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LETTERS

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Experimental demonstration of a heralded entanglement source

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The heralded generation of entangled states is a long-standing goal in quantum information processing, because it is indispensable for a number of quantum protocols[1,2]. Polarization entangled photon pairs are usually generated through spontaneous parametric down-conversion[3], but the emission is probabilistic. Their applications are generally accompanied by post-selection and destructive photon detection. Here, we report a source of entanglement generated in an event-ready manner by conditioned detection of auxiliary photons[4]. This scheme benefits from the stable and robust properties of spontaneous parametric down-conversion and requires only modest experimental efforts. It is flexible and allows the preparation efficiency to be significantly improved by using beamsplitters with different transmission ratios. We have achieved a fidelity better than 87% and a state preparation efficiency of 45% for the source. This could offer promise in essential photonics-based quantum information tasks, and particularly in enabling optical quantum computing by reducing dramatically the computational overhead[5,6].

Quantum entanglement is one of the key resources in quantum information and quantum foundation. Besides its fundamental interest to reveal fascinating aspects of quantum mechanics, they are also crucial for a variety of quantum information tasks[1,2]. In particular, photonic entangled states are robust against decoherence, easy to manipulate and show little loss, both in fibre and free-space transmission, and thus are exceptionally well suited to long-distance quantum communication and linear optical quantum computing[6,7]. Consequently, an event-ready source of entangled photonic states is of great importance, both from fundamental and practical points of view. Entanglement sources based on the probabilistic generation process of spontaneous parametric down-conversion (SPDC) allow for demonstrations of a number of quantum protocols, but do not permit on-demand applications or deterministic quantum computing, and significantly limit the efficiency of multiphoton experiments. Alternative solutions, such as the controlled biexciton emission of a single quantum dot[8–10] or the creation of heralded entanglement from atomic ensembles[11] face severe experimental difficulties, including a liquid-helium temperature environment and large-volume set-ups.

There has been considerable progress towards the demonstration of heralded photonic Bell pairs. The scheme by Knill, Laflamme and Milburn (KLM)[12] provides a theoretical breakthrough as proof that efficient quantum computing is possible with linear optics. Although the KLM scheme allows the nearly non-probabilistic creation of entanglement, the method they use is still intrinsically probabilistic. The fact that the KLM scheme uses a single photon source, perfect photon-number-resolving detectors and moreover requires a large computational capacity makes it barely accessible experimentally. The proposal of Browne and Rudolph[5] comprises a significant advance in achieving experimental implementation by using photonic Bell pairs as the primary resource and experimentally realistic detectors. Using their proposal, the number of optical operations per logical two-qubit gate reduces to ∼100, in contrast to the original KLM scheme, which would have ∼100,000 (refs 5,6,12). Central to such a dramatic improvement is the use of a heralded entanglement source[5,6].

Various ideas based on conditional detection of auxiliary photons or multiphoton interference have recently been proposed to overcome the probabilistic character of SPDC[4,13–18]. Following this approach, we demonstrate an experimental realization of a heralded entangled photon source by adopting the proposal of Śliwa and Banaszek[4]. This source provides a substantial advance over other general methods by using linear optics[12,13]. In the experiment, we use only commercial threshold single-photon counting modules (SPCM) as detectors and passive linear optics. The source is capable of supporting on-demand applications such as the controlled storage of photonic entanglement in quantum memory[19] to realize a quantum repeater scheme[20]. Moreover, it can be used in on-chip waveguide quantum circuit applications, which have promise in new technologies in quantum optics[21].

