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Heralded generation of entangled photon pairs

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Entangled photons are a crucial resource for quantum communication and linear optical quantum computation. Unfortunately, the applicability of many photon-based schemes is limited due to the stochastic character of the photon sources. Therefore, a worldwide effort has focused on overcoming the limitation of probabilistic emission by generating two-photon entangled states conditioned on the detection of auxiliary photons. Here we present the first heralded generation of photon states that are maximally entangled in polarization with linear optics and standard photon detection from spontaneous parametric downconversion[1]. We use the downconversion state corresponding to the generation of three photon pairs, where the coincident detection of four auxiliary photons unambiguously heralds the successful preparation of the entangled state[2]. This controlled generation of entangled photon states is a significant step towards the applicability of a linear optics quantum network, in particular for entanglement swapping, quantum teleportation, quantum cryptography and scalable approaches towards photonics-based quantum computing[3].

Photons are generally accepted as the best candidate for quantum communication due to their lack of decoherence and the possibility that they may be manipulated easily. However, it has also been discovered that a scalable quantum computer can in principle be realized by using only single-photon sources, linear optical elements and single-photon detectors[4]. Several proof-of-principle demonstrations of linear optical quantum computing have been provided, including controlled-NOT gates[5–8], Grover's search algorithm[9,10], Deutsch–Josza algorithm[11], Shor's factorization algorithm[12,13] and a promising model of one-way quantum computation[14]. A main issue in the development of photonic quantum information processing is that the best current source for photonic entanglement—spontaneous parametric downconversion (SPDC)—is a process in which the photons are created at random times. All photons involved in a protocol need to be measured, including detection of the desired output state. This impedes the applicability of many of the beautiful proof-of-principle experiments, particularly when dealing with multiple photon pairs[3] and standard detectors without photon number resolution.

Other leading technologies in this field are based on other physical systems, including single trapped atoms and atomic ensembles[15], quantum dots[16] or nitrogen-vacancy centres in diamond[17]. Although very promising, each of these quantum state emitters faces significant challenges in realizing heralded entangled states, typically due to low coupling efficiencies, uncertainty in the emission time or the distinguishability in frequency of the photons created.

The probabilistic nature originating from SPDC can be overcome by several approaches conditioned on the detection of auxiliary photons[2,18,19]. It has been shown that the production of one heralded polarization-entangled photon pair using only conventional downconversion sources, linear optical elements and projective measurements requires at least three entangled pairs[20]. We describe an experimental realization (suggested by Śliwa and Banaszek) for producing heralded two-photon entanglement, which relies on triple-pair emission from a single downconversion source[2]. This scheme shows significant advantages compared to other schemes, in which either several SPDC sources and two-qubit logic gates[18] or more ancilla photons[19] are required.

Current downconversion experiments allow for the simultaneous generation of three photon pairs[21–24] with typical detection count rates, dependent on the experimental configuration, of $\sim 1 \times 10^{-3}$ to 1×10^{-1} Hz. We use a set-up of this kind so that the coincident detection of four auxiliary photons is used to predict the presence of two polarization-entangled photons in the output modes. The auxiliary photons thus herald the presence of a Bell state and it is not necessary to perform a measurement on that state to confirm its presence.

Figure 1 provides a schematic diagram of the set-up used to generate the heralded state $|\phi^+\rangle = (1/\sqrt{2})\,(|H\rangle_{t_1}|H\rangle_{t_2} + |V\rangle_{t_1}|V\rangle_{t_2})$, where H and V denote horizontal and vertical polarization, respectively, and t_1 and t_2 correspond to the transmitted modes after the beamsplitters. To generate the heralded state, $|\phi^+\rangle$, three photon pairs must be emitted simultaneously into spatial modes a_1 and a_2, resulting in

$$|\Psi_3\rangle = \frac{1}{2}\Big(|HHH\rangle_{a_1}|VVV\rangle_{a_2} - |HHV\rangle_{a_1}|VVH\rangle_{a_2} + |VVH\rangle_{a_1}|HHV\rangle_{a_2} - |VVV\rangle_{a_1}|HHH\rangle_{a_2}\Big)$$

