Observation of eight-photon entanglement

Xing-Can Yao, Tian-Xiong Wang, Ping Xu, He Lu, Ge-Sheng Pan, Xiao-Hui Bao, Cheng-Zhi Peng, Chao-Yang Lu*, Yu-Ao Chen and Jian-Wei Pan*

The creation of increasingly large multipartite entangled states is not only a fundamental scientific endeavour in itself1−3, but is also the enabling technology for quantum information4,5. Tremendous experimental effort has been devoted to generating multipartite entanglement with a growing number of qubits6−16. So far, up to six spatially separated single photons10−14 have been entangled based on parametric down-conversion17. Multiple degrees of freedom of a single photon have been exploited to generate forms of hyper-entangled states10,19. Here, using new ultra-bright sources of entangled photon pairs20, an eight-photon interferometer and post-selection detection, we demonstrate for the first time the creation of an eight-photon Schrödinger cat state1 with genuine multipartite entanglement. The ability to control eight individual photons represents a step towards optical quantum computation21,22, topological error correction 23 and testing entanglement dynamics under decoherence24.

In our experiment, we aim to create eight-photon Schrödinger cat states1, also known as Greenberger–Horne–Zeilinger states (GHZ)25, which can be written in the form

\[ |\text{GHZ}_8\rangle = \frac{1}{\sqrt{2}} (|H\rangle^\otimes 8 + |V\rangle^\otimes 8) \quad (1) \]

where \(H\) and \(V\) denote the horizontal and vertical polarizations of the single photons. It involves an equal superposition of eight individual photons in two opposite polarization states. To this end, we first prepare four pairs of polarization-entangled photons in the state \(|\phi^+\rangle = (|H\rangle|H\rangle + |V\rangle|V\rangle)/\sqrt{2}\) using parametric downconversion (PDC)27, and use an eight-photon interferometer to combine them into the Schrödinger cat state (equation (1)).

The first challenge of this experiment is the very low eight-photon coincidence count rate. Detecting eight photons requires all four independent pairs of entangled photons to be present at the same time, so the eight-photon coincidence event count rates are equal to the product of the downconversion probability and \(\xi\) is the overall collection and detection efficiency of a single photon pair. This drops quickly for small \(p\) and \(\xi\). From the \((p \times \xi)\) data from previous six-photon experiments20, one can only expect an eight-photon event count rate of \(\sim 2.8 \times 10^{-5}\) Hz, which is experimentally unfeasible. This demands a considerable improvement in the brightnes of entangled photons.

The second experimental challenge is noise control in the generation of the multipart photon entangled state. Although increasing the single-pair generation rate \(p\) (and therefore the two-photon count rate) can be straightforward when using a higher-power pumping laser, it will inevitably result in a higher double-pair emission rate \((\sim p^2)\), which has been considered to be the main source of noise in multiphoton experiments15,26,27. It is therefore necessary to keep the pumping laser power at a moderate level. In the following we will discuss the eight-photon interferometer and post-selection detection arrangement, which is designed to mitigate the high-order emission noise.

To obtain entangled photon sources with both high count rate and high fidelity, we adopt the Bell-state synthesizer scheme proposed by Kim and colleagues20. As shown in Fig. 1a, a type-II β-barium borate (BBO) crystal is pumped by a femtosecond laser to generate entangled photon pairs \((|H\rangle|V\rangle + |V\rangle|H\rangle)/\sqrt{2}\). However, in ultrafast type-II PDC there are two types of undesired timing information correlated to the polarization that degrade the purity of entanglement. In the first, the group velocities experienced by the different polarizations are not the same; this can be eliminated using a pair of birefringent compensators17. In the second, which only occurs in ultrafast pulsed PDC, the \(H\) and \(V\) polarized light differ in their spectral (and temporal) widths28,29. Most previous multiphoton experiments10−14 have relied on passing the PDC photons through narrow-band filters to select only the most entangled photons (the exception to this is described in ref. 30, where heralded pure-state single photons were generated by controlling the modal structure of collinear PDC photon-pair emission). Such a passive filtering process, however, is inefficient, and many photons are unnecessarily wasted.