To demonstrate the basic principle of the heralded entangled photon source, we present in Fig. 1 the scheme from Śliwa and Banaszek[4]. With an input comprising an SPDC source emitted

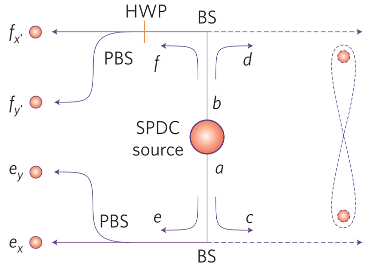

Figure 1 | Schematic set-up. The heralded generation of entangled photon pairs is implemented with an optical circuit composed of non-polarizing partial reflecting beamsplitters (BS), a half-wave plate (HWP) and two polarizing beamsplitters (PBS). The BSs split mode $\hat{a}$ ($\hat{b}$) into a trigger mode $\hat{e}$ ($\hat{f}$) and an output mode $\hat{c}$ ($\hat{d}$). The auxiliary trigger photons are detected in ($\hat{f}_{x'}$, $\hat{f}_{y'}$) in the diagonal (+/−) basis and in ($\hat{e}_x$, $\hat{e}_y$) in the linear (H/V) basis. The set-up will output an entangled photon pair after successful triggering of the four auxiliary photons.

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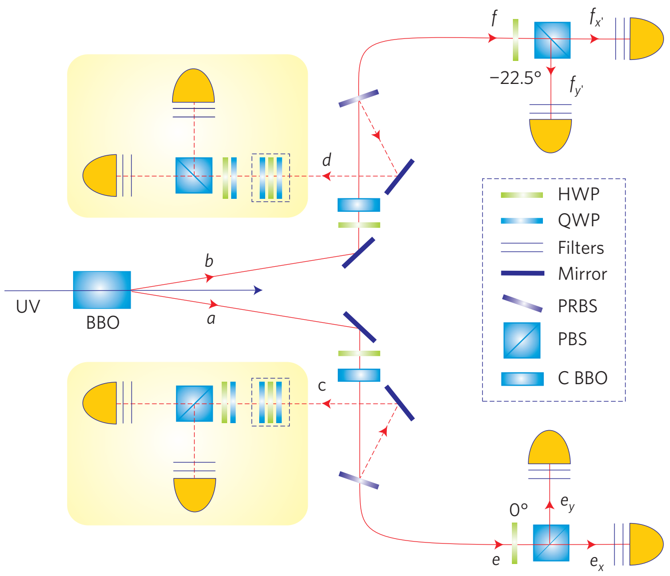

Figure 2 | Experimental set-up for an event-ready entanglement source. After emission, the longitudinal and spatial walk-off of the photons in modes $\hat{a}$ and $\hat{b}$ will be compensated by a HWP and a correction BBO (C BBO) before the photons are directed onto the partial reflecting beamsplitter (PRBS). To control the additional phase introduced by the PRBS we used a combination of two quarter-wave plates (QWP) and one HWP. All photons are filtered by narrow bandwidth filters ($\Delta\lambda \approx 3.2$ nm) and are monitored by silicon avalanche single-photon detectors. Coincidences are recorded by a laser clocked FPGA (field programmable gate array) based coincidence unit.

from modes $\hat{a}$,$\hat{b}$, the scheme heralds an entangled photon pair in $\hat{c}$,$\hat{d}$ modes conditioned by triggers from four photons in $\hat{e}$,$\hat{f}$ modes. A three-pair component of the down-converted photons entangled in polarizations is used as an input to the optical circuit. The quantum state of the three-pair photon term is given by[22]

$$|\Psi_3\rangle = \frac{1}{12}(\hat{a}_x^\dagger \hat{b}_y^\dagger - \hat{a}_y^\dagger \hat{b}_x^\dagger)^3 |\mathrm{vac}\rangle \qquad (1)$$

where $|\mathrm{vac}\rangle$ denotes the vacuum state, and $\hat{a}^\dagger$ and $\hat{b}^\dagger$ are the creation operators of photons in modes a and b. Horizontal and vertical polarization are represented by x and y, respectively. The optical circuit (see Methods) transforms $|\Psi_3\rangle$ into[4]

$$|\Psi_3'\rangle = \frac{1}{\sqrt{2}} R T^2 |\theta\rangle_{\mathbf{t}} |\Phi^+\rangle_{\mathbf{s}} + \sqrt{1 - \frac{T^4 R^2}{2}} |\Gamma\rangle_{\mathrm{ts}} \qquad (2)$$