These photons are guided to non-polarizing beamsplitters (BS_1 and BS_2) with various splitting ratios. This scheme only succeeds when four photons are reflected and measured in a fourfold coincidence. The two reflected photons of BS_1 are projected onto the $|H/V\rangle$ basis for mode r_1, and the two reflected photons of BS_2 are measured in the $|\pm\rangle = (1/\sqrt{2})\,(|H\rangle \pm |V\rangle)$ basis for mode r_2. We are interested in the case where one photon is present in each of the modes $r_{1H,1V}$ and $r_{2+,2-}$. Considering only these terms, the output state results in

$$|\Psi_3\rangle = C(\theta_1, \theta_2) \cdot |H\rangle_{r_{1H}}|V\rangle_{r_{1V}}|+\rangle_{r_{2+}}|-\rangle_{r_{2-}} \cdot \frac{1}{\sqrt{2}}\Big(|H\rangle_{t_1}|H\rangle_{t_2} + |V\rangle_{t_1}|V\rangle_{t_2}\Big) \quad (1)$$

where $C(\theta_1, \theta_2)$ is a constant depending on the transmission coefficients of the beamsplitters. The coincident detection of one and only one photon in each of the modes r_{1H}, r_{1V}, r_{2+} and r_{2-} heralds the presence of an entangled photon pair in state $|\phi^+\rangle$ in the output modes t_1, t_2. In the present scheme such a case can only be achieved by three-pair emission by means of SPDC. The contribution from two-pair emission is suppressed by destructive quantum interference in the half-wave plate (HWP) rotation used for $r_{2+,2-}$. This quantum interference, together with the use of number-resolving detectors, ensures that the remaining two photons are found in

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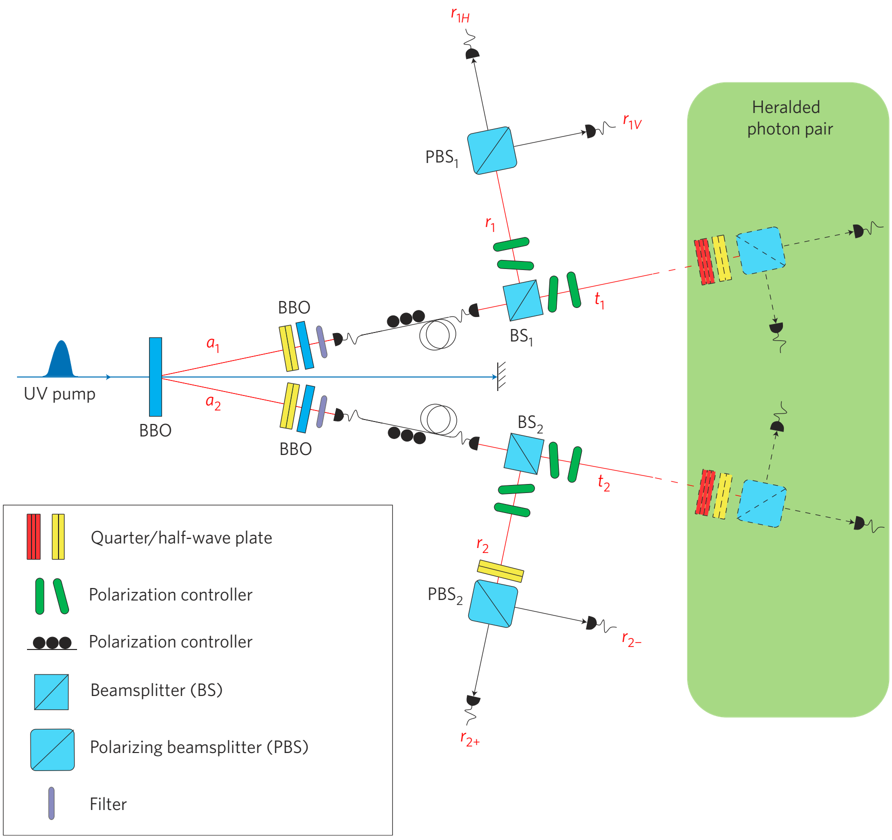

