A photonic entanglement filter with Rydberg atoms

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Devices capable of deterministically manipulating photonic entanglement are of paramount importance, because photons are ideal messengers for quantum information. However, due to the non-interacting nature of photons, many photonic quantum operations have only been demonstrated using probabilistic linear-optical approaches, leading to an overwhelming resource overhead and poor scalability. Here we report a novel entanglement filter that transmits the desired photonic entangled state and blocks unwanted ones. In contrast to previous probabilistic approaches, our experiment exploits the strong and controllable photon–photon interaction enabled by Rydberg atoms, so the filtering of undesired states succeeds in every experimental trial. Photonic entanglement with near-unity fidelity can be extracted from an input state with an arbitrarily low initial fidelity. The protocol is inherently robust, and succeeds both in the Rydberg blockade regime and in the interaction-induced dissipation regime. Such an entanglement filter opens new routes towards achieving scalable photonic quantum information processing with multiple ensembles of Rydberg atoms.

Entangled photonic states are indispensable resources for large-scale quantum architectures1–4. Therefore, advancing the deterministic quantum control of photonic entanglement is at the heart of quantum information processing5–8. As one of the key elements in quantum photonics, an entanglement filter (EF) transmits the entanglement of the desired quantum states, while blocking the transmission of unwanted photonic components9. It has a plethora of potential applications, including photonic entanglement generation10, all-optical quantum information processing11,12 and entanglement distillations13,14. However, its scalability and applicability have been limited by the fact that all photonic EF protocols so far have been based on linear-optical approaches9,15–17, which remove unwanted photonic states only in a probabilistic way. The probabilistic nature and the requirement for ancillary quantum resources have led to poor scalability and overwhelming resource consumption. Moreover, the output entanglement fidelity in the linear-optical approach is ultimately limited by the finite interference visibility between photons.

Scalable quantum photonic applications will largely benefit from an ideal EF that deterministically removes undesired states, unconditionally achieves a high entanglement fidelity, and demands no extra photonic resources. Unfortunately, the realization of such a superior EF protocol has remained elusive due to the lack of a strong and controllable photon–photon interaction in linear-optical approaches. In recent years, cold Rydberg atoms have been employed to facilitate the interactions between photons and to achieve intrinsically deterministic quantum photonic operations, such as single-photon generation18–21 and manipulation22–26, entanglement preparation27–29 and photon–photon gates30.

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In this Article we demonstrate an above-envisioned superior EF by exploiting cold Rydberg atomic ensembles to mediate the interaction between photons. As illustrated in Fig. 1, our EF acts on photons a and b, whose horizontal (H) and vertical (V) polarizations are used for qubit encoding. For example, if the entangled Bell state $|\psi^+\rangle = |H_a\rangle|V_b\rangle + |V_a\rangle|H_b\rangle$ is chosen as the target state and a product state $|H_a\rangle|H_b\rangle + |V_a\rangle|V_b\rangle$ is used as the input, the filter removes the $|H_a\rangle|H_b\rangle$ and $|V_a\rangle|V_b\rangle$ components while transmitting the desired entanglement. In contrast to previous probabilistic linear-optical approaches, our protocol eliminates the unwanted states in a deterministic way, outputs high-fidelity entangled states, and requires no extra quantum resources. Furthermore, the upper bound for transmitting entangled photons through the linear-optical EF is 1/16 (refs. 9,15), while the transmission of our protocol can, in principle, reach up to unity. Currently, the transmission is only limited by the finite photon storage efficiency $\eta_s = 0.24$ and readout efficiency $\eta_r = 0.36$ (Supplementary Section I).

As shown in Fig. 1, our experiment makes use of two Rydberg ensembles to achieve a polarization-selective interaction between photonic qubits. The working principle is to convert the unwanted photonic components into double Rydberg excitations in the same atomic ensemble and to achieve the deterministic removal of these states with either Rydberg blockade of the interaction induced by two-body dissipation. Using photon storage based on the Rydberg electromagnetically induced transparency (EIT), the 480-nm control laser field $\Omega_c^a$ ($\Omega_c^b$) coherently transfers the 780-nm photon in state $|H_a\rangle$ ($|V_a\rangle$) into a collective atomic excitation in the down (upper) ensemble:

$$|D_a\rangle = \sum^N_{j=1} |g^a\rangle_1 \cdots |r^a_j\rangle \cdots |g^a\rangle_N / \sqrt{N},$$

$$|U_a\rangle = \sum^N_{j=1} |g^a\rangle_1 \cdots |l^a_j\rangle \cdots |g^a\rangle_N / \sqrt{N},$$

where $|g\rangle$ is the atomic ground state, $|r\rangle$ is a Rydberg state and $U/D$ denotes the upper/down ensemble. To isolate the interaction between photons a and b, an adjacent Rydberg level $|r\rangle$ is employed to transfer the qubit state $|H_a\rangle|V_b\rangle$ to the excitation $|D_a\rangle$ ($|U_a\rangle$) in the down (upper) ensemble.

