Two-Photon Entanglement and EPR Experiments Using Type-II Spontaneous Parametric Down Conversion

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Abstract

Simultaneous entanglement in spin and space-time of a two-photon quantum state generated in type-II spontaneous parametric down-conversion is demonstrated by the observation of quantum interference with 98 % visibility in a simple beam-splitter (Hanburry Brown-Twiss) anticorrelation experiment. The nonlocal cancellation of two-photon probability amplitudes as a result of this double entanglement allows us to demonstrate two different types of Bell's inequality violations in one experimental setup.

1 Introduction

Two-particle entangled states play a particularly important role in the study of the Einstein-Podolsky-Rosen (EPR) paradox [1] and in the test of Bell's inequalities [2]. Entangled states are states of two or more particles that can not be written as products of single particle states. [1]. The physical consequences resulting from the EPR states violate classical local realism [3].

In the past, EPR type two-particle entanglement has been demonstrated by two types of experiments: (1) two-particle polarization correlation measurements; most of the historical EPR-Bohm experiments [4] and the measurements testing Bell's inequality exhibited nonlocal two-particle *polarization* correlation [5]. These experiments demonstrated the EPR type two-particle spin-type entanglement. (2) two-particle interference (fourth order interference) experiments; recent two-particle nonclassical interference experiments demonstrated two-particle *space-time* entanglement [6].

Usually two-photon entanglement appears in the form that if one wants to measure the linear polarization of a single photon, one would find that neither of them has a preferred polarization direction, however, whenever a single photon is measured to be polarized in a certain direction the other one must be polarized orthogonal to that direction. A typical EPR type two-photon space-time entangled state, was proposed by Franson recently [7]. In this state one can never predict "which path" for a single photon, however, if one of the photons traveled through the longer (shorter) path the other must have traveled through the longer (shorter) path. The signature of this state is a cosine sum frequency interference fringe pattern of the coincidence counting rate.

The non-local spin or space-time two-particle entanglement phenomena is unusual from the classical theory point of view. The third type of simultaneous two- particle entanglement both in spin and in space-time will be discussed in detail by reporting several experiments. In these experiments, it is interesting to see that the measurement of the spin and space-time observables of either particle determines the value of these observables for the other particle with unit probability.

2 EPR experiments

Spontaneous parametric down-conversion (SPDC) is one of the most effective sources for generating two-photon entangled states. In SPDC a pump beam is incident on a birefringent crystal. The nonlinearity of the crystal leads to the spontaneous emission of a pair of entangled light quanta which satisfy the phase matching condition [8],

$$\omega_1 + \omega_2 = \omega_p, \quad \vec{k}_1 + \vec{k}_2 = \vec{k}_p \tag{1}$$

where ω_i is the frequency and $\vec{k}_i$ the wave vector, linking pump (p), signal (1), and idler (2). The down-conversion is called type-I or type-II depending on whether the photons in the pair have parallel or orthogonal polarization. The light quanta of the pair that emerges from the nonlinear crystal may propagate in different directions or may propagate collinearly. The frequency and propagation directions are determined by the orientation of the nonlinear crystal and the phase matching relations in (1).

In order to understand the two-photon behavior of SPDC, consider the experiment which is shown in Fig. 1, a simple beam-splitting experiment. Assume that a type-II BBO ($\beta - BaB_2O_4$) crystal is used for the SPDC. The collinear down-conversion beam is split by a beamsplitter. The beamsplitter is assumed to be polarization dependent so that the o-ray is transmitted and the e-ray is reflected. Single photon counting detectors D_1 and D_2 are placed in the transmission and reflection output ports of the beamsplitter for detecting the o-ray and the e-ray, respectively. An introduction of the effective wavefunction $\Psi(t_1, t_2)$ is helpful for understanding the physics of the phenomenon.

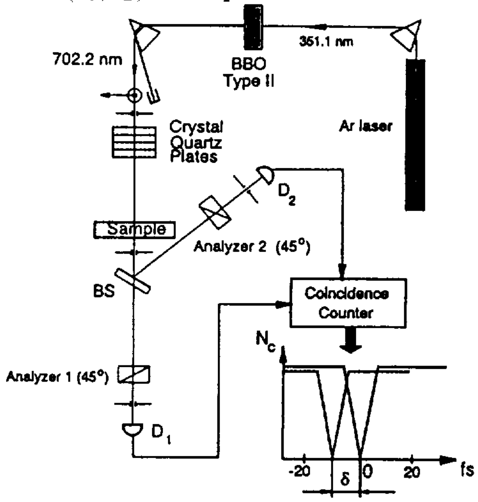

Figure 1. Schematic experiment for study of the type II SPDC biphoton. BS is a beamsplitter. D_1 and D_2 are photon counting detectors. A coincidence circuit is used for recording the coincidence rate.