Figure 1 | Set-up for the heralded generation of entangled photon pairs. Six photons are created simultaneously by using higher-order emissions in an SPDC process. The photons pass through a narrowband filters, are coupled to single-mode fibres, and are then brought to beamsplitters. The reflected modes are analysed in the $|H/V\rangle$ basis and in the $|\pm\rangle$ basis, respectively, using polarizing beamsplitters (PBS) and a half-wave plate (HWP) orientated at 45°. State characterization of the heralded photon pair in the transmitted modes is performed through polarization analysis using quarter-wave plates (QWPs), HWPs and PBSs.

Table 1 | List of the photon-number probabilities $P_{n_1;n_2}$ of having n_1 and n_2 photons in the output modes t_1 and t_2.

	17/83	30/70	50/50	70/30
$P_{0;0}$	$(9.74\pm0.002)\times10^{-1}$	$(9.63\pm0.003)\times10^{-1}$	$(9.15\pm0.006)\times10^{-1}$	$(8.68\pm0.02)\times10^{-1}$
$P_{1;0}+P_{0;1}$	$(2.57\pm0.02)\times10^{-2}$	$(3.67\pm0.03)\times10^{-2}$	$(8.19\pm0.06)\times10^{-2}$	$(1.23\pm0.03)\times10^{-1}$
$P_{1;1}$	$(2.58\pm0.16)\times10^{-4}$	$(6.14\pm0.35)\times10^{-4}$	$(3.06\pm0.13)\times10^{-3}$	$(8.03\pm0.65)\times10^{-3}$
$P_{2;0}+P_{0;2}$	$(2.75\pm0.51)\times10^{-5}$	$(3.57\pm0.84)\times10^{-5}$	$(3.72\pm0.36)\times10^{-4}$	$(7.49\pm0.14)\times10^{-4}$
$P_{2;1}+P_{1;2}$	0	$(5.94\pm3.43)\times10^{-6}$	$(3.66\pm1.38)\times10^{-5}$	$(1.07\pm0.76)\times10^{-4}$
$P_{2;2}$	0	0	0	0

The events with the same sum of photon numbers in modes t_1 and t_2 are compared to the probability of obtaining one photon in each of the output modes. The error for each probability follows a Poissonian distribution of the measured counts. (See Supplementary Information for a more detailed analysis, including polarization modes.)

the transmitted modes. If a high transmission of the beamsplitters is chosen, it can still be assumed with high probability that the two photons are transmitted, even without the use of number-resolving detectors.

In the present case, which uses standard detectors (Perkin Elmer photo-avalanche diodes), the transmission of the non-polarizing beamsplitters should ideally be as high as possible so that a measured four-photon coincidence corresponds to precisely four photons and thus heralds our desired state. Therefore, to demonstrate this dependency we chose beamsplitters with the different transmission rates 17%, 50% and 70%. Obviously, the disadvantage of increasing the probability of heralding a $|\phi^+\rangle$ state—which in principle can be approximately unity—is a reduction in the fourfold coincidence rate for triggering this state. It is only recently that improvements in laser sources have enabled stable UV beams with sufficient power to keep the measurement time reasonable; in our case the typical counting time for one measurement setting varied from 24 h to 72 h. The actual rates R for the fourfold coincidences were about $R_{17/83}=83$, $R_{50/50}=14$ and $R_{70/30}=0.4\ \mathrm{min}^{-1}$.