This problem can be circumvented using the interferometric Bell-state synthesizer (Fig. 1a). The photon pairs are first guided through two birefringent compensators to remove the walk-off effects, and then superposed on a polarization beamsplitter (PBS) with their path length finely adjusted to achieve perfect temporal overlapping. A half-wave plate (HWP) inserted in one arm rotates the polarization by 90° and ensures that the photon pairs have the same polarization when they reach the PBS. As the PBS transmits \(H\) and reflects \(V\) polarizations, there are two possible outcomes: both photons are transmitted (t–t) or both are reflected (r–r), as displayed in the right panel of Fig. 1a. The PDC photons, originally with \(e\) polarization (with a smaller spectral bandwidth) and o polarization (with a larger spectral bandwidth), are now separated at the exit ports of the PBS and detected by different detectors. Therefore, the timing information in the ultrafast type-II PDC cannot be used to distinguish between the t–t and r–r paths. Subsequently, the two polarization state amplitudes, \(|H\rangle|H\rangle\) and \(|V\rangle|V\rangle\), become quantum-mechanically indistinguishable and form a coherent superposition state \(|\phi^+\rangle = (|H\rangle|H\rangle + |V\rangle|V\rangle)/\sqrt{2}\). This effectively disentangles the timing information from the polarization information of the photon pair. Also note that, because it is never the case that two photons exit the same port of the PBS, in principle no post-selection is required.

We next engineer these photon pairs into the eight-photon Schrödinger cat state (equation (1)). Four e-polarized photons, each from an entangled pair, are combined on a linear optical network consisting of three PBSs (Fig. 1b). It is possible to check that only if all the four incoming photons have the same polarization can they be transmitted \((|HHHH\rangle)\) or reflected \((|VVVV\rangle\) by the...
trally filtered by narrow-band filters (peak transmission rate, ≏ 90% without the use of narrow-band filters. Using a spectrometer, we measured the spectral linewidth of the PDC photons, giving a two-photon coincidence count rate of ≏ 1 MHz with a fidelity of ≏ 94% in the |±⟩ = (|H⟩ + |V⟩)/√2 basis. We estimate a single-pair generation rate of p = 0.058 and a collection and detection efficiency of η = 0.265. To test the indistinguishability between the independent photons, we observed Hong–Ou–Mandel type interferences for the photons overlapping on the three PBSs with an average visibility of ≏ 76%.

To analyse each photon’s polarization state, we used a combination of a quarter-wave plate (QWP), a HWP and a PBS, accompanied by two single-mode fibre coupled single-photon avalanche photodiodes. The signals obtained for the 16 detectors were fed into a homemade field programmable gate array (FPGA)-based programmable coincidence logic unit. This unit registered a complete set of the 256 possible combinations of eight-photon coincidence events (if and only if the eight detectors in each output mode fire simultaneously), which were used for the analysis of the eight-photon cat state. Any detected nine-photon coincidence events were discarded, thereby reducing noise from higher-order PDC emissions.

In our experiment, we were able to obtain approximately nine eight-photon coincidence events per hour. To verify that the eight-photon Schrödinger cat state (equation (1)) had been created, we first showed that under the condition of registering eight-photon coincidences, only |H⟩⊗8 and |V⟩⊗8 are observed, and no others. This was done by comparing the counts of all 256 possible polarization combinations in the H/V basis. The experimental data are shown in Fig. 3a, where the |H⟩⊗8 and |V⟩⊗8 terms can be seen to dominate the overall coincidence events with a signal-to-noise ratio (defined as the ratio of the average of the desired components to that of the non-desired ones) of 530:1. To verify that |H⟩⊗8 and |V⟩⊗8 are indeed in a coherent superposition, we also performed measurements in the basis ⟨(|H⟩ ± e^iθ|V⟩)/√2, where θ = kπ/8 (k = 0, 1, . . . , 7). For example, it is easy to check, for k = 0, that the cat state of equation (1) can be rewritten in an expression containing 128 (out of 256) terms, where those with an even number of

