Experimental Study of Entanglement Manipulation using Parametric Down-Conversion

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We report an experiment on entanglement manipulation for two polarization entangled photon pairs using parametric down-conversion. Our experimental scheme, which has been proposed in [Phys. Rev. **A64**, 012304(2001)], is a modification of the concentration scheme proposed by Bennett, *et al.* [Phys. Rev. **A53**, 2046(1996)]. To demonstrate this scheme experimentally, we prepared entanglement controllable photon pair source, which uses parametric down-conversion from two separated Type I phase matched BBO crystals, and we observed four photon interference. In this poster session, we will report our latest experimental result.

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In many applications in quantum information processing, it is essential that two separated parties, Alice and Bob, share maximally entangled particles in advance. Practically, a quantum channel is usually noisy. It is thus important that Alice and Bob share maximally entangled pairs even through such channels. For that purpose, entanglement concentration [1] and purification (or distillation) [2] have been originally proposed. Until today, many schemes to obtain maximally entangled particles by LOCC have been proposed, however only one simplest method, which was based on local filtering (Procrustean method[1]), was demonstrated experimentally [3].

Recently, we proposed an experimentally feasible concentration/purification scheme[4], in which a maximally entangled photon pair is obtained from two photon pairs in identically partially entangled states. The basic idea of this scheme is based on the concentration scheme proposed by Bennett, *et al.* [1]. In our scheme, Alice and Bob use only linear optical elements and photon detectors, so that this scheme is feasible today. Moreover, unlike the scheme used in [3], our scheme is applicable to quantum channels with several kinds of unknown fluctuations[4]. To demonstrate our scheme experimentally, we prepared entanglement controllable photon pair source [5, 6, 7], which uses parametric down-conversion from two separated Type I phase matched BBO crystals, and observed four photon interference. This kind of interference technique, which had been already observed by parametric down-conversion from Type II phase matched BBO crystals in [8, 9, 10], is useful for other quantum information processing by linear optical elements and photon detectors [11, 12, 13, 14].

First, we show how the two separated parties, Alice and Bob, can obtain a maximally entangled photon pair from two identically partially entangled photon pairs by LOCC. Let us assume that two pairs of photons are given to Alice and Bob in the following polarization entangled states

$$|\alpha,\beta\rangle_{12}|\alpha,\beta\rangle_{34} \equiv (\alpha|1\rangle_{1\mathrm{H}}|1\rangle_{2\mathrm{H}}+\beta|1\rangle_{1\mathrm{V}}|1\rangle_{2\mathrm{V}}) \otimes(\alpha|1\rangle_{3\mathrm{H}}|1\rangle_{4\mathrm{H}}+\beta|1\rangle_{3\mathrm{V}}|1\rangle_{4\mathrm{V}}),$$

where α and β are complex numbers satisfying $|\alpha|^2+|\beta|^2=1$ and $|n\rangle$ is the normalized n-photon number state. The subscript numbers represent the spatial modes, and H and V represent horizontal and vertical polarization modes, respectively. As shown in Figure 1, Alice receives photons in modes 1 and 3, and Bob receives photons in modes 2 and 4. Using the linear optical elements in Figure 1, Alice and Bob receive photons in the state,

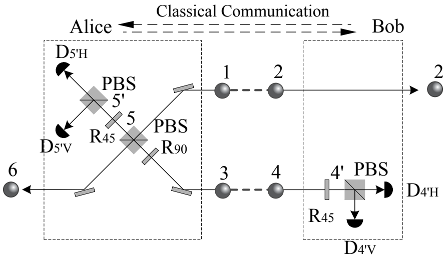

Figure 1: The schematic diagram of the proposed purification scheme. Polarization beam splitters (PBS) transmit H photons and reflect V photons. $\lambda/2$ wave plates R_{45} and R_{90} rotate the polarization by 45° and 90° respectively. Recently, this detection scheme in Alice's side is noticed as nondeterministic quantum parity check [14, 16], the basic idea was described in [15], and this kind of logic operation was used in [13, 11, 4].