The first term of equation (2) is composed of a tensor product of two states: the state $|\theta\rangle_{\mathbf{t}} = \hat{e}_x^\dagger \hat{e}_y^\dagger \hat{f}_{x'}^\dagger \hat{f}_{y'}^\dagger |\mathrm{vac}\rangle$ denoting one photon in each of the four trigger modes, and the maximally entangled photon pair in the output modes

$$|\Phi^+\rangle_{\mathbf{s}} = \frac{1}{\sqrt{2}}(\hat{c}_x^\dagger \hat{d}_x^\dagger + \hat{c}_y^\dagger \hat{d}_y^\dagger)|\mathrm{vac}\rangle \qquad (3)$$

The normalized state $|\Gamma\rangle_{\mathrm{ts}}$ is a superposition of all states that do not exactly have one photon in each of the trigger mode $\hat{e}_x$, $\hat{e}_y$, $\hat{f}_{x'}$ and $\hat{f}_{y'}$. Hence, the scheme for the heralded entanglement source is clearly based on the fact that when detecting a coincidence of four single photons in the trigger modes ($\hat{e}_x$, $\hat{e}_y$; $\hat{f}_{x'}$, $\hat{f}_{y'}$), the two photons in output modes ($\hat{c}_x$, $\hat{c}_y$) and ($\hat{d}_x$, $\hat{d}_y$) non-destructively collapse to the maximally entangled state $|\Phi^+\rangle_{\mathbf{s}}$.

In the experiment, we generate the three-pair photon states (1) using a photon source (see Methods) and consequently implement the transformation of the linear optical circuit. A schematic diagram of our experimental set-up is shown in Fig. 2, which is based on the proposal of ref. 4.

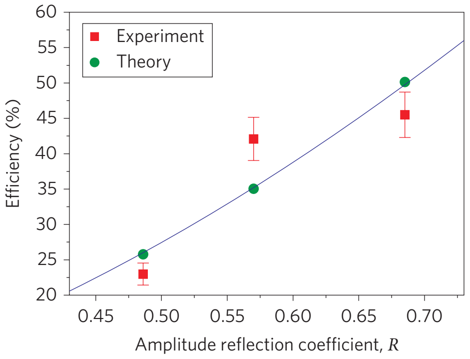

Figure 3 | Efficiency of state preparation. Theoretical and experimental values of preparation efficiency for amplitude reflection coefficients $R = 0.486$, 0.570 and 0.685 are shown. The error bars represent Poissonian statistics of counts. The curve is a function of equation (5), with an average detection efficiency $\eta_t = 0.1823$ for triggers. $\mathrm{eff}_{\mathrm{theory}}$ is an increasing function of R, up to 100%. The quantum efficiency of detectors q used is ~60%. For each 50/50, 60/40 and 70/30 BS ratio, our experimental coupling efficiencies of trigger (p_t) and signal detectors (p_s) are as follows: (p_t, p_s); (27.8%, 21.5%), (28.8%, 22.2%) and (34.5%, 25.0%), respectively. Note that pq is defined as the detection efficiency η.

While taking all experimental imperfections into account (see Methods), it is crucial to evaluate the performance of this source. We have therefore measured the state preparation efficiency and its fidelity, where the efficiency is defined by the number of heralded photon pairs created from the source per trigger signal. For an ideal case, one trigger signal of a fourfold single-photon coincidence perfectly heralds one photon pair creation. In our experiment, performed with standard SPCMs, it is clear that additional terms yielding triggers will thus result in a reduction of the preparation efficiency. To overcome this obstacle, we limit their emergence by decreasing the transmission coefficients of the beamsplitter. In this regime, the probability of transmitting more than the minimum number of photons to the trigger becomes lower, and, as such, the danger of under counting photons in the trigger detectors decreases. However, enhancing the preparation efficiency in this way will lower the overall preparation rate.

