Heralded Nondestructive Quantum Entangling Gate with Single-Photon Sources

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Heralded entangling quantum gates are an essential element for the implementation of large-scale optical quantum computation. Yet, the experimental demonstration of genuine heralded entangling gates with free-flying output photons in linear optical system, was hindered by the intrinsically probabilistic source and double-pair emission in parametric down-conversion. Here, by using an on-demand single-photon source based on a semiconductor quantum dot embedded in a micropillar cavity, we demonstrate a heralded controlled-NOT (CNOT) operation between two single photons for the first time. To characterize the performance of the CNOT gate, we estimate its average quantum gate fidelity of $(87.8 \pm 1.2)\%$. As an application, we generated event-ready Bell states with a fidelity of $(83.4 \pm 2.4)\%$. Our results are an important step towards the development of photon-photon quantum logic gates.

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Entangling gates are a crucial building block in scalable quantum computation, as it enables the construction of any quantum computing circuits when combined with single-qubit gates [1]. One of the canonical examples is the controlled-NOT (CNOT) gate, which flips the target qubit state conditional on the control qubit. Photons are generally accepted as the best candidate for a qubit due to their negligible decoherence and ease of single-qubit operation. Unfortunately, ambitions to implement optical CNOT gates are hampered as they require strong interactions between individual photons well beyond those presently available. Surprisingly, projective measurements with photodetector can induce an effective nonlinearity sufficient for the realization of entangling gates using linear optics [2]. Since then, many schemes to implement optical CNOT gates have been theoretically proposed [3–5] and experimentally demonstrated [6–17].

Early demonstrations came at the expense of destroying the output states by detecting the photons [6–11], thus limiting the scaling to a larger system. To be scalable, heralded CNOT gates are necessary [2,12]. Specifically, a successful operation is heralded by the detection of ancillary photons. Such heralded gates are highly important as they provide information classically feed forwardable, which is crucial for a scalable architecture both in the standard circuit model [1,2] and one-way model using cluster states [18–20]. Implementations of heralded CNOT gates assisted with entangled [12–16] or single ancilla photons [17] have been reported. However, the demonstrations mainly employed probabilistic photon sources such as pair sources based on spontaneous parametric down-conversion (SPDC) [21]. Because of the probabilistic nature of SPDC that involves multiphoton emissions, one cannot obtain a photon pair or a heralded single photon deterministically with high generation rate [22], and daunting scalability issues raise if we wish to use these photons. Also, as multiple pair events are always present and detectors without photon number resolution are commonly used, which introduce false heralding signals, postselection is necessary in the demonstrations to confirm a successful gate operation [23]. For this reason, while the schemes in principle work in a heralded way, the previous experiments are actually a destructive version of the heralded CNOT gates, limiting their further applications. To overcome these issues, on-demand photon sources will be the fundamental assets.

Semiconductor quantum dots (QDs) confined in a microcavity are particularly appealing emitters of on-demand photons, which can deterministically emit single photons [24–27] as well as entangled photon pairs [28,29]. They have been shown to generate single photons simultaneously exhibiting high brightness, near-unity single-photon purity, and indistinguishability [27,30], and currently have the best all-around single-photon source performance [31,32]. Until now, QD single-photon sources (SPSs) have already been used to realize optical CNOT gates in a

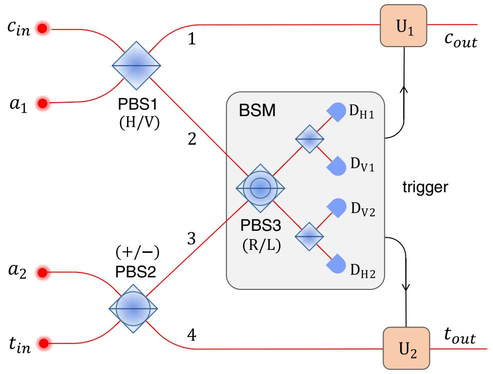

FIG. 1. An optical heralded CNOT gate [17]. Polarizing beam splitters are used, where PBS1 (PBS2, PBS3) transmit $|H\rangle$ ($|+\rangle$, $|R\rangle$) states and reflect $|V\rangle$ ($|-\rangle$, $|L\rangle$) ones. One performs a Bell state measurement (BSM) on the incoming photons and the heralded CNOT gate finally depends on the ancilla measurement outcome and related Pauli operators U_1, U_2.

semiconductor waveguide chip [33] and bulk optics with partial polarizing beam splitters (PBSs) [34] and multipath interference [35]. Nevertheless, none of them are heralded since they necessarily destroy the output states.