To implement the EF in the blockade regime, high-lying Rydberg states with principal quantum numbers $n_s = 76$ and $n_a = 77$ are employed. As a result, the storage of unwanted components $|H_a\rangle|H_b\rangle$ and $|V_a\rangle|V_b\rangle$ into double Rydberg excitations in the same ensemble—that is, $|D_a\rangle|D_b\rangle$ or $|U_a\rangle|U_b\rangle$—is strongly suppressed by the blockade effect. On the other hand, the two ensembles are separated by 150 μm, well beyond the Rydberg blockade radius, such that the desired entangled state $|\psi^+\rangle$ can be stored as $1/\sqrt{2}$ ($|D_a\rangle|U_b\rangle + |U_a\rangle|D_b\rangle$) of the atoms. After the storage process, the Rydberg excitations are converted back to photonic qubits in state $|\psi^+\rangle$ through collective emission by sequentially applying 480-nm readout light fields.

The polarization-selective photon blockade effect is shown in Fig. 2a,b. Two weak coherent laser pulses with average photon number $\langle n \rangle$ of 0.1 are used to approximate single photons a and b. After passing through the EF, the photons are detected in the $|H\rangle$/$|V\rangle$ basis by single-photon counting modules (SPCMs). Figure 2a displays the measured two-photon populations of the input state, which are distributed...
Fig. 2 | Blockade-based EF. a, b. Normalized two-photon populations of the input (a) and output (b) states, obtained from photon correlation measurements. The real part of the reconstructed density matrix of the input (c) and output (d) states. The colour bar represents the value of the matrix elements from −0.5 to 0.5. Data in a and b are presented as mean values ± s.d., and the error bars are derived from the Poisson distribution of photoelectric counting events. In the blockade-based EF experiment, the overall coincidence count rate is ~25 h⁻¹, with a typical sample time of 2 h. The ‘EF’ label connecting adjacent panels indicates the EF operation.

Fig. 3 | Extracting entanglement from an arbitrarily noisy input. The measured input- (diamonds) and output- (circles) state fidelities as a function of the input-state amplitude ratio α/β. Solid line: expected input fidelity at different α/β. Data are presented as mean values ± s.d., and the error bars are derived from the Poisson distribution of photoelectric counting events. For the minimal α/β case, the overall coincidence count rate is ~25 h⁻¹, with a typical sample time of 2 h. The arrows pointing from the input-state fidelities to the output-state fidelities represent the EF operation. The shading below the dashed line shows the region where the fidelities of classical input states overlapping with the target state (Ψ⁺) are below 0.5.

Fig. 4 | Interaction-induced two-body decoherence. a, b. Illustration of two-body decoherence induced by distance-dependent interaction, showing phase-matched emission (a) and dissipative emission (b). c, d. The suppression ratio \( \chi = \frac{\rho_{HH} + \rho_{HV}}{\rho_{HH} + \rho_{VV}} \) as a function of evolution time \( t \) for \( n_a = 47, n_b = 48 \) (c) and \( n_a = 55, n_b = 56 \) (d). The solid curves show simulations based on the two-body decoherence mechanism. Data in c and d are presented as mean values ± s.d., and the error bars are derived from the Poisson distribution of photoelectric counting events. In the decoherence-based EF experiment, the overall coincidence count rate is about 110 h⁻¹, with a typical sample time of 4 h.