For collinear type-II SPDC, a two-photon part of the state exiting the crystal may be calculated from the standard theory of SPDC [9].

$$|\Psi\rangle = \sum_{1,2} \delta(\omega_1 + \omega_2 - \omega_p)\psi(k_1 + k_2 - k_p)a_o^\dagger(\omega_1(k_1))a_e^\dagger(\omega_2(k_2))0\rangle \tag{2}$$

The effective wavefunction may be calculated for the system presented in Fig.1 [9]

$$\Psi(t_1, t_2) = \langle 0|E_1^{(+)}E_2^{(+)}|\Psi\rangle. \tag{3}$$

$$\Psi(t_1, t_2) = v(t_1 + t_2)u(t_1 - t_2) \tag{4}$$

$$\begin{aligned} v(t) &= v_0 exp(-i\omega_p t/2) \\ u(t) &= u_0 exp(-i\omega_d t/2) \int_{-\infty}^{\infty} d\nu[1 - exp(-\nu DL)]/(i\nu DL)exp(-i\nu t) \\ &= exp(-i\omega_d t/2)\Pi(t) \end{aligned}$$

$$\Pi(t) = \begin{cases} u_0 & DL > t > 0 \\ 0 & \end{cases} \tag{5}$$

where v_0, u_0 are constants (normalization). We have approximated the pump to be a plane wave in the calculation. If the pump beam were taken to be a Gaussian with bandwidth σ_p, it is not difficult to show that the constant v_0 will be replaced by a Gaussian function $v_0 exp(-\sigma_p^2 t^2/8)$.

Equation (4)demonstrates a two dimensional wavepacket, referred to as the two-photon effective wavefunction or for short the *Biphoton* [8, 9]. It is clear that the biphoton is entangled in space-time because the wavefunction can not factor into a function of t_1 times a function of t_2.

Fig. 1 illustartes the experimental set up for the verification of Π-shaped biphoton. The beamsplitter is polarization independent, so that both the o-ray and the e-ray could be transmitted or reflected to trigger D_1 or D_2. A Glan Thompson linear polarization analyzer, oriented at 45^o relative to the o-ray and e-ray polarization planes of the BBO crystal, is placed in front of each of the detectors. Birefringent material, for example a set of quartz plates, is introduced into the single incident beam for manipulating the optical delay δ between the o-ray and the e-ray. The fast axes of the quartz plates were carefully aligned to match the o-ray or e-ray polarization planes of the BBO crystal. In order to see the *natural spectral shape* of the SPDC, no any narrowband spectral filters are used except UV cut off filters to get rid of the pump scattered light [10].

It is interesting to see that when no quartz plates are used the two terms in the effective wavefunction (4) do not show any interference since $\Pi(t_1 - t_2)$ and $\Pi(t_2 - t_1)$ do not overlap. Physically it means that the o-ray and the e-ray photons are well distinguished in space-time. Now consider the case of having a quartz plate in the down-conversion incident beam. If we align the quartz carefully to match its fast axis to the o-ray polarization direction of the BBO, an optical delay, $\delta \cong (n_o - n_e)l/c$, is introduced between the o-ray and the e-ray of BBO, where n_o and n_e are the index of refraction of the quartz plates for the o-ray and the e-ray of BBO, and l is the thickness of the quartz plate. The effective wavefunction becomes (consider the analyzers are set at 45^o),

$$\Psi(t_1, t_2) = \alpha_i \alpha_r v(t_1 + t_2 - \varphi)[u(t_1 - t_2 + \delta) - u(-t_1 + t_2 + \delta)] \tag{6}$$

It is easy to see from eq.(6) that there is interference now, because the two terms overlap. When $\delta = DL/2$,the two terms completely overlap and therefore cancel each other. This may be considered as a perfect anti-correlation.

$$\begin{aligned} R_c &= R_{c0}[1 - \rho(\delta)] \\ \rho &= \begin{cases} 0 & -\infty < \delta < 0 \\ \kappa\delta & 0 < \delta \le DL/2 \\ 1 - \kappa(\delta - Dl/2) & DL/2 \le \delta < DL \\ 0 & DL < \delta < \infty \end{cases} \end{aligned} \tag{7}$$

The width and the shape of the biphoton can be evaluated by the width and the shape of R_c.