To show the relation between the efficiency of state preparation and the transmission coefficients of the partial reflecting beamsplitters, we have chosen beamsplitters with three different reflection/transmission (R/T) ratios: 48.6/51.4, 57.0/43.0 and 68.5/31.5 (Fig. 2). In the following we will abbreviate them as 50/50, 60/40 and 70/30, respectively. This relation is shown in Fig. 3. The experimental efficiency can be represented in a straightforward manner as the following relation by the number of triggers n_t, the average detection efficiency η_s for output states and the number of sixfold coincidences n_s among four trigger modes and two output modes

$$\mathrm{eff}_{\mathrm{exp}} = \frac{n_s}{n_t \eta_s^2} \qquad (4)$$

For each experimental detection efficiency η_s and R/T ratio of 0.129 (50/50), 0.133 (60/40) and 0.15 (70/30), the average coincidence counts (n_s, n_t) observed for 10 h are (37, 9,710), (37, 4,940) and (14, 1,347), respectively. As can be seen from Fig. 3, the experimental results are highly consistent with theoretical estimations (see Supplementary Information):

$$\mathrm{eff}_{\mathrm{theory}} = \frac{R^2}{(1 - \eta_t T/2)^2} \qquad (5)$$

where η_t represents the average detection efficiency for trigger photons. Thus, with this set-up we have significantly improved the preparation efficiency in comparison with that provided by the standard procedure through SPDC. One can consider single input pulses from a UV laser and output photon pairs form SPDC as trigger signals and output states, respectively. The probability of generating one entangled photon pair per UV pulse means the preparation efficiency of the standard procedure through SPDC[22].

To quantify the entanglement of the output photons and evaluate how the prepared state is similar to the state $|\Phi^+\rangle_s$, we determined the state fidelity by analysing the polarization state of the photons in modes $(\hat{c}, \hat{d})$ in the three complementary bases: linear (H/V), diagonal (+/−) and circular (R/L). For an experimental state $\hat{\rho}$, the fidelity is explicitly defined by

$$F = \mathrm{Tr}(\hat{\rho}\left|\Phi^+\right\rangle_{ss}\left\langle\Phi^+\right|) = \frac{1}{4}(1 + \langle\hat{\sigma}_x\hat{\sigma}_x\rangle - \langle\hat{\sigma}_y\hat{\sigma}_y\rangle + \langle\hat{\sigma}_z\hat{\sigma}_z\rangle) \qquad (6)$$

where $\left|\Phi^+\right\rangle_{ss}\left\langle\Phi^+\right| = \frac{1}{4}(\hat{I} + \hat{\sigma}_x\hat{\sigma}_x - \hat{\sigma}_y\hat{\sigma}_y + \hat{\sigma}_z\hat{\sigma}_z)$, $\hat{\sigma}_z = |\mathrm{H}\rangle\langle\mathrm{H}| - |\mathrm{V}\rangle\langle\mathrm{V}|$, $\hat{\sigma}_x = |+\rangle\langle+| - |-\rangle\langle-|$ and $\hat{\sigma}_y = |\mathrm{R}\rangle\langle\mathrm{R}| - |\mathrm{L}\rangle\langle\mathrm{L}|$. Equation (6) implies that we can obtain the fidelity of the prepared state $\hat{\rho}$ by consecutively carrying out three local measurements $\hat{\sigma}_x\hat{\sigma}_x$, $\hat{\sigma}_y\hat{\sigma}_y$ and $\hat{\sigma}_z\hat{\sigma}_z$ on the photons in the output modes $(\hat{c}_x, \hat{c}_y)$ and $(\hat{d}_x, \hat{d}_y)$ (see Methods). In the experiment, we only used threshold SPCMs to perform measurements. The experimental results are shown in Fig. 4. The experimental integration times for each local measurement, with respect to different R/T ratios of the beamsplitter, were ~19 h (50/50), ~17 h (60/30) and ~36 h (70/30). For all three splitting ratios, we recorded more than 50 events of desired six-photon coincidences for each local measurement: ~65 (50/50), ~58 (60/30) and ~62 (70/30). As can be seen from Table 1, the measured values for the fidelity are sufficient to violate the CHSH-type Bell's inequality[23] for Werner states by three standard deviations. As we only used threshold SPCMs as detectors, the measured coincidences are then affected by unwanted events. In our experiment, the effect of the dark count rate in the detectors on the sixfold coincidence is rather small. (For the dark count contribution, the main feature is that one detector is triggered by dark counts and the other five detectors are triggered by the down-conversion photons. Given a three-pair state, the probability of generating a sixfold coincidence count within any particular coincidence window is $S \approx \eta^6$, whereas the leading dark count contribution is $S_d \approx \eta^5 D$, where $D = n_d t$ and n_d is the average dark count rate of the detector and t denotes the coincidence window. In our experiment, $n_d \approx 300$ Hz and $t = 12 \times 10^{-9}$ s. It is then clear that the dark count rate in the detectors contributes a very small part of the sixfold coincidences: $S_d/S = n_d t/\eta \approx 2 \times 10^{-5}$. Here $\eta = 15\%$ is used for the estimation.)