To characterize the EF in the nonclassical regime, quantum state tomography was performed for the input and output states. The density matrix \( \rho_{in} \) of the input state is reconstructed and shown in Fig. 2c; this has a fidelity of \( F_{in} = 49.3(7)% \) overlapping with the target state (Ψ⁺). The EF removes the undesired components and improves the fidelity to up to \( F_{out} = 98.8(5)% \) (Fig. 2d). The reduction of \( F_{out} \) from unity is mainly caused by the 0.61(6)% infidelity from background
density matrices for input and output states with different evolution times. The weaker than that of the states \( C \) is nearly two orders of magnitude using lower-lying Rydberg states \( \alpha \) and \( \beta \). The reconstructed density matrices for input and output states with different evolution times. The colour bar represents the value of the matrix elements from -0.5 to 0.5. c Same as a, but for \( n_a = 55, n_b = 56 \). The solid curves show simulations based on the two-body decoherence model. Data in a and c are presented as mean values ± s.d., and the error bars are derived from the Poisson distribution of photoelectric counting events. The overall coincidence count rate is -110 h⁻¹, with a typical sample time of 4 h.

An ideal EF should pose no prerequisite on the fidelity of the input state and should extract the desired entangled state from an arbitrarily noisy input. To demonstrate this essential capability, \( (a|H|a + b|V|b)(a|H|b + b|V|a) \) is employed as the input state. By varying the amplitude ratio \( a/b \), the input fidelity \( F_{in} \) can be tuned in the classical regime between 0.5 and 0.5 (Fig. 3 diamonds). When the EF is applied, the fidelities of the corresponding output states are improved to a near-unity level (Fig. 3, circles). In the case of \( a/b = 0.185 \), our EF improves the input-state fidelity, \( F_{in} = 0.070(12) \), by more than one order of magnitude. The measured state fidelity, \( F_{out} = 0.954(22) \), is limited by the decreased signal-to-background ratio for small \( a/b \), and the background-corrected fidelity \( F_{cor} = 0.992(25) \) is not affected by the low input-state fidelity.

Developing novel Rydberg quantum photonic protocols with low principal quantum number \( n \) holds promise to alleviate some of the decoherence and loss mechanisms associated with high-\( n \) states, such as long-lived Rydberg contaminants, energy-level drifts induced by background electric fields, and density-dependent dephasing. To this end, we demonstrate an EF in the absence of the blockade effect using lower-lying Rydberg states \( n_a = 47 \) and \( n_b = 48 \), whose van der Waals interaction coefficient \( C \) is nearly two orders of magnitude weaker than that of the states \( n_a = 76 \) and \( n_b = 77 \). Therefore, the \( |H|a|H|b \) and \( |V|a|V|b \) components can be stored as double Rydberg excitations in the same ensemble.

The distance-dependent van der Waals interaction strength \( V_{ff} = C/\kappa^6 \) varies strongly for Rydberg atom pairs with different separations \( \kappa^6 \) and leads to the accumulation of random phases and a fast two-body decoherence during the quantum evolution [22]:

\[
|U|a|U|b \propto \sum_{j \neq l} e^{i \chi_{jl}} |H|a|^l|H|b^j \ldots |H|a^j|H|b^l \ldots |H|a^j|H|b^l|H|a^j|H|b^l|U|a|D|b \rangle.
\]

If the readout is performed immediately after storage, that is, without two-body decoherence, the spatial mode of the retrieved photons will be highly directional, as a result of the mode-matched collective emission (Fig. 4a). However, the accumulation of interaction-induced random phases deteriorates the collective coherence of the excitations and leads to spontaneous photon emission in random directions during the readout (Fig. 4b). In the experiment, only photons in the mode-matched direction are collected, so the retrieved \( |H|a|H|b \) and \( |V|a|V|b \) components are suppressed due to dissipation. The entangled state \( |\psi^+ \rangle \) is stored in the decoherence-free-subspace \( 1/\sqrt{2} (|D|a|U|b + |U|a|D|b) \), and is hence immune to this dissipation. Figure 4c displays the measured suppression ratio \( \chi \) as a function of the dissipative evolution time \( t \). The ratio \( \chi \) decreases to 0.440(45) with just a short evolution time of 0.2 µs and is further suppressed to 0.037(17) after 4 µs.

Similar to \( \chi \), the output-state fidelity depends on the quantum evolution time \( t \) in the dissipative regime. Quantum state tomography was performed on the photonic state retrieved at a different time and the corresponding state fidelities are shown in Fig. 5a.

