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Optimizing the photon pair collection efficiency: A step toward a loophole-free Bell's inequalities experiment

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We show that the photon pair collection efficiency in coincidence measurements can be maximized when the two-photon state is generated in the process of spontaneous parametric down-conversion in a thin crystal. This effect can be used to close part of the so-called detection loophole in Bell's inequalities experiments. The effect is also demonstrated experimentally. [S1050-2947(98)50804-9]

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I. INTRODUCTION

In the last 25 years a number of experiments have been performed in order to test the Einstein-Podolsky-Rosen (EPR) hypothesis of local realism in quantum mechanics [1] with or without the use of Bell-type inequalities [2,3]. Nearly all of those experiments utilized pairs of photons in polarization- or momentum-entangled states as test particles, coming from atomic cascade transition or, more recently [3], from spontaneous parametric down-conversion. A general critical analysis of such experiments has been carried out by Santos [4], concluding that, despite all efforts, none of them can be considered a definitive test.

Due to imperfections in the experimental setup, one is forced to make supplementary assumptions to the original question, restricting the range of validity of the answers drawn from the experimental results. According to Santos, the more frequent supplementary assumptions are consequences of two general hypotheses: the linear extrapolation rule and a mechanistic picture of the photon, both related to the so-called *detection loophole*. The linear extrapolation rule, or the fair sampling assumption is necessary because of the relatively low quantum efficiency of the photon counters. The mechanistic picture of the photon, or the passed subensemble assumption, arises in order to overcome the failure of the detection system in *collecting* all the photon pairs prepared by the source. The pair detection efficiency is determined not only by the quantum efficiencies, but also by the detectors' apertures and by the transverse spatial correlation between the two photons. We will refer to the combination of the last two factors as the *pair collection efficiency*. In atomic cascade transition sources, the three-body nature of the process leads to poor spatial correlation between the two photons [4], and the pair collection efficiency is low.

More recent experiments [2] use spontaneous parametric down-conversion (SPDC) as a source of entangled photon pairs. Photon pairs generated by SPDC can be entangled in polarization and momentum, simultaneously, which represents an advantage over atomic sources. The momentum correlation by itself is, in principle, the solution to the pair collection efficiency problem. However, since the photon pair is entangled in momentum, not in position, wide input aperture detectors or spatial filters should be used, at the cost of more background light reaching the active detection area. As discussed by Eberhard [5], background light has a deleterious effect in the determination of the minimum detector quantum efficiency required by a loophole-free experiment.

In this work we present a method to maximize the pair collection efficiency, keeping the detectors' apertures to small sizes, with no additional optics between the source and detectors. The method is based on the angular spectrum transfer from the pump field to the two-photon field in SPDC [6].

II. THEORY

Let us define the overall pair detection efficiency as

$$\eta_{12}=\frac{R_{12}}{\sqrt{R_1R_2}}, \tag{1}$$

where R_{12} is the coincidence count rate between the two detectors (say, D_1 and D_2), and R_1, R_2 are D_1, D_2 single count rates, respectively. It is understood that R_{12} is corrected for accidental coincidence counts, and R_1, R_2 are corrected for background and dark counts. Assuming that the two detectors have quantum efficiencies η_1 and η_2, the limit value for η_{12} in a lossless optical system would be