Demonstration of efficient scheme for generation of “Event Ready” entangled photon pairs from single photon source

Qiang Zhang,1,2 Xiao-Hui Bao,1 Chao-Yang Lu,1 Xiao-Qi Zhou,1 Tao Yang,1 Terry Rudolph,3,4 and Jian-Wei Pan1,2

1Hefei National Laboratory for Physical Sciences at Microscale & Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, P.R. China
2Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, 69120 Heidelberg, Germany
3Optics Section, Blackett Laboratory, Imperial College London, London SW7 2BZ, United Kingdom
4Institute for Mathematical Sciences, Imperial College London, London SW7 2BW, United Kingdom

We present a feasible and efficient scheme, and its proof-of-principle demonstration, of creating entangled photon pairs in an event-ready way using only simple linear optical elements and single photons. The quality of entangled photon pair produced in our experiment is confirmed by a strict violation of Bell’s inequality. This scheme and the associated experimental techniques present an important step toward linear optics quantum computation.

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There is a considerable worldwide effort to produce clean single photon sources; whole conferences and journal issues have been devoted to the topic. Leading technologies in this effort are based on physical systems as diverse as quantum dots, single trapped atoms, filtered signal photons from parametric down-conversion and surface acoustic waves in silicon, to name but a few. Although they will find immediate uses in quantum communication, one of the more exciting possibilities for single photon sources is that they may be utilized with only linear optical elements and photon number detectors to build a quantum computer, as was shown in the seminal paper of Knill, Laflamme and Milburn.

A first necessary step to turn single photons into a useful resource for quantum information processing is to generate “event ready” entangled pairs from them. Although the KLM scheme shows that this is in principle possible, in practise their proposal requires keeping complicated interferometers stable over a photon wavelength; moreover the gates succeed with probability only 1/16. By contrast we present here a new idea for generating entangled photon pairs from single photons which succeeds with a probability of up to 3/16.

Our scheme for generation of a maximally entangled pair of photons given four single photons as input is shown in Fig. 1 which works as follows:

Four single photons A1,A2,B1,B2 are each prepared in the state $|H\rangle + |V\rangle$, corresponding to polarization of 45-degrees. Photons A1 and A2 interfere at one polarizing beam splitter (PBS), B1 and B2 interfere at another PBS. The state after the two PBS’s is

$$|\psi\rangle = \frac{1}{4}(|HV\rangle_{A1}|0\rangle_{A2} + |0\rangle_{A1}|HV\rangle_{A2} + |H\rangle_{A1}|H\rangle_{A2} + |V\rangle_{A1}|V\rangle_{A2})$$

FIG. 1: Scheme for creation of “event ready” entangled photon pairs from single photons. RPBS represents a 45-degree oriented PBS.

The outputs A2' and B2' then undergo Type-II fusion - specifically they are interacted at a PBS oriented at 45-degrees (accomplished by inserting one half-wave plate in each of the two inputs and two outputs of an ordinary PBS), and then undergo polarization sensitive detection. Whenever there is a coincidence between detectors D1 (either D1h or D1v) and D2 (either D2h or D2v), photon A1' and B1' will be collapsed into a maximally entangled Bell state. To understand why, note from Eq. 1 that the four-photon state has 16 terms before entering the 45-degree oriented PBS. However, the photons in the state of $|HV\rangle |0\rangle |0\rangle |HV\rangle$ will “stick” together because of the “photon bunching” effect when passing through the 45-degree oriented PBS. Therefore, choosing the conditions where there is one and only one photon in each photon-number detector D1 and D2, i.e. a coincidence between D1 and D2, we have post-selected the items $|HV\rangle |0\rangle |0\rangle |HV\rangle$.
\(|V\rangle_{B1}(V)_{B2}\rangle\) from Eq. 1.