**Fig. 5** | EF via dissipative quantum evolution. a, The measured state fidelity as a function of dissipative evolution time \( t \) with \( n_a = 47, n_b = 48 \). b, The reconstructed density matrices for input and output states with different evolution times. The colour bar represents the value of the matrix elements from -0.5 to 0.5. c, Same as a, but for \( n_a = 55, n_b = 56 \). The solid curves show simulations based on the two-body decoherence model. Data in a and c are presented as mean values ± s.d., and the error bars are derived from the Poisson distribution of photoelectric counting events. The overall coincidence count rate is ~110 h⁻¹, with a typical sample time of 4 h.
To understand this temporal dynamics, we performed Monte-Carlo simulations based on the two-body decoherence model (Supplementary Section III.1 provides details). The simulated result (Fig. 5a, solid curve) agrees well with the measured fidelities at different times $t$. During the dissipative evolution, the undesired components in the density matrix $\rho$ are gradually suppressed (Fig. 5b). After 4 $\mu$s of evolution, the EF improves the state fidelity from $F_{\text{in}} = 0.495(7)$ to $F = 0.951(17)$.

The dissipative EF protocol is very robust to the principal quantum number $n$. For higher Rydberg states, $n = 55$, the larger interaction variation leads to a quicker dissipation of the unwanted photonic components (Fig. 4d) and consequently a faster improvement of the state fidelity with evolution time $t$. In Fig. 5c, an entanglement fidelity of $F = 0.978(15)$ is achieved with $t = 2.8$ $\mu$s. In principle, the dissipative scheme can also be realized with very low $n$ by harnessing the resonant dipole–dipole interactions. Our simulation shows that efficient entanglement filtering can be achieved even with $|r_2| = |19D_5/2, m_f = 5/2$) and $|r_3| = 2|0F_{1/2}, m_s = 3/2$) (Supplementary Section III.2). Combined with the blockade-based scheme at high $n$, the working range of our EF spans over a large spectrum of Rydberg states.

Currently, the measured storage efficiency $\eta_s = 0.24$ and readout efficiency $\eta_r = 0.36$ are mainly limited by the finite optical depth (-3.5) and can be improved further. By incorporating the atomic ensemble into an optical resonator, $\eta_s$ and $\eta_r$ can be increased to near unity, and high entanglement transmission can be achieved. The transmission of photonic entanglement through our filter is currently known by measuring the transmitted photon pairs. In principle, we can also combine the well-developed nondestructive photon/atom detection techniques to herald the transmission of entangled photons. Moreover, the target state of our EF is not limited to $|\Psi^+\rangle$. In principle, our EF can extract any of the four Bell states from an arbitrary input state. For example, we have also demonstrated entanglement filtering for $|\Psi^-angle$ from input state $|H_f\rangle|V_b = 1/\sqrt{2}(|\Psi^+\rangle + |\Psi^-\rangle)$, with an output-state fidelity of 0.989(10) (Supplementary Section IV). In summary, we have reported the realization of a novel and scalable EF enabled by Rydberg atoms. We emphasize that, although our protocol is realized using Rydberg atoms, it is, in principle, applicable to any quantum system with controllable qubit interactions and a matter–light quantum interface.

Our EF opens new avenues for a number of novel quantum photonic applications and studies. First, by scaling up to an array of Rydberg ensembles, the efficient generation and manipulation of multi-photons entanglements, such as Dicke states and Greenberger–Horne–Zeilinger states, can be realized. Moreover, our protocol is not based on photon–photon interference, so the qubits do not need to be indistinguishable. This unique feature allows effective quantum control between photons with different temporal-spatial profiles and even with different colours, as long as they can be coupled to appropriate atomic transitions. Last, but not least, our EF also succeeds in the dissipative regime by exploiting the interaction-induced two-body decoherence. The extension of such a scheme to an array of interacting Rydberg excitations could enable the dissipative preparation of long-range correlated states, such as Wigner crystal [12], and the exploration of novel many-body quantum dynamics with interaction disorders that can be tuned by orders of magnitude.

Online content
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Data supporting the plots within this paper are available through Zenodo at https://doi.org/10.5281/zenodo.7631438. Further information is available from the corresponding author upon reasonable request.

Code availability
The code used in this study is available from the corresponding author upon reasonable request.

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Author contributions
G.-S.Y., B.X. and S.S. built the experimental set-up, performed the measurements and carried out data analysis. Y.C., G.-S.Y. and T.S. developed the theoretical model and accomplished numerical simulations. L.L. conceived the idea and supervised the experiment. G.-S.Y., Y.C. and L.L. wrote the paper with input from all authors.

Competing interests
The authors declare no competing interests.

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