric counting events.

TABLE I. **Violation of Bell's inequality.** The error bar represents the 1σ standard deviation.

θ_c	θ_t	$E(\theta_c, \theta_t)$
$\pi/8$	0	0.706(6)
$\pi/8$	$\pi/4$	0.714(6)
$-\pi/8$	0	0.702(6)
$-\pi/8$	$\pi/4$	-0.700(6)
		$S = 2.823(12)$

visibilities is observed in Fig. 4. The values of $E(\theta_c, \theta_t)$ at polarization angle settings for Bell's inequality are shown in Table I, from which the Bell parameter $S = E(\pi/8, 0) + E(\pi/8, \pi/4) + E(-\pi/8, 0) - E(-\pi/8, \pi/4)$ is determined. The measured value $S = 2.823(12)$ approaches the ideal value of $|S| = 2\sqrt{2}$, and violates the Clauser-Horne-Shimony-Holt inequality $|S| \leq 2$ by more than 60 standard deviations, thus clearly confirming the entanglement between the output photons and the quantum nature of our gate.

To quantitatively understand the performance of our quantum logic gate, we thoroughly investigate possible sources of error in the experiment, and identify three major contributions to the CNOT gate infidelity: background detection events, single-photon impurity and imperfection in photon indistinguishability (see Supplementary Section IV). We emphasize that the above-mentioned error mechanisms are not intrinsic to our experiment, and can be mitigated with further technical efforts.

Background detection events, which mainly come from the dark counts of SPCMs, occur randomly and lead to an infidelity of 0.088(4) % for ZZ basis. This effect can be suppressed by increasing the signal-to-background ratio. Currently, our single-photon generation efficiency $\eta = 0.30(1)$ is mainly limited by the optical depth and can be improved by incorporating an optical resonator to enhance the collective emission. Moreover, the residual multi-photon components from the single-photon source induce unexpected coincidences in $|10\rangle$ and $|11\rangle$ bases, and lead to an infidelity of 0.067(19) % for ZZ basis. The detrimental multi-photon components can be further suppressed with stronger Rydberg interactions obtained by using, for example, smaller atomic sample. In addition, the imperfect photon indistinguishability reduces quantum interference visibility and causes errors during the controlled state flip of the target qubit, leading to an infidelity of 0.06(8) % for ZZ basis. To further improve the indistinguishability, quantum optimal control techniques can be applied to the photon read-out stage for the precise manipulation of the photon's amplitude and phase profiles. The infidelity for XX basis contributed by the above-mentioned mechanisms is comparable.

In summary, we experimentally demonstrate a photon-photon quantum logic gate with fidelity up to 99.84(3) % based on near-optimal single photons generated by Rydberg atoms. We emphasize that the achieved high fidelity is not limited to the interference-based gate protocol used here. For example, photon-photon quantum logic gates have been realized using schemes based on matter-light interactions^{29,30}, and a major source of infidelity in these experiments comes from the detrimental multi-photon components in the photonic qubits, which can be circumvented with our near-optimal single photons.

Our results open up new perspectives for highly demanding applications such as photonic quantum information processing and distributed matter-light quantum architectures (see Supplementary Section VI for detailed discussion on potential applications). For example, high-fidelity single photons and two-photon gates enable the preparation of photonic cluster states, which are the key elements of the all-optical quantum repeaters^{2,9} that circumvent the requirement of long-lived quantum memories. By increasing the size of the cluster states and extending their dimensions to higher than two, fault-tolerant photonic quantum computing can be implemented¹³. Furthermore, high-quality single photons from Rydberg atoms can be injected into integrated photonic chips¹⁵, realizing photonic quantum circuits with excellent multi-photon quantum interference. Last, high-quality single photons and entangled photon pairs enable near-perfect interconnections between distant quantum modules that employ atomic qubits as local quantum processors, building up large-scale quantum architectures⁴ with low overall error rates.

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Data availability

Data are available from the corresponding authors upon request.

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Author contributions

All authors contributed substantially to this work.

Competing interests

The authors declare no competing interests.

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