An alternative way to see what happens is as follows. Similar to the case of “entanglement swapping” \[11, 12\], we can rewrite the state after the initial two PBS’s as:

\[
|\psi\rangle = |\phi^+\rangle_{A1'}A2' |\phi^+\rangle_{B1'B2'}
= |\psi^\prime\rangle_{A2'B2'} |\phi^+\rangle_{A1'B1'}
+ |\psi^-\rangle_{A2'B2'} |\phi^\prime\rangle_{A1'B1'}
+ |\phi^+\rangle_{A2'B2'} |\phi^\prime\rangle_{A1'B1'}
+ |\phi^-\rangle_{A2'B2'} |\phi^\prime\rangle_{A1'B1'}.
\]

(2)

To generate an entangled photon pair in A1’ and B1’ mode, two PBSs are placed after the 45-degree oriented PBS to make a partial Bell-state measurement. When there is a coincidence between D1h and D2h, or between D1v and D2v, the state of photon A2' and photon B2' must be \(|\phi^+\rangle_{A2'B2'}\) and the state of photon A1', B1' will be collapsed into \(|\phi^+\rangle_{A1'B1'}\). Alternatively, coincidence between D1h and D2v or between D1v and D2h demonstrates that photon A2', B2' are in the state of \(|\psi^\prime\rangle_{A2'B2'}\), which will collapse the photon A1', B1' in a state of \(|\psi^\prime\rangle_{A1'B1'}\). \[13\].

In our experiment, the four single photons are achieved by filtering signal photons from type II spontaneous parametric down-conversion(SPDC) \[14\]. The setup of our experiment is shown in Fig. 2. A 394nm ultra violet(UV) pulse passes through a nonlinear crystal (BBO) twice and generates two polarization entangled photon pairs in the state \(|\phi^+\rangle = \frac{1}{\sqrt{2}}(|H\rangle|H\rangle + |V\rangle|V\rangle)\), via SPDC. The power of the UV pulse is 600 mw and produces 10,000 pairs per second. Four 45-degree linear polarizers are utilized to disentangle the photon pairs into single photons(A1-2, B1-2) each in the state \(|+\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)\). To make itself a perfect single photon source, photon A1(B1) needs to take their twin photon A2(B2) as a trigger signal and vice versa \[8\], which means photon A1(B1) cannot be seen as a single photon source until photon A2(B2) is detected. Therefore, to guarantee that the photon sources are real single photon source, four photon coincidences are necessary in our experiment. The four photon coincidence also has another advantage: In Eq. 2, only the desired item \(|\phi^+\rangle_{A2'B2'} |\phi^+\rangle_{A2'B2'}\) or \(|\psi^\prime\rangle_{A2'B2'} |\phi^\prime\rangle_{A1'B1'}\) can provide a four-fold coincidence between detectors D1(D1h or D1v), D2(D2h or D2v), D3 and D4, so the four-fold coincidence can help to post select the desired state instead of photon number detection in the original scheme.

With the help of a prism 1(2) mounted on a micrometer translation stage, single photon A1(B1) and A2(B2) are interfered at a PBS as suggested in Fig. 1. Scanning the prism 1(2)’s position to overlap the input single photons perfectly at the PBS’s, we can achieve an "Hong-Ou-Mandel" type interference curve \[12\]. We lay the prism 1(2) on the position which provides the best interference visibility (about 94%).