In this Letter, we demonstrate the first heralded CNOT operation between two single photons using a QD coupled in a micropillar cavity. Under pulse resonant excitation, the QD SPS generates high-quality single photons that are deterministically demultiplexed into four indistinguishable SPSs (two serve as input photons and two are ancilla) for CNOT gates. Heralded by the detection of two ancillary photons, we achieved a heralded CNOT gate with a fidelity of $(87.8 \pm 1.2)\%$ and ~85 operations/min increased by at least an order of magnitude compared to early experiments, and generated an event-ready Bell state with a fidelity of $(83.4 \pm 2.4)\%$. Our results are an important step towards scalable optical quantum information processing (QIP).

The scheme for a heralded CNOT gate requires only four single photons and three polarizing beam splitters in mutually unbiased bases as described in Fig. 1. We prepare polarization-encoded photons, and define horizontal $|H\rangle$ and vertical $|V\rangle$ polarization as logical states $|0\rangle$ and $|1\rangle$. The input state of the control and target qubits are $|\psi\rangle_{c_{\mathrm{in}}} = \alpha|H\rangle + \beta|V\rangle$ and $|\psi\rangle_{t_{\mathrm{in}}} = \gamma|H\rangle + \delta|V\rangle$, where complex coefficients α and β (γ and δ) satisfy $|\alpha|^2 + |\beta|^2 = 1$ ($|\gamma|^2 + |\delta|^2 = 1$), and subscript represents the photon's path (holding for the rest of the paper). Two ancillary single photons are in the states of $|\psi\rangle_{a_1} = 1/\sqrt{2}(|H\rangle + |V\rangle)$ and $|\psi\rangle_{a_2} = |H\rangle$ [17,36]. The four single photons are then superimposed at PBS1 and PBS2, as shown in Fig. 1. When there is only one photon in each path after PBS1 and PBS2, we obtained a four-photon state with a probability of 1/4, which is further rewritten as follows (see Supplemental Material for details [36]):

$$\begin{aligned}|\Psi\rangle = {} & (I_1 I_4 U_{14} |\psi\rangle_1^{c_{\mathrm{in}}} |\psi\rangle_4^{t_{\mathrm{in}}} \otimes |\Phi^+\rangle_{23} \\ & + I_1 \sigma_{x4} U_{14} |\psi\rangle_1^{c_{\mathrm{in}}} |\psi\rangle_4^{t_{\mathrm{in}}} \otimes |\Psi^+\rangle_{23} \\ & + \sigma_{z1} I_4 U_{14} |\psi\rangle_1^{c_{\mathrm{in}}} |\psi\rangle_4^{t_{\mathrm{in}}} \otimes |\Phi^-\rangle_{23} \\ & + \sigma_{z1} \sigma_{x4} U_{14} |\psi\rangle_1^{c_{\mathrm{in}}} |\psi\rangle_4^{t_{\mathrm{in}}} \otimes |\Psi^-\rangle_{23})/2, \end{aligned} \tag{1}$$

where U_{14} refers to the CNOT operation between photons in path c_{in} and t_{in} (further refer to path 1 and 4), and the output photons in path c_{out} and t_{out} describe the result of CNOT gates; $|\Phi^{\pm}\rangle$ and $|\Psi^{\pm}\rangle$ are standard Bell states in $|H\rangle/|V\rangle$ basis; I_i, σ_{zi}, and σ_{xi} are identity, Pauli Z, and Pauli X operations on the photon in path i ($i = 1, 4$).

