Efficient extraction of polarization-entanglement in ultrafast type-II SPDC

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Abstract: We report a new interferometric scheme in which post-selection-free polarization-entangled photons in ultrafast type-II SPDC can be generated. Unlike the usual ultrafast type-II SPDC, the quality of polarization-entanglement in our scheme is independent of pump pulse duration, crystal thickness, and spectral filters. It is also robust against environmental disturbance and partially-mixed partiall-entangled states can be easily generated.

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Photon pairs that are entangled in their polarization degree of freedom have shown to be useful recently not only to study foundations of quantum physics but also in recent applications in quantum information science and quantum metrology. Such two-photon polarization entangled states are usually prepared with the spontaneous parametric down-conversion field generated from monochromatic-laser pumped, type-II phase matched non-linear optical crystal. (It may also be generated by using type-I phase matched crystals, but the bandwidth of the photons are much bigger than that of type-II SPDC.) Although the usual type-II SPDC scheme is widely used for generating polarization entangled photons, the photon pair emission times are completely random. This is a serious drawback in applications, such as, quantum teleportation, multi-photon entanglement generation, quantum cryptography, etc., where knowledge of the approximate times of emission are required.

Much of the emission time uncertainty is eliminated when the type-II SPDC is pumped by an ultrafast laser. Unfortunately, differences in the spectral and temporal properties of the photon pair cause the polarization-entanglement to suffer with ultrafast pumping. It is, however, possible to "concentrate" the entanglement by passing the photons through narrow-band filters, effectively retaining only the more highly entangled pairs. This method, naturally, is very inefficient as most of the photons are simply wasted and the thicker the crystal, the narrower the bandwidth of the filters should be. Therefore, there is simply little or no gain in the number of usable entangled photons by using thicker crystals in this case.

In this paper, we demonstrate a new interferometric entanglement concentration or entanglement extraction scheme in ultrafast type-II SPDC. Unlike the usual ultrafast type-II SPDC, the quality of polarization-entanglement in our scheme is independent of pump pulse duration, crystal thickness, and spectral filters. Therefore, there are no wasted photons in our scheme and all the photon pairs that are initially generated in the crystal appear polarization-entangled at the output of of the interferometer. The interferometer is robust against environmental disturbance and partially-entangled partially-mixed states can be easily generated.

The experimental setup can be seen in Fig. 1. A 3 mm thick type-II BBO crystal is pumped by an ultrafast laser pulse with 390 nm central wavelength and 130 fsec duration. Attention is restricted to the intersections of the cones made by the e-ray and the o-ray exiting the BBO crystal. In each of these two directions, a photon of either polarization may be found, with the orthogonal polarization found in the conjugate beam. The polarization state of the photon pair at this point, and without any spectral filtering, is given by $\rho = \frac{1}{2}(|H_1\rangle|V_2\rangle\langle V_2|\langle H_1| + |V_1\rangle|H_2\rangle\langle H_2|\langle V_1|)$. In cw-pumped type-II SPDC, the amplitudes $|H_1\rangle|V_2\rangle$ and $|V_1\rangle|H_2\rangle$ may be made indistinguishable by introducing a set of quartz plates of appropriate thickness to compensate the group velocity difference between the e-ray and o-ray. In ultrafast type-II SPDC, this cannot be done because of additional timing information introduced by the pump pulse. Until now, the only way to obtain good polarization-entanglement in ultrafast type-II SPDC has been either to use a very thin nonlinear crystal ($\sim 100\ \mu$m) or to use very narrow-band spectral filters.

We now explain the interferometric entanglement concentration scheme. First the $\lambda/2$ plate, oriented at 45°, in one arm of the interferometer rotates photon polarization by 90°. If the two arms of the interferometer is equal, then there are only two possible outcomes at the polarizing beamsplitter (PBS): both photons are reflected or both photons are transmitted. Note now that one detector always detector e-ray and the other detector always detect o-ray of the crystal. This is because distinguishing e-o information is now decoupled from polarization by the action of polarization beamsplitter. Therefore, the temporal and spectral differencees between the photon pair have no bearing on the polarization entanglement. The resulting quantum state is then given by $|\Phi\rangle = \frac{1}{\sqrt{2}}(|H_1\rangle|H_2\rangle + e^{i\varphi}|V_1\rangle|V_2\rangle$ where the phase φ can be varied by tilting quartz plates QP2 shown in Fig. 1. Therefore, all four Bell-states can be easily prepare by simply tilting QP2 and/or by introducing a $\lambda/2$ plate at one output port of the polarizing beamsplitter.

The experimental data are shown in Fig. 1. The SPDC photons were centered at 780 nm and the coincidence window for this experiment was about 3 nsec. Quartz plates QP1 and QP2 were oriented their optic axes vertically and QP2 was tilted for choosing the phase angle φ. The interferometer arm delay τ was scanned for two different polarizer settings: 45°/45° and 45°/−45°. Here we used 20 nm FWHM spectral filters, which is much bigger than the SPDC spectrum, to reduce background noise. The observed visibility is about 91% and such a high-visibility quantum interference cannot occur in usual ultrafast type-II SPDC experiment (the theoretical maximum visibility is less than 20% under the same condition). This scheme also offers an easy method to generate partially-entangled partially-mixed states: one simply needs to choose $\tau \neq 0$. Details on the theory and the experiment can be found in Ref. [1] and Ref. [2].

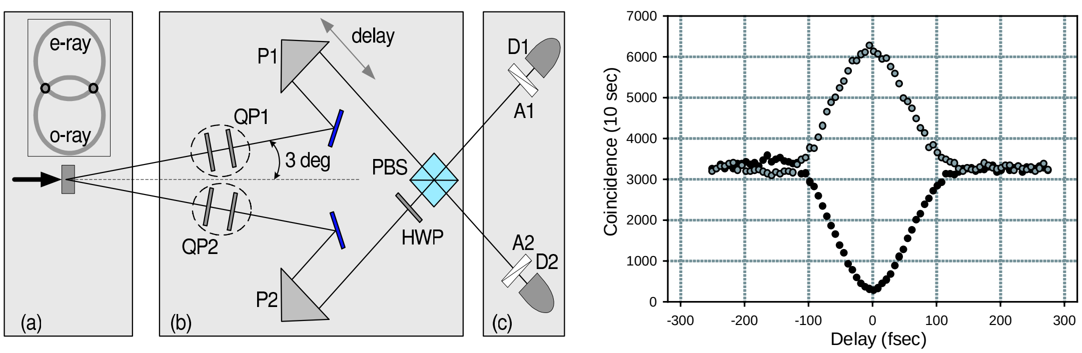

Fig. 1. Experimental setup and data. (a) Ultrafast type-II SPDC generates the two-photon polarization state which is in a mixed state, (b) interferometric entanglement concentration scheme, (c) analyzers and detectors. Visibility is about 91%.

We believe that the method described in this paper may be useful for generating pulsed Bell-states for broad class of quantum information experiments. This research was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, NSA, NSF, and ONR. The Oak Ridge National Laboratory is managed for the U.S. DOE by UT-Battelle, LLC, under contract No. DE-AC05-00OR22725.

References

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