$$\begin{aligned}|\Psi\rangle =& \frac{\alpha^2}{\sqrt{2}}|0\rangle_{5'}(|1\rangle_{4'\mathrm{H}}+|1\rangle_{4'\mathrm{V}})|1\rangle_{6\mathrm{H}}|1\rangle_{6\mathrm{V}}|1\rangle_{2\mathrm{H}} \\ &+\frac{\beta^2}{2}(|2\rangle_{5'\mathrm{H}}|1\rangle_{4'\mathrm{H}}-|2\rangle_{5'\mathrm{H}}|1\rangle_{4'\mathrm{V}} \\ &-|2\rangle_{5'\mathrm{V}}|1\rangle_{4'\mathrm{H}}+|2\rangle_{5'\mathrm{V}}|1\rangle_{4'\mathrm{V}})|0\rangle_6|1\rangle_{2\mathrm{V}} \\ &+\frac{\alpha\beta}{\sqrt{2}}(|1\rangle_{5'\mathrm{H}}|1\rangle_{4'\mathrm{H}}|\Phi^{(+)}\rangle_{62}-|1\rangle_{5'\mathrm{H}}|1\rangle_{4'\mathrm{V}}|\Phi^{(-)}\rangle_{62} \\ &+|1\rangle_{5'\mathrm{V}}|1\rangle_{4'\mathrm{H}}|\Phi^{(-)}\rangle_{62}-|1\rangle_{5'\mathrm{V}}|1\rangle_{4'\mathrm{V}}|\Phi^{(+)}\rangle_{62}),\end{aligned}$$

where $|\Phi^{(\pm)}\rangle_{62} \equiv 1/\sqrt{2}(\ |1\rangle_{6\mathrm{H}}|1\rangle_{2\mathrm{H}} \pm |1\rangle_{6\mathrm{V}}|1\rangle_{2\mathrm{V}}\ )$ is the state of the maximally entangled photon pair. If Alice and Bob detect a single photon at $\mathrm{D}_{5'\mathrm{H}}$ and $\mathrm{D}_{4'\mathrm{H}}$ (or $\mathrm{D}_{5'\mathrm{V}}$ and $\mathrm{D}_{4'\mathrm{V}}$) and the state is projected to $|1\rangle_{5'\mathrm{H}}|1\rangle_{4'\mathrm{H}}|\Phi^{(+)}\rangle_{62}$ (or $|1\rangle_{5'\mathrm{V}}|1\rangle_{4'\mathrm{V}}|\Phi^{(+)}\rangle_{62}$), they can share a maximally entangled photon pair in the state $|\Phi^{(+)}\rangle_{62}$. (If Alice and Bob are allowed to perform the postselection in mode 6 and 2, they need not distinguish a single photon from two or more photons, because Alice obtains vacuum in mode 6 whenever she obtains two photons in mode 5′.)

To demonstrate our entanglement manipulation, we prepared entanglement controllable photon pair source [5, 6, 7], which uses parametric down-conversion from two separated Type I phase matched BBO crystals. The setup of polarization entangled photon source is shown in Figure 2. A mode-locked Ti:Sapphire laser at

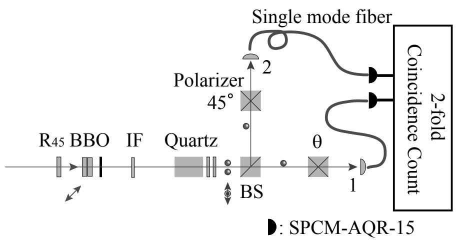

Figure 2: The setup of our experiment for polarization entangled photon pair.

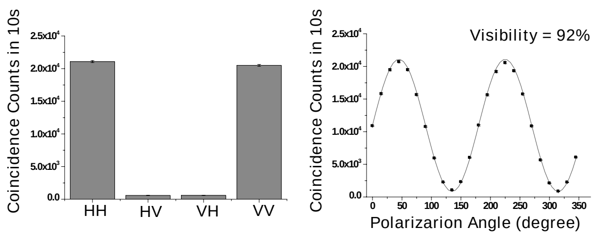

Figure 3: Experimental test of the entanglement of the photon pair. These results are consistent with the state $|\Phi^{(+)}\rangle_{12}$.

a wavelength of 790nm, a pulse width of 100fs, and a repetition rate of 82MHz, was frequency doubled at an average power of 350mW and directed into BBO crystals for parametric down-conversion. When only one photon appears in each port of BS, these two photons are entangled. To confirm the entanglement, we collected all photons in single-mode optical fibers through polarizers and then performed coincidence measurement. (In order to control the entanglement of the photon pair, we rotate the polarization of pump beam from 45°.) The result of the coincidence measurement is shown in Figure 3. As expected, coincidence counts displayed sinusoidal fringes with high visibility (92%). We can obtain $\sim$ 2000 coincidence counts per second, this result is comparable to a recent teleportation experiment [17].

