Experimentally achieve two photon entanglement on various emitting angle

Anning Zhang (张安宁)[1*], Min Li (李 敏)[2], and Yahui Feng (冯亚辉)[2]

[1]*Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education,*
and Institute of Physics and Department of Physics, Hunan Normal University,
Changsha 410081, China
[2]*State Key Laboratory of Precision Spectroscopy, Department of Physics,*
East China Normal University, Shanghai 200062, China
[*]*Corresponding author: anzhang@hunnu.edu.cn*

Received January 23, 2013; accepted July 12, 2013; posted online , 2013

Twin photon generation at various emission angles is observed. It is found that different kinds of twin photons using only one crystal under different conditions are obtained. Twin photon generation is more effective at smaller emission angles. Two-photon entanglement is also achieved after compensation.

OCIS codes: 270.0270, 270.5585.
doi: 10.3788/COL201311.092701.

Quantum information is a remarkably new research field that includes quantum computation[1,2], quantum communication[3−5], and quantum precision measurement[6,7], among others. Most quantum information applications are based on quantum entanglement[8,9]. Today, the most widely used and experimentally feasible detectors for this field are entanglement witnesses[10], which are derived from positive, but not completely positive, maps. Badziąg *et al.* presented an alternative, purely geometric approach to entanglement identification[11,12], which provide a sufficient criterion for entanglement expressed in terms of simple conditions on correlation functions that were easily tested through local measurements. Badziąg gives us an experimentally accessible geometric separability criterion for entanglement, which works well for composite systems with arbitrary dimensions.

In this letter, we achieve two-photon entanglement using spontaneous parametric down-conversion (SPDC) and demonstrate two-photon entanglement using Badziąg's criterion. We also observe that the twin photons emitted in well-behaved spatial mode can be chosen at the variously emitting angles.

We achieved entanglement using a noncollinear Type-II SPDC process. In Fig. 1, OA is the optic axis, $\vec{k}_{\rm e}$ is the pump wave vector, $\vec{k}_{\rm p}$ is the extraordinary wave vector, and $\theta_{\rm e}^{\rm o}$ is the emission angle of extraordinary SPDC photons.

After calculation, we derived the relationship between the pump propagating angle (θ) and the emission angle of SPDC photons ($\theta_{\rm e}^{\rm o}$). At pump wavelengths fixed at 412, 390, and 351 nm, the relationships between the pump propagation angle and the SPDC emission angle are shown in Fig. 2.

The experimental setup is shown in Fig. 3. The wavelength of the UV diode laser was 411.8 nm, and the power of the laser was 85 mW. After focusing the light using a 50-mm focus lens through the 25-μm-diameter pinhole, the power of the laser was roughly 60 mW in T00 mode. The second lens in the path is a collimating 50-mm lens that also focuses the laser towards the 2-mm-thick beta barium borate (BBO) crystal. HR400 (HR800) is a highly reflective mirror for 400-nm (800 nm) light. CC is the compensator crystal, which compensates for the wake-off of the SPDC photons in BBO crystal. $\lambda/2$ is the half-wave plate (HWP), and PBS is the polarizing beam

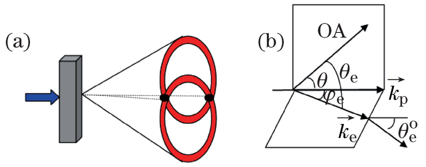

Fig. 1. Non-collinear degenerate Type-II SPDC.

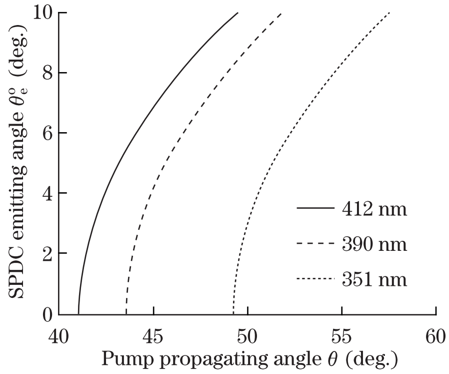

Fig. 2. Type-II tuning curve for BBO crystal.

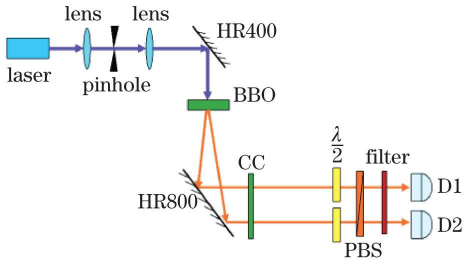

Fig. 3. Experimental setup.

splitter. The filter is a 20-nm bandpass filter with a center wavelength 820 nm. D1 and D2 are single photon detectors. We get the coincidence counts using our laboratory-made circuit.