Obviously, one can get the CNOT operation U_{14} by performing a jointly projective measurement of Bell states on ancillary photons in paths 2 and 3 together with their related Pauli operations on the output photons in path 1 and 4, as described in Eq. (1). For standard linear optical Bell-state analyzer, only two of the four Bell states can be distinguished [37]. In Fig. 1, two Bell states are $|\Psi^+\rangle_{23}$ (indicating coincidences between detectors D_{H1} and D_{V2} or between detectors D_{V1} and D_{H2}) and $|\Phi^-\rangle_{23}$ (indicating coincidences between detectors D_{H1} and D_{H2} or between detectors D_{V1} and D_{V2}). Thus, if there are coincidences between detectors D_1 (D_{H1} or D_{V1}) and D_2 (D_{H2} or D_{V2}), then 1-bit trigger information will be sent to do the related Pauli operations on the outputs (for $|\Psi^+\rangle_{23}$, $U_1 = I_1$ and $U_2 = \sigma_{x4}$; for $|\Phi^-\rangle_{23}$, $U_1 = \sigma_{z1}$ and $U_2 = I_4$), and we will get the desired heralded CNOT gate. The total success probability is 1/8 [36], which can be improved to a optimal value of 1/4 by harnessing complete Bell-state analyzer with more photons [38,39] and hybrid degree of freedoms [40].

Note that when there are multiple photons or no photon in path 2 or 3, unwanted coincidences might happen between detectors D_1 (D_{H1} or D_{V1}) and D_2 (D_{H2} or D_{V2}), leading to uncorrected CNOT operations. However, these cases can be excluded with photon-number-resolving detectors (PNRDs) [41,42] and photon bunching effect [43] provided by PBS3 in $|R\rangle/|L\rangle$ basis (please refer to Ref. [36]). For a high-performance heralded CNOT gate, a truly on-demand SPS together with PNRDs will be the key resources. Here, we demonstrate it by using the best all-around QD-based SPS and pseudo-PRNDs constructed by multiple superconducting nanowire single-photon detectors (SNSPDs).

As shown in Fig. 2, we use the state-of-the-art self-assembled InAs/GaAs QDs embedded inside a micropillar cavity [25] to create single photons of near-perfect purity, indistinguishability, and high brightness. To reach the best QD-cavity coupling with optical resonance at ~893 nm, the whole sample wafer was mounted in an ultrastable liquid-helium-free bath cryostat and cooled down to 4 K. Under pulse resonant excitation with a laser repetition rate ~76 MHz, ~6.4 MHz polarized resonance fluorescence single photons are directly registered by a single-mode fiber coupled SNSPD with a detector efficiency ~80%