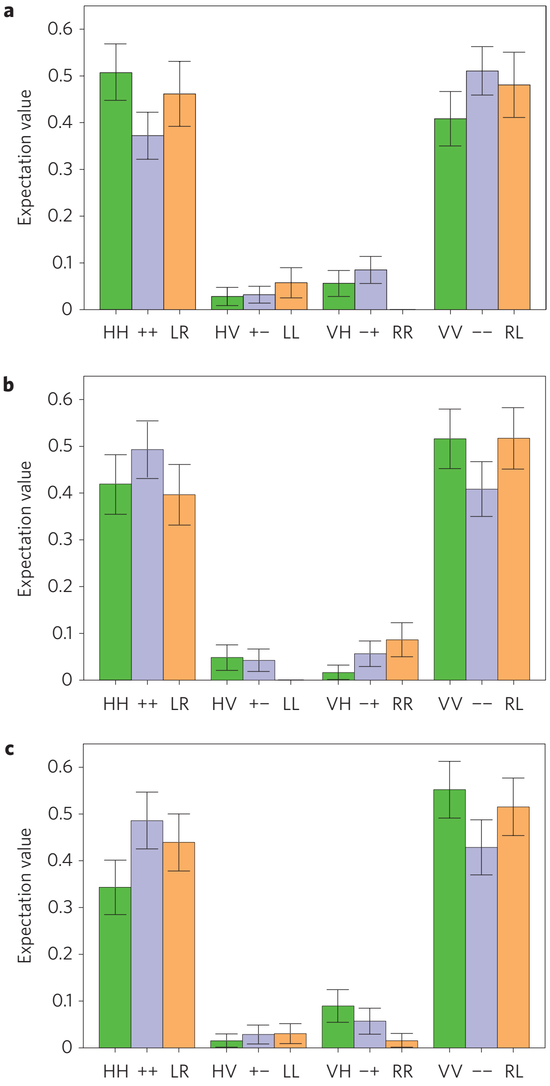

Figure 4 | Experimental data for fidelity measurements. a–c, Complete three-setting local measurements for $\hat{\sigma}_z\hat{\sigma}_z$, $\hat{\sigma}_x\hat{\sigma}_x$ and $\hat{\sigma}_y\hat{\sigma}_y$, corresponding to three complementary bases of $|\mathrm{H}\rangle/|\mathrm{V}\rangle$, $|+\rangle/|-\rangle$ and $|\mathrm{R}\rangle/|\mathrm{L}\rangle$, with $|+\rangle = (|\mathrm{H}\rangle + |\mathrm{V}\rangle)/\sqrt{2}$, $|-\rangle = (|\mathrm{H}\rangle - |\mathrm{V}\rangle)/\sqrt{2}$, $|\mathrm{R}\rangle = (|\mathrm{H}\rangle + i|\mathrm{V}\rangle)/\sqrt{2}$ and $|\mathrm{L}\rangle = (|\mathrm{H}\rangle - i|\mathrm{V}\rangle)/\sqrt{2}$. The plots are for three different splitting ratios R/T of the partial reflecting beamsplitters 50/50 (**a**), 60/40 (**b**) and 70/30 (**c**). The error bars relate to Poissonian statistics of counts.