Using this photon pair source, we performed a four photon interference experiment. The setup is shown in Figure 4. We produced the two entangled photon pairs with the scheme described in Figure 2, by reflecting the pump beam in opposite direction using the dichroic mirror(d). This dichroic mirror was moved by motorised stage in order to adjust the path difference between two photon pairs. The result of the fourfold coincidence measurement is shown in Figure 5. The visibility of four photon interference is roughly 50%. This is the first experimental result of four photon interference for photon pair source using two separated Type I phase matched BBO crystals. Now, we are trying to obtain four photon interference with higher visibility. In this poster session, we will report our latest results.

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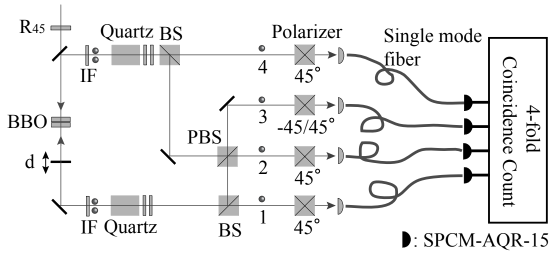

Figure 4: The setup of the four photon interference experiment.

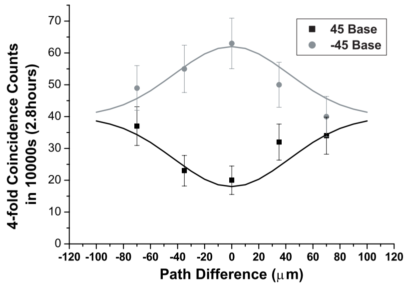

Figure 5: Observation of four photon interference. The number of fourfold coincidence events per 10000s is plotted as a function of the path difference between two photon pairs . The angles of polarizers in mode 1, 2, and 4 are all 45° . The two plots correspond to the angles 45° and $-45°$ of the polarizer in mode 3.

References

[1] C. H. Bennett, H. J. Bernstein, S. Popescu, and B. Schumacher, Phys. Rev. **A53**, 2046 (1996).

[2] C. H. Bennett, D. P. DiVincenzo, J. A. Smolin, and W. K. Wootters, Phys. Rev. **A54**, 3824 (1996); C. H. Bennett *et al.*, Phys. Rev. Lett. **76**, 722 (1996); D. Deutsch *et al.*, *ibid.* **77**, 2818 (1996).

[3] P. G. Kwiat, S. Barraza-Lopez, A. Stefanov, and N. Gisin, Nature (London) **409**, 1014 (2001).

[4] T. Yamamoto, M. Koashi, and N. Imoto, Phys. Rev. **A64**, 012304 (2001).

[5] A. G. White, D. F. V. James, P. H. Eberhard, and P. G. Kwiat, Phys. Rev. Lett. **83**, 3103 (2000).

[6] Y. H. Kim, S.P. Kulik, and Y. Shih, Phys. Rev. **A62**, 011802(R) (2000).

[7] K. Usami *et al*, quant-ph/0107121.

[8] D. Bouwmeester *et al.*, Phys. Rev. Lett. **82**, 1345 (1999).

[9] J.-W. Pan *et al.*, Nature (London) **403**, 515 (2000).

[10] J. -W. Pan *et al.*, Phys. Rev. Lett. **86**, 4435 (2001).

[11] J. -W. Pan, C. Simon, C. Brukner, and A. Zeilinger, Nature (London) **410**, 1067 (2001).

[12] E. Knill, R. Laflamme, and G. J. Milburn, Nature (London) **409**, 46 (2001).

[13] M. Koashi, T. Yamamoto, and N. Imoto, Phys. Rev. **A63**, 030301(R) (2001).

[14] T. B. Pittman , B. C. Jacobs, and J. D. Franson, Phys. Rev. **A64**, 062311 (2001).

[15] J. -W. Pan and A. Zeilinger, Phys. Rev. **A57**, 2208 (1998).

[16] T. B. Pittman, B. C. Jacobs, and J. D. Franson, Phys. Rev. Lett. **88**, 257902 (2002).

[17] T. Jennewein, G. Weihs, J.-W. Pan, and A. Zeilinger Phys. Rev. Lett. 88, 017903 (2002).