In this experiment, we varied the pump propagation angle. At a pump propagation angle of 41.6°, the SPDC emission angle was 2.54°. The N1 count was 23459± 138 Hz, and the N2 count was 14682±79 Hz. The coincidence count in the experiment was 1729±27 Hz, but the random coincidence count was 34±0.1 Hz. In this case, the coincidence count we obtained was much higher than the random coincidence count of two single channels. That is, we obtained twin photons that were born at the exact same time. If we change the propagation angle, we can still obtain twin photons using the same crystal at different emission angles. For example, we set the propagation angle of the BBO to 42.3° and we received the signal and idler photons at 3.8°. In this case, the experimental coincidence count was 181±6 Hz versus 2.5±0.1 Hz for random coincidence. A comparison of the experimental results using different SPDC emission angles revealed that twin photon generation was more effective at smaller emission angles. That is, twin photons are generated more effectively when the propagation angle of the twin photons is more similar to that of the pump photon. Entanglement photon pairs are routinely achieved using non-linear crystals. The phase matching conditions should be calculated very carefully because SPDC processing operates within a wide range with different conversion efficiencies.

We achieved entanglement after using CC. When we fixed the D1 polarization horizontally, vertically, at 45°, and at −45°, and reversed the angle of the HWP in the D2 channel, we obtained a series of coincidence measure results, as shown in Fig. 4.

Two-photon state representation is given by the correlation tensor

$$\rho = \frac{1}{4}\sum_{\mu_1,\mu_2=0}^{3} T_{\mu_1\mu_2}\sigma_{\mu_1}\otimes\sigma_{\mu_2}, \qquad (1)$$

where $\sigma_{\mu_n} \in \{\sigma_x, \sigma_y, \sigma_z\}$ is the local Pauli operator of the nth party , $T_{\mu1\mu2} = Tr[\rho(\sigma_{\mu_1}\otimes\sigma_{\mu_2})]$ are the components of the generalized correlation tensor $\widehat{T}$. As shown in Refs. [11,12], the simple and useful criterion is

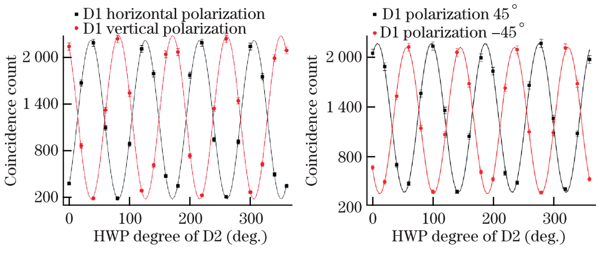

Fig. 4. Experimental results.

$$\varepsilon = \frac{(\widehat{T},\widehat{T})}{T^{\max}}. \qquad (2)$$

If $\varepsilon > 1$, the bipartite entanglement occurred in the two-photon state. Moreover, since $T^{\max} \leqslant 1$, then the state is entangled if $(\widehat{T},\widehat{T}) > 1$. The condition is universal. It demonstrates entanglement in all Bell states ($\varepsilon = 3$) using the same setup even if there is no single linear witness, which detects entanglement of all these states. In our experiment, we get $\langle\sigma_x\sigma_x\rangle = 0.85 \pm 0.05, \langle\sigma_y\sigma_y\rangle = 0.64 \pm 0.04$ and $\langle\sigma_z\sigma_z\rangle = 0.61 \pm 0.04$. Then, we have the value $\varepsilon = 1.77 \pm 0.23$. If we only measured two correlations such as $\langle\sigma_y\sigma_y\rangle$ and $\langle\sigma_z\sigma_z\rangle$, detecting entanglement using the criterion $(\widehat{T}, \widehat{T}) > 1$ is insufficient. To identify the two-photon state, we need to measure three correlations instead of two measurements.

In conclusion, we observe that twin photons emitted in well-behaved spatial modes can be selected at various emission angles. Moreover, twin photon generation is more effective at smaller emission angles. Furthermore, we demonstrate two-photon entanglement by using Badziąg's criterion, which works in the Hilbert spaces with arbitrary dimensions.

This work was supported by the National Natural Science Foundation of China (No. 60907031), the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry, and Shanghai Municipal Science and Technology Commission (No. 09JC1404700).

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