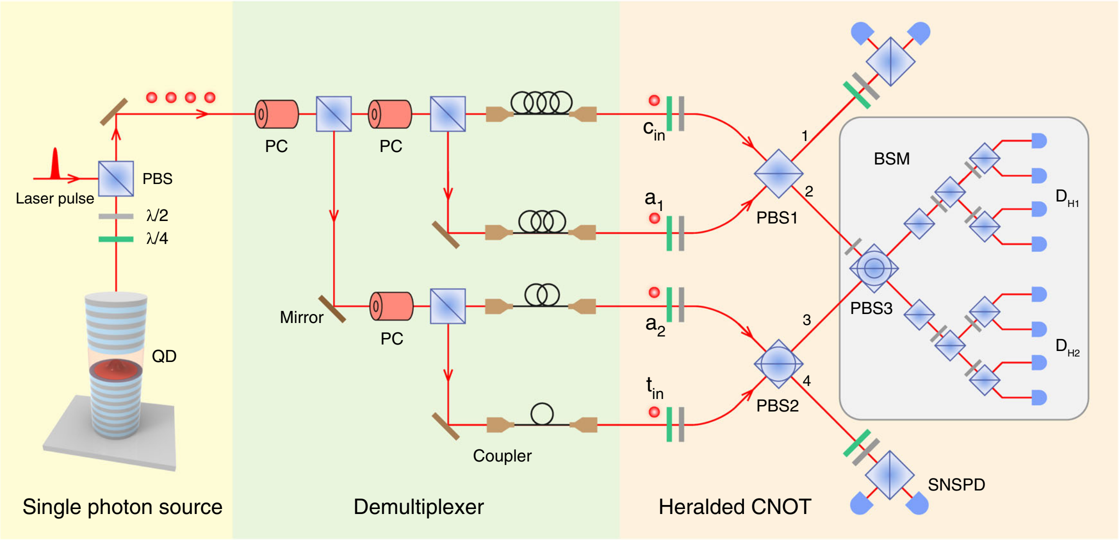

FIG. 2. The experimental setup. A single InAs/GaAs quantum dot, resonantly coupled to a microcavity, is used to create pulsed resonance fluorescence single photons. For demultiplexing, three pairs of Pockels cells (extinction ratio $> 100:1$) and PBSs (extinction ratio $> 2000:1$) are used to actively translate a stream of single photons into four spatial modes. Four single-mode fibers with different lengths (each fiber output port is mounted on a translation stage, without drawn), are used to precisely compensate time delays. Then we adjust the wave plates to prepare general input states, and polarized states $|+\rangle$ and $|H\rangle$ for ancillary photons as described in Fig. 1. These single photons are fed into the heralded CNOT gate. We perform a jointly projective measurement of the Bell state $|\Phi^+\rangle$ by adjusting a half wave-plate (between PBS2 and PBS3) at zero degree, yielding the desired output state of the CNOT operation. The wave plates and a PBS are used for making the polarization basis projection. The single photons are then detected by pseudo-PNRDs constructed by SNSPDs. A successful heralded CNOT operation will be achieved if there is a coincidence between PNRDs D_{H1} and D_{H2} (or D_{V1} and D_{V2}, not show). All fourfold coincidences are recorded by a multichannel coincidence count unit for estimating the gate fidelity [36].

(without any filters). The measured second-order correlation function at zero-time delay is 0.03(1), yielding single-photon purity of ~97%. The photon indistinguishability is measured by a Hong-Ou-Mandel interferometer, yielding a visibility of 0.91(1) between two photons separated by ~6.5 μs [44].

The produced single-photon stream is then deterministically demultiplexed into four spatial modes using the demultiplexer constructed by three pairs of Pockels cells (PCs) and PBSs which are customized for the SPS [36,45]. These PCs will actively control the photon polarization when loaded with high-voltage electrical pulses, synchronized to the laser pulses and operated at a repetition rate ~0.76 MHz. That means in each operation cycle, every 100 single photons will be divided equally into four paths [36]. Thanks to the high transmission efficiency ($> 99\%$) and high single-mode fiber coupling efficiency (~85%), we can reach the average optical switches efficiency ~83% [36,45]. By using single-mode fibers of different lengths and mounting each fiber output end on a translation stage, we can precisely compensate time delays of the four single photons that are fed into the CNOT gate.

Our heralded CNOT operation depends on the ancilla measurement outcome and their related Pauli operators. For simplicity, we perform a jointly projective measurement of Bell state $|\Phi^+\rangle$ on ancillary photons in path 2 and 3, indicating that the output state is exactly the outcome of a CNOT gate. As shown in Fig. 2, $|\Phi^+\rangle$ corresponds to the coincidence between detectors D_{H1} and D_{H2} or between detectors D_{V1} and D_{V2} (not show). We note that unwanted coincidences between heralded detectors can be excluded by pseudo-PNRDs and photon bunching effect [36,43].

To experimentally evaluate the CNOT operation, we exploit an efficient approach proposed by Hofmann [46]. We prepare the input qubits in the computation basis ($|H\rangle/|V\rangle$) as well as the superposition states ($|+\rangle/|-\rangle$). Then we measure the coincidence counts of all possible combinations in each basis recorded by a homemade multichannel coincidence count unit, as summarized in Fig. 3(a) and 3(b). We can see that the gate works well in both bases and the achieved experimental fidelities (defined as the probability of obtaining the correct output averaged over all four possible inputs) are estimated to be the $F_1 = (87.8 \pm 2.1)\%$ in $|H\rangle/|V\rangle$ basis and $F_2 = (88.6 \pm 2.1)\%$ in $|+\rangle/|-\rangle$ basis [36]. With the two complementary fidelities F_1 and F_2, we can bound the quantum process fidelity F_{proc} according to $(F_1 + F_2 - 1) \leq F_{\mathrm{proc}} \leq \min(F_1, F_2)$, yielding $(76.4 \pm 2.9)\% \leq F_{\mathrm{proc}} \leq (87.8 \pm 2.1)\%$. The process fidelity F_{proc} is directly related to the entangling capability, which means it can produce entangled states from separable states. Our result is clearly over the threshold of 0.5 that is sufficient to confirm the gate's entangling ability [46]. Moreover, if the average fidelity of three distinct classical operations exceeds 2/3, one can say that local operations and