To characterize our heralded state, all polarization-dependent measurement outcomes in output modes t_1 and t_2 that were triggered by the fourfold coincidence in modes r_{1H}, r_{1V}, r_{2+}, and r_{2-} were analysed as a function of the beamsplitter transmission. The measured probabilities of finding the various photon numbers in the output modes are shown in Table 1 and allow for the reconstruction of the diagonal elements of the density matrix in the photon number basis $|n_1\rangle_{t_1}|n_2\rangle_{t_2}$, where n_1 and n_2 are the Fock or photon-number states per spatial mode (see Supplementary Information). The dependency of the photon-number statistic on the beamsplitter ratio can be clearly seen as the vacuum

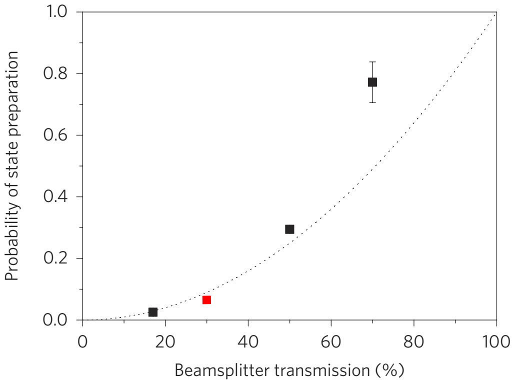

Figure 2 | Probability of heralded entanglement generation for various beamsplitter transmissions. Deviation from the expected quadratic behaviour (line) originates from high-order emissions, which increase the probability of measuring photon pairs in the output modes for higher beamsplitter transmissions. The red data point originates from the experiment with reduced laser power and the error bars follow from Poissonian statistics.

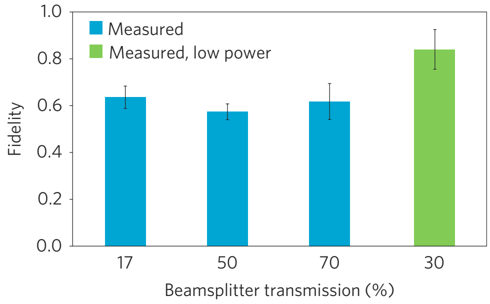

Figure 3 | Experimentally obtained fidelities for the two-qubit polarization state with respect to the ideal state $|\phi^+\rangle$ for various beamsplitter transmissions. The effect of higher-order emission is demonstrated by an additional experimental run with reduced laser power (green). For this experiment, a beamsplitter transmission of 30% was chosen to optimize the required measurement time. As expected, the probability of obtaining the heralded state $|\phi^+\rangle$ increases with transmittance of the beamsplitters, but the polarization-state fidelities are not affected. The error bars are derived from Monte Carlo simulations based on a Poissonian distribution of the measured counts.

contribution $P_{0,0}$ decreases with higher transmission rates. The resulting probability of heralded entanglement generation is graphically shown in Fig. 2 as a function of the beamsplitter transmission. These probabilities, defined as $P = C_6/(C_4 \cdot \eta^2)$, where C_6 (C_4) is the six(four)fold coincidence rate and η is the total photon detection efficiency per mode, are $P_{17/83} = (2.5 \pm 0.2)\%$, $P_{50/50} = (29.4 \pm 1.0)\%$ and $P_{70/30} = (77.2 \pm 6.6)\%$ for the different transmission rates. Remarkably, these probabilities are achieved due to the high visibility of $(86.2 \pm 0.7)\%$ for the destructive four-photon quantum interference.