Table 1 | Experimental fidelity of the entangled output state with respect to the reflection coefficients *R* of the beamsplitters.

Reflection coefficient (*R*)	Fidelity
0.486	0.870 ± 0.028
0.570	0.875 ± 0.030
0.685	0.882 ± 0.028

In conclusion, we have demonstrated a heralded source for photonic entangled states that is capable of circumventing the problematic issue of the probabilistic nature of SPDC. This source is based on the well-known technique of type-II SPDC, which is robust, stable and needs only modest experimental efforts by using standard technical devices. Photon-number-resolving detectors are not involved in the set-up, which is therefore not subject to the restrictions inherent to other schemes implementing heralded entanglement sources[13,15]. To evaluate the performance of our source, we measured the fidelity of the output state, and demonstrated the relation between the amplitude reflection coefficient of the used beamsplitters and the preparation efficiency of the source. A fidelity of better than 87% and a state preparation efficiency of 45% have been achieved. For future applications, the simple optical circuit of our source could be miniaturized as an integrated optics architecture on a chip using the silica-on-silicon technique[24]. Using waveguides instead of bulk optics would be beneficial to stability, performance and scalability of the system[21,25]. We note that during the preparation of the manuscript presented here, we learned of a parallel experiment by Barz *et al.*[26].

Methods

Optical circuit. The transformation of the optical circuit consists of beamsplitter and HWP operations. The beamsplitter operation describes the following transformation of the annihilation operators of modes $\hat{a}_k$ and $\hat{b}_k$ (note that we use annihilation operators to denote the corresponding modes): $\hat{a}_k = \sqrt{R}\hat{c}_k + \sqrt{T}\hat{e}_k$ and $\hat{b}_k = \sqrt{R}\hat{d}_k + \sqrt{T}\hat{f}_k$, for $k = x,y$. $R(T)$ is the amplitude reflection (transmission) coefficient of the beamsplitter. For modes $\hat{f}_x$ and $\hat{f}_y$, the transformation of HWP at

-22.5° is defined by $\hat{f}_x = (\hat{f}_{x'} - \hat{f}_{y'})/\sqrt{2}$ and $\hat{f}_y = (\hat{f}_{x'} + \hat{f}_{y'})/\sqrt{2}$. The optical circuit is able to prevent false signals rising from two-pair emission. This is an important feature of the scheme[4], because the creation probabilities for two pairs are much larger than for three pairs. Furthermore, contributions from the higher-order terms of SPDC can be limited by controlling the corresponding creation probabilities[4]. It is also worth noting that for a given three-pair photon state, the probability of creating a heralded entangled state, that is, $T^4R^2/2$, is controllable by changing the transmission coefficients of the beamsplitter, which can be up to ~0.011 (ref. 4).

Photon source. The required photon pairs were generated by type-II SPDC from a pulsed laser in a β-barium-borate (BBO) crystal. We used a pulsed high-intensity UV laser with a central wavelength of 390 nm, a pulse duration of 180 fs and repetition rate of 76 MHz. For an average power of 880 mW UV light and after improvements in collection efficiency and stability of the photon sources, we observe $\sim 80 \times 10^3$ photon pairs per second with a visibility of $\mathcal{V} = (91 \pm 3)\%$ measured in the diagonal (+/−) basis. (The visibility is defined by $\mathcal{V} = (N_{\mathrm{d}} - N_{\mathrm{ud}})/(N_{\mathrm{d}} + N_{\mathrm{ud}})$, where N_{d} (N_{ud}) denotes the number of twofold desired (undesired) coincidence counts. Then there exists a direct connection between visibility and fidelity of a measured state $\hat{\rho}$: $F = \mathrm{Tr}(\hat{\rho}|\Psi^-\rangle\langle\Psi^-|) = \frac{1}{4}(1 + \mathcal{V}_x + \mathcal{V}_y + \mathcal{V}_z)$, where $\mathcal{V}_k$ for $k = x,y,z$ denotes the visibility of the photon pair in the diagonal, circular and linear bases, respectively. Here $|\Psi^-\rangle$ is the singlet Bell state.) Then the probability of creating three photon pairs is approximately 5.7×10^{-5} per pulse, which is ~33 times larger than that of the next leading order term. The estimation of the three-pair creation probability per pulse is based on the experimental pair generation rate and the theoretical n-pair creation probability[22] $p_n = (n+1)\tanh^{2n} r/\cosh^4 r$, where r is a real-valued coupling coefficient. From the twofold coincidence measurement result, the experimental pair generation rate is $p' = (80 \times 10^3)/(0.15^2 \times 76 \times 10^6) \approx 4.7\%$. We assume that $p_1 = p'$, and r can be directly derived from p_1. Thus the estimated creation probabilities p_3 and p_4 are obtained.