After the interference, the output modes A2’, B2’ are directed into the 45-degree oriented PBS as is shown in Fig. 2. To further generate the “event ready” entangled photon pairs, we vary B2’s path length by scanning the Delay Mirror such that photon A2’ and B2’ arrive at the 45-degree oriented PBS simultaneously. However, due to the poor four-fold coincidence (about 0.3 per minute) and the ultrashort coherence length of the single photons (about 200 \(\mu m\)), it is not easy to achieve a good spatial and temporal overlap of photons A2’ and B2’ at the 45-degree oriented PBS. As such, we developed an easier way to achieve the interference with a slight modification of the setup. We change the two half-wave plates at the input modes of the 45-degree oriented PBS from 45 degrees to 0 degrees. With the modification, the “photon bunching” effect will disappear and the orthogonally polarized photons in the terms \(|HV\rangle_{A2'}\) or \(|HV\rangle_{B2'}\) will be separated by the 45-degree oriented PBS,
and will give a coincidence between Detectors 1 and 2. When the two modes A2' and B2' are overlapped perfectly and a coincidence between D1 and D2 is observed, the states of the two output modes will be collapsed into \(\langle H|V\rangle + e^{i\phi}|V\rangle|H\rangle/\sqrt{2}\), where \(\phi\) is the phase difference of the two input path modes. As is shown in Fig. 3 we scan the delay mirror with a step motor to observe the two-photon interference curve and lock the delay at the position with the best visibility, which is just the position for the photons to perfectly overlap. Since only two photon are involved in the above process, the coincidence between photon A1' and photon B1' conditioned on the detection of photon A2' and photon B2' is obtained or not, we analyze the polarization correlation between photon A1' and photon B1' conditioned on coincidences of D1 and D2. We utilize two polarizers in modes A1' and B1' to analyze the polarization coherence. B1's polarizer is put at 0 or 45 degree, and we change the polarizer in A1's mode to do the analysis. If the entangled photon pair is produced, the twofold coincidence between A1' and B1' should show two sine curves as functions of \(\theta_{A1'}\), as \(\theta_{B1'}\) is set at 0 or 45 degree respectively. Fig. 4 shows the experimental result for the coincidences between A1' and B1', given that photons A2' and B2' have been registered as a trigger. The experimentally obtained coincidences shown in Fig. 4 have been fitted by a joint sine function with the same amplitude for both curves. The observed visibility of 89% clearly surpasses the 0.71 limit of Bell’s inequality [10], which indicates the photon pair is genuinely entangled.

The high-visibility sinusoidal coincidence curves in the experiment imply a violation of the Clauser-Horne-Shimony-Holt (CHSH) [17] inequality, \(S < 2\) for any local theory, where \(S = E(a,b) - E(a',b') + E(a',b) + E(a,b')\). Here \(E(a,b)\) are the usual expectations of differences in correlation/anti-correlation of the outcomes, where a, \(a'\) (b, \(b'\)) is the polarizer setting for photon A1' (B1'). In our experiment, we set \(a = 0\), \(a' = 45\), \(b = 22.5\) and \(b' = 67.5\), which maximizes the prediction of quantum mechanics of \(S\) to \(S_{qm} = 2.8\) and leads to a contradiction between locality and the predictions of quantum mechanics. In our experiment, the four correlation coefficients between photon 1 and 3 gave the following results: \(E(0, 22.5) = 0.57 \pm 0.05\), \(E(0, 67.5) = -0.67 \pm 0.04\), \(E(45, 22.5) = 0.65 \pm 0.04\), and \(E(45, 67.5) = 0.69 \pm 0.04\). Hence \(S = 2.58 \pm 0.07\) which violates the classical limit of 2 by 6 standard deviations. This clearly confirms the quantum entanglement between the two photons.

In summary, we have presented a feasible and efficient scheme to create “event ready” entangled photon pairs with single photon sources and detectors. We also pro-
vide a proof-in-principle experimental demonstration of
the scheme with the help of filtered signal photons from
down conversion. The generated “event ready” entangled
photon pairs present a strict violation of Bell’s inequal-
ity by 6 standard deviations. Although our experiment is
only a proof-in-principle demonstration which still needs
post-selection, the techniques developed in the experi-
ment can be readily used to generate heralded entangled
photon pairs with the help of photon number detectors
\[18, 19\], which will find more application in long distance
quantum communication \[20\] and large scale quantum
computation \[21\].

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sired condition is only 2/16. However,
the item \((|HV\rangle_{A1'}|0\rangle_{A2'}|0\rangle_{B1'}|HV\rangle_{B2'} +
|0\rangle_{A1'}|HV\rangle_{A2'}|HV\rangle_{B1'}|0\rangle_{B2'})/4\) may collapse pho-
ton A1’ and B1’ into the maximally entangled state
\((|HV\rangle_{A1'}|0\rangle_{B1'} + |0\rangle_{A1'}|HV\rangle_{B1'})/\sqrt{2}\) when there is a
coincidence between D1h(D2h) with D1v(D2v), with a
probability of 1/16. We only demonstrate the former
2/16 probability of success in the experiment.

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