The detection of more than one photon per spatial mode results from eight or more photon emissions due to the technical limitation of working in the high laser-power regime for optimizing count rates. Clearly, the detected sixfold coincidences for obtaining the $P_{1,1}$ contribution also capture the higher-order emission, covering $\sim$10% of the coincidences for the high laser-power case. Naturally, the averaging of correlated and anti- or non-correlated measurement results decreases the quantum correlations of the desired output state. For fair and sensitive representation of this effect, an additional set of polarization-correlation measurements was performed. Although these polarization measurements were triggered by a fourfold coincidence, the requirement of obtaining an additional twofold coincidence intrinsically leads to a post-selection of the two-photon polarization density matrix (see Methods). The corresponding fidelity values , F^{post}, of this measured photon pair with the corresponding entangled quantum state $|\phi^+\rangle$ were $F^{\text{post}}_{17/83} = (63.7 \pm 4.9)\%$, $F^{\text{post}}_{50/50} = (57.5 \pm 3.4)\%$ and $F^{\text{post}}_{70/30} = (61.9 \pm 7.7)\%$ for the different beamsplitter ratios (by means of local unitary transformations).

To demonstrate the dependency of the state fidelities on laser power (Fig. 3), an additional experimental run was performed with a reduced laser power of 620 mW and beamsplitter transmissions of 30%. The post-selected density matrix of this state in Fig. 4b clearly shows an improvement of the polarization correlations, which is quantified by a fidelity $F^{\text{post}}_{30/70} = (84.2 \pm 8.5)\%$. From these data, we can extract the tangle τ (ref. 25), a measure of entanglement that ranges from 0 for separable states to 1 for maximally entangled states, as $\tau_{30/70} = 0.55 \pm 0.19$. This density matrix, as commonly written in the coincidence basis, would allow a violation of local realistic theories by almost two standard deviations as it implies a maximum

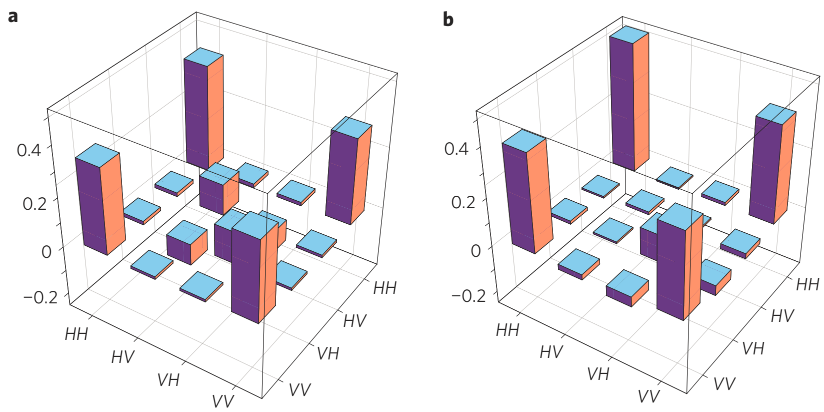

Figure 4 | Effect of higher-order emission on polarization correlations. The trade-off for the increased coincidence rates is manifested in the contribution of higher-order emission. **a**, Experimentally obtained polarization density matrix with a laser power of 1.2 W and a beamsplitter transmission of 50%. The captured eight-photon contribution leads to the background of a $|\psi^-\rangle$ state. **b**, The reduction of the background is demonstrated when reducing the laser power. The experimentally reconstructed two-qubit polarization density matrix is measured with a laser power of 0.62 W and a beamsplitter transmission of 30%. The imaginary part of the density matrices is less than 0.09 for all elements and hence not shown.

Clauser–Horne–Shimony–Holt[26,27] Bell parameter of $S = 2.36 \pm 0.22$. This laser-power-dependent noise is therefore not intrinsic to the set-up and is only a result of technical limitations, which can be overcome in future experiments by using photon-number discriminating detectors or high-efficient downconversion sources.