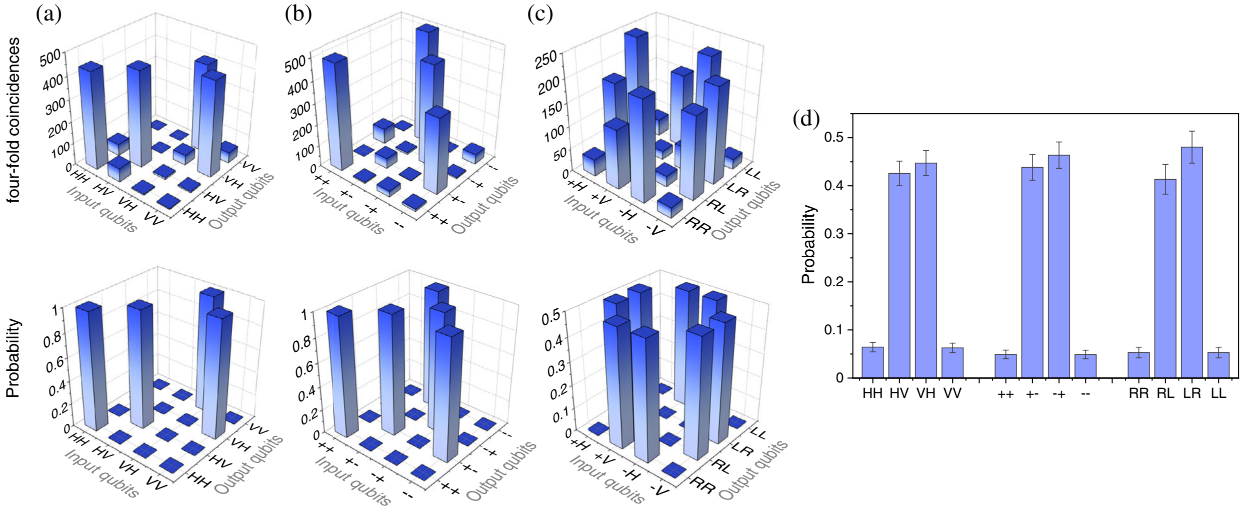

FIG. 3. Experimentally achieved heralded CNOT gate and event-ready Bell states (collected in 6 min). Up: fourfold coincidences for all possible combinations of inputs and outputs; down: ideal gates with 100% fidelity. (a) In $|H\rangle/|V\rangle$ basis. (b) In $|+\rangle/|-\rangle$ basis. (c) We measure the output qubits in $|R\rangle/|L\rangle$ basis when the control and target qubits are in $|+\rangle/|-\rangle$ and $|H\rangle/|V\rangle$ bases. (d) Bell state $|\Psi^-\rangle$ produced by the heralded CNOT gate for input state $|-\rangle_c|V\rangle_t$. The coincidence counts are measured in mutually unbiased bases (here we show the probabilities).

classical communications cannot reproduce the gate [47]. We demonstrate it by preparing the control input in $|+\rangle/|-\rangle$ basis and target input in $|H\rangle/|V\rangle$ basis, and performing the measurement on output qubits in $|R\rangle/|L\rangle$ basis. The experimental result is shown in Fig. 3(c), which gives fidelity $F_3 = (87.0 \pm 2.2)\%$. The average gate fidelity of F_1, F_2, and F_3 is $(87.8 \pm 1.2)\%$, obviously exceeding the boundary of $2/3$.