![Figure 1](https://example.com/figure1.png)

**Figure 1 | Experimental scheme for generating eight-photon Schrödinger cat states. a**: Left: an initial photon pair is generated by a non-collinear type-II PDC and passes through a pair of birefringent compensators (not shown) consisting of a 1 mm BBO crystal and a HWP. After one photon’s polarization is rotated by 90° using the HWP, the two photons are superposed on a PBS. Right: the principle of an interferometric Bell-state synthesizer. Here, the photon leaves the BBO crystal with ‘e’ and ‘o’ polarizations with different spectral widths, which are separated by the PBS and detected by different detectors. This effectively disentangles the timing information from the polarization information of the photon pair, generating high-fidelity entangled photons. **b**: Left: an interferometer combining four incoming e-polarized photons (each from an entangled pair) with three PBSs. With coincidence detection, the four pairs of entangled photons are transformed into the eight-photon Schrödinger cat state (equation (1)). Right: graph state representation of the process of engineering the four photon pairs into the eight-photon cat state. The graph state can be thought of as being constructed by first preparing the qubits at each vertex in the state |±⟩ = (|H⟩ + |V⟩)/√2 and then applying controlled phase gates between pairs of neighbouring qubits.
the $|\tilde{-}\rangle$ component (for example, $|+\rangle\otimes|e\rangle$, $|+\rangle\otimes|\tilde{-}\rangle\otimes|e\rangle$) occur, but combinations with an odd number of $|\tilde{-}\rangle$ do not. This is confirmed by measurement results that have a signal-to-noise ratio of $\approx 4:1$. From these, we determine the expectation values of the observables, $\langle M^k \rangle = \langle \cos \theta \tau + \sin \theta \tau \rangle^{\otimes k}$, which yield an average value of 0.610 ± 0.026 (Fig. 3b).
We can determine the fidelities of the cat states and detect the presence of genuine multipartite entanglement by using the tool of 'entanglement witness'. The fidelity is a measure of to what extent the desired state is created and can be calculated by the overlap of the experimentally produced state with the ideal one. For the cat state (equation (1)),

$$O_H = \frac{|S_{10}/S_{01}|}{1} \left( (|H|\langle H|)^{\otimes 8} + (|V|\langle V|)^{\otimes 8} \right) + \frac{1}{16}\sum_{k=0}^{7}(-1)^k M_k^{\otimes 8}$$

From the experimental data shown in Fig. 3, we calculate the fidelity of our eight-photon Schrödinger cat state as 0.708 ± 0.016. For the cat-type entangled states, it is sufficient to prove the presence of genuine multipartite entanglement if their fidelities exceed the threshold of 0.5. Thus, with a high statistical significance (~14 standard deviations), genuine eight-photon entanglement is confirmed experimentally.

In conclusion, by exploiting the new techniques using an ultra-bright entangled photon source, a noise-reduction multiphoton interferometer and post-selection detection, we have experimentally generated and characterized the eight-photon Schrödinger cat state. Being able to entangle eight individual single photons surpasses the state-of-the-art six-photon capability and will enable new quantum optics and quantum information experiments with multiphoton entanglement in previously inaccessible parameter regimes. As well as the eight-photon technique, we can also take advantage of the photons’ other degrees of freedom (such as spatial mode and/or orbital angular momentum) to further expand the Hilbert space, which would allow experimental control of entangled states up to 16–24 qubits. Such a multiphoton set-up can facilitate many applications in optical quantum computing. One immediate application is to demonstrate the topological error correction scheme with eight-photon graph states. It can serve as a moderately sized quantum simulation testbed for studying interesting phenomena in solid-state physics and quantum chemistry. It may also allow tests of the stability and dynamics of different families of entangled states (such as Schrödinger cat states and one- and two-dimensional cluster states) under the effect of decoherence, which may provide new insights into our understanding of the intriguing questions of the classical to quantum transition.

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