These two-photon density matrices, together with the measured photon number probabilities, allow calculation of the state fidelities $F^{\text{meas}} = \langle \phi^+ | \rho | \phi^+ \rangle$ of the output states, including vacuum and higher-order terms. These measured total state fidelities can be extracted as $F^{\text{meas}}_{17/83} = (0.0164 \pm 0.0010)\%$, $F^{\text{meas}}_{30/70} = (0.0517 \pm 0.0029)\%$, $F^{\text{meas}}_{50/50} = (0.176 \pm 0.013)\%$ and $F^{\text{meas}}_{70/30} = (0.497 \pm 0.041)\%$, which have significantly improved compared to standard downconversion sources. These results suggest that, with gradual increases in the coincidence rate and the fidelity of entangled photons, the utility of this scheme for quantum information processing tasks may not be far out of reach.

This experiment presents the first feasible scheme for the generation of heralded entangled photon pairs with SPDC and single-photon detectors. This conditional method achieves a high preparation efficiency of up to 77% and measured fidelities of up to 84% for the post-selected two-photon state. These results successfully underline its potential applicability for entanglement-based technologies. In conclusion, we present a multiphoton experiment that generates the heralded entangled states required for long-distance quantum communication and scalable quantum computing.

Note that, during the course of the work presented here, we learned of a parallel experiment by Wagenknecht and colleagues[28].

Methods

We simultaneously produced six photons in the $|\Psi_3\rangle$ state by using higher-order emissions of a non-collinear type-II SPDC process. A mode-locked Mira HP Ti:sapphire oscillator was pumped by a Verdi V-18 laser (Coherent Inc.) to reach output powers high enough to be able to take advantage of third-order SPDC emissions. The pulsed-laser output ($\tau = 200$ fs, $\lambda = 808$ nm, 76 MHz) was frequency-doubled using a 2-mm-thick lithium triborate (LBO) crystal, resulting in UV pulses of 1.2 W c.w. average. We achieved a stable source of UV pulses by translating the LBO with a stepper motor to avoid optical damage to the antireflection coating of the crystal (count rate fluctuations less than 3% over 24 h). Dichroic mirrors were then used to separate the upconverted light from the infrared laser light. The UV beam was focused on a 2-mm-thick β-barium borate (BBO) crystal cut for non-collinear type-II parametric downconversion. HWPs and additional BBO crystals were used to compensate walk-off effects and allow the production of any Bell state. Narrowband interference filters ($\Delta\lambda = 3$ nm) were included to spatially and spectrally select the downconverted photons, which were then coupled into single-mode fibres to guide them to the analyser set-up. There, the photon pairs were directed to non-polarizing beamsplitters, for which the splitting ratios were chosen depending on the particular experiment. The reflected modes were then analysed in the $|H/V\rangle$ basis and in the $|\pm\rangle$ basis. At this specific angle, where the HWP rotates the polarization by 45°, any possible four-photon state emitted into the four modes $r_{1H,1V}$ and $r_{2+,2-}$ will result only in a threefold coincidence because of $|+-\rangle_{r_2} = (|HH\rangle_{r_2} - |VV\rangle_{r_2})/\sqrt{2}$. Thus, these two photons will never be split up at the PBS and therefore never contribute to a fourfold coincidence detection. The typical photon coupling rates and detector efficiencies for each spatial mode were ~23% and 42%.

Our density matrix was reconstructed by a tomographic set of measurements, where combinations of the single-photon projections $|H/V\rangle$, $|\pm\rangle$ and $|R/L\rangle = (1/\sqrt{2})(|H\rangle \pm i|V\rangle)$ on each of the two photons in modes t_1 and t_2 were used. The most likely physical density matrix for our two-qubit state was extracted using a maximum-likelihood reconstruction[29–31]. Uncertainties in quantities extracted from these density matrices were calculated using a Monte Carlo routine and assumed Poissonian errors.

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Author contributions

S.B. and G.C. designed and performed experiments, analysed data and wrote the manuscript. A.Z. supervised the project and edited the manuscript. P.W. designed experiments, analysed data, wrote the manuscript and supervised the project.

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 P.W.