As an application of the heralded CNOT gate, we produce event-ready entangled states by preparing a separable state $|-\rangle_c|V\rangle_t$ at the inputs. Corresponding to the CNOT operation, we expect outputting a maximally entangled Bell state $|\Psi^-\rangle = 1/\sqrt{2}(|HV\rangle - |VH\rangle)$. To verify that it was implemented successfully, we measured the correlation between the polarizations of control and target photons in a different basis, as shown in Fig. 3(d). The average fidelity of the produced state is $F_{\Psi^-} = (83.4 \pm 2.4)\%$, which clearly surpassed the classical threshold of 0.5 [48,49] and ensures entanglement. Moreover, we can achieve ~85 CNOT operations/min [36] (defined as all output fourfold coincidence counts over the collected time for the input state), which is increased by at least an order of magnitude compared to previous experiments in Table I.

Our demonstrated CNOT gate is heralded and has a high heralding efficiency that could be up to one in principle. What we mean by heralding efficiency is, for a given input state, the probability of achieving a desired CNOT gate when there are coincidences between heralded detectors. For simplicity, we define the experimental heralding efficiency η_h as the ratio between probabilities of fourfold and twofold coincidence counts [36]. One can achieve $\eta_h \approx 0.008$ in the experiment due to the imperfect single photon efficiency η_s ($\eta_s = \eta_f \eta_w \eta_l$, here η_f, η_w and η_l are the efficiencies for photon brightness at the fiber output of confocal system, switches and optical line) when detector efficiency $\eta_d = 0.8$ [36]. However, it is still increased by at least an order of magnitude compared to previous experiments. Also, by coupling QDs to an asymmetric

TABLE I. A comparison of linear optical CNOT gates (for more, see Ref. [36]). SPSs: single-photon sources; PNRDs: photon-number resolving detectors; P_s: theoretical success probability; η_h: heralding efficiency; /: not exit; $\cdots$: unreported.

Experiments	On-demand SPSs	(pseudo) PNRDs	Heralded	P_s	η_h	Operation/min
O'Brien *et al.* [6]	No	No	No	1/9	/	< 1
Okamoto *et al.* [11]	No	No	No	1/16	/	< 2
Gasparoni *et al.* [12]	No	No	No[a]	1/4	$< 10^{-4}$	< 5
Bao *et al.* [17]	No	No	No[a]	1/8	$< 10^{-5}$	< 1
He *et al.* [34]	Yes	No	No	1/9	/	$\cdots$
Gazzano *et al.* [35]	Yes	No	No	1/9	/	$\cdots$
This work	Yes	Yes	Yes	1/8	~0.008	~85

[a] measurement of output states for postselection due to the multiple pair emission of SPDC.

microcavity [30], the output brightness η_f of our QD SPS will hopefully reach to near-unity. Moreover, the switches efficiency can gradually increase close to one in principle [36], which also helps improving η_s. With ideal η_s, η_h could reach to one using perfect PNRDs [36]. Additionally, the indistinguishability and purity of QD-based SPSs can be both improved to near unity [31,34], indicating that the fidelity of CNOT gates can also reach to near unity and the count rates can be further greatly extended.

In summary, by using high-quality single photons produced from QD-micropillar based on-demand SPSs and pseudo-PNRDs constructed by SNSPDs, we have for the first time implemented an optical heralded CNOT gate of high fidelity, high rates, and heralding efficiency increased by at least an order of magnitude. Our results are promising for various QIP tasks such as complete Bell state analysis in quantum teleportation [55,56] and heralded creation of multiphoton entanglement especially cluster states [18,57,58], which is important for large-scale quantum computation.

Interestingly, the single photons for our CNOT gates can be generated by separate sources that can be far away. Then one can realize remote entanglement generation and quantum gates, which are useful for distributed quantum computing and will find new applications in the future quantum internet. Furthermore, our system can be incorporated in realistic fiber systems [59,60] using QD SPSs at telecommunication band [61,62]; thus one can further explore long-distance quantum communication and fiber-optic quantum network. Finally, we suggest that recent developments of integrated optics [63] could be particularly useful to fully realize the demonstrated experiment for miniaturized and scalable photonic QIP.

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