Fig.2 reports typically observed 'V-shape' coincidence rate measurements as a function of the optical delay δ, which verifies the Π-shape effective wavefunction [10]. Each of the data points corresponds to different numbers of quartz plates remaining in the path of the down-conversion incident beam. It is easy to find that the vertex of the V-shape function has a displacement of $(72 \pm 3)fs$ from zero, which corresponds to a time delay of $DL/2$ in a $(0.56 \pm 0.05)mm$ BBO crystal.

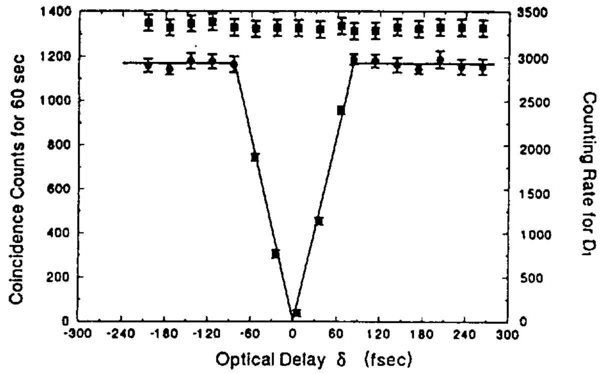

Figure 2. Lower curve: Coincidence counts as a function of optical delay, which corresponds to a certain number of quartz plates. The solid curve is a fitting curve of eq.(7). Upper curve: Single detector counts.

A strong correlation which appears in the form of almost a 100% destructive quantum interference is a clear demonstration of the situation where the Einstein-Podolsky-Rosen argument [1] is directly applicable. The triangular shape of the correlation function is a clear signature of the rectangular shape of original two-photon effective wavefunction. The discussion of the effective wavefunction is important also for the understanding of the two-photon double entanglement.

3 Double Bell's inequality

Taking advantage of the spin and space-time entanglement of the biphoton, another type of two-photon interference phenomena can be demonstrated. With the addition of a Pockel's cells, and a re-orientation of the quartz plates and polarizers, the coincidence counting rate exhibits interference modulation of the pump frequency when manipulating the voltage across the Pockel's cell, regardless of the optical delay by the quartz plates (*which is much greater than the coherence length of the signal and idler down-conversion fields*). This two-photon interference effect is again due to a nonclassical two-photon state which is entangled both in spin and in space-time.

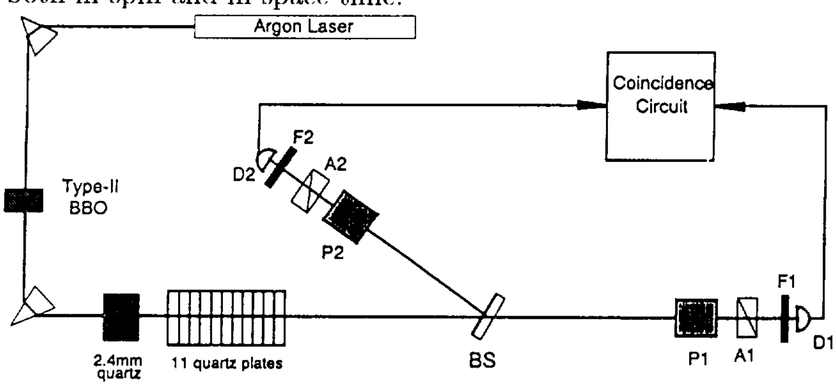

Figure 3. Schematic set up for the new type two-photon interferometer.

The schematic set up of the experiment is illustrated in Fig.3. The type-II SPDC is the same as that in the quantum beats experiment. The collinear down-conversion beam passes through a set of crystal quartz plates before the beamsplitter. The first three quartz plates, which sum to $2.4mm$ in thickness, are oriented in a way to make the two terms of the Π-shape function completely overlap (see the discussion in section 2). 11 more crystal quartz plates follow these three. The fast axes of these 11 quartz plates are aligned carefully to be oriented at 45^o relative to the o- ray and the e-ray polarization planes of the BBO in order to introduce a new basis associated with the fast and slow axecies. Each of these quartz plates is $(1 \pm 0.1)mm$ in thickness, resulting in an optical delay $\Delta l \cong 9\mu m$ between the fast and the slow rays of the quartz crystal at wavelengths around 700 nm. The optical delay is about $99\mu m$ after 11 quartz plates in comparison with the coherence length of the field which is about 25μm. Therefore, the $|X\rangle$ and the $|Y\rangle$ components of the original o-ray and e-ray of suffer enough optical delay to be non-overlapping, where $|X\rangle$ and $|Y\rangle$ correspond to the fast and the slow axes of the quartz plates. A Pockel's cell with fast and slow axes carefully aligned to match the $|X\rangle$ and the $|Y\rangle$ axes is placed after the quartz plates in each output port of the beamsplitter for fine control of the optical delay between the $|X\rangle$ and the $|Y\rangle$. The spectral filters f_1 and f_2 have Gaussian shape transmission functions centered at $702.2nm$, with bandwidths of $19nm$(full width at half maximum).