Experimental imperfections. With single photon resolving detectors and 100% detection efficiency, one can see that the three-pair state can provide a maximally entangled photon pair in the output modes deterministically with a 100% probability, if and only if the remaining photons give rise to a fourfold coincidence among the four trigger modes. With the widely used standard SPCM, one cannot discriminate pure single photons from multiphotons, which in reality leads to a significant problem of under-counting photons. Accordingly, the trigger detectors can herald a successful event even though more than two photons from either mode ($\hat{a}_x$, $\hat{a}_y$) or ($\hat{b}_x$, $\hat{b}_y$) or both have been transmitted to the trigger channels. Furthermore, experimentally we were only able to obtain an average detection efficiency of about $\eta = 15\%$ as a result of the limited collection and detector efficiencies. Here the mean detection efficiency is averaged over the coupling efficiency of eight fibre couplers and the quantum efficiency of the detectors. In addition to the imperfect detections, there are two other factors that affect the performance of our source: the non-ideal quality of the initially prepared pairs and the higher-order terms of down-converted photons. For perfectly created pairs, destructive two-photon interference effects[27–29] will extinguish the contribution of two-pair emission to the trigger signal. With an experimental visibility of (91 ± 3)%, imperfectly created states may still give rise to a contribution of two-pair events that leads to the detection of auxiliary triggers. In addition, four-pair emission can again contribute to both the triggers and the output. Although the experimentally estimated creation probability for a four-pair emission is only $\sim 1.7 \times 10^{-6}$ per pulse and is much smaller than the probability for a three-pair photon state, $\sim 5.7 \times 10^{-5}$ per pulse, the four-pair contribution can lead to an error of the theoretical estimation of the expected preparation efficiency of ~4.5%. The four-pair contribution is evaluated in the same way as the three-pair state, where the limited detection efficiency of the trigger detectors is considered in the calculation (see Supplementary Information). In Fig. 3, the fluctuations of our experimental data mainly result from the intrinsic statistics of detector counts, and the stability of optical alignment.

Experimental fidelity *F*. Every expectation value for a correlation function is obtained by making a local measurement along a specific polarization basis, then computing the probability over all the possible events. For example, to obtain the expectation value of *RR* correlation $\mathrm{Tr}(\hat{\rho}|\mathrm{RR}\rangle\langle\mathrm{RR}|)$, we perform measurements along the circular basis and then obtain the result through the number of coincidence counts of RR over the sum of all coincidence counts of RR, RL, LR and LL. All the other correlation settings are performed in the same way. The fidelity *F* can then be evaluated directly.

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Author contributions

C.W., X.-H.B., Y.-A.C., Q.Z. and J.-W.P. designed the experiment. C.W., C.-M.L., A.R., A.G., Y.-A.C. and K.C. performed the experiment. C.W., C.-M.L., A.R., X.-H.B., K.C. and J.-W.P. analysed the data. C.W., C.-M.L., K.C. and J.-W.P. wrote the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper at www.nature.com/naturephotonics. Reprints and permission information is available online at http://npg.nature.com/reprintsandpermissions/. Correspondence and requests for materials should be addressed to K.C. and J.-W.P.