The down-conversion $|o\rangle$ and $|e\rangle$ polarized photons both have certain probabilities to be in the $|X\rangle$ or the $|Y\rangle$ state when passing through the crystal quartz plates and the Pockel's cells. The optical delay between the $|X\rangle$ and the $|Y\rangle$ is then introduced by the anisotropic refractive index of the quartz plates and the Pockel's cells. The coincidence time window in this experiment is $1.8nsec$, which is much shorter than the distance between the Pockel's cells. Bell inequality measurements can be performed for both space-time variables and for spin variables in one experiment. For the 45^o oriented polarizers, the coincidence counting rate is predicted to be,

$$R_c = R_{c0}\{1 - exp[-\sigma_p^2(\Delta l/2c)^2]\cos(\Omega_1\Delta l_1 + \Omega_2\Delta l_2)/c\} \tag{8}$$

where $\Delta l_i/c$ is the optical delay introduced by the ith Pockel's cell (to simplify the calculation, we assumed the optical delays introduced by the Pockel's cells are the same).

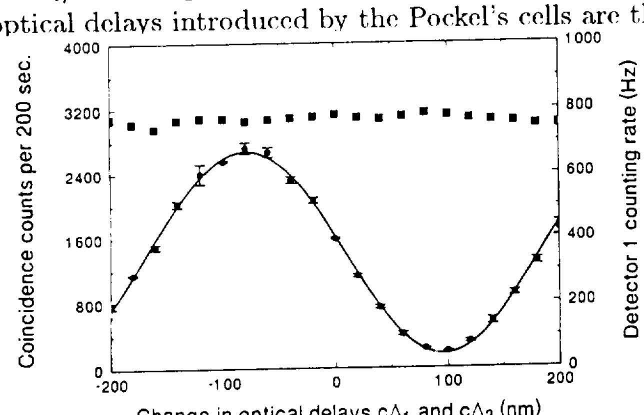

Figure 4. A typical observed sum frequency modulation when the cross voltages of the two Pockel's cells are manipulated (negative values correspond to negative voltages). The interference visibility is $(88.2 \pm 1.2)\%$, which violates a Bell inequality for space-time variables by more than 14 standard deviations.[11, 12]

The manipulation of Δl_P is realized by changing the applied voltage of the Pockel's cells. The coincidence counts are direct measurements, with no "accidental" subtractions. It is clear that the modulation period corresponds to the pump wavelength, i.e., $351.1nm$. Contrary to the coincidence counting rate, the single detector counting rate remains constant when Δl_P is manipulated, as is reported in the upper part of Fig. 4.

It is interesting to see that in the same experiment, a test of a spin variable Bell inequality can be made by manipulating the orientation of the polarizers at a totally constructive or destructive space-time interference point. Because of the symmetries present in the measurement, we are able to study one simple form of Bell's inequalities for polarization variables [13],

$$\delta = |[R_c(\pi/8) - R_c(3\pi/8)]/R_0| \leq 1/4 \tag{9}$$

and the measured result is $\delta = 0.309 \pm 0.009$, implying a violation of more than 6 standard deviations.[12]

4 Conclusion

Experiments starting with type-II down-conversion are a very effective mechanism for generating two-photon entangled states (biphoton). The type-II SPDC biphoton is entangled both in space-time and spin. A two-photon effective wave function produced by Type-II spontaneous parametric down conversion is studied for its natural shape in space-time. The double entanglement of the two-photon state makes it possible to perform EPR type two-photon interference experiments in a simple beam-splitting set up and test Bell's inequalities for space-time variables and spin variables in the same experiment. Two-photon interference visibility as high as $(98 \pm 2)\%$ has been observed. Experimental tests for the space-time variables and spin variables Bell inequalities have been measured with violations of 14 and 6 standard deviations, respectively, in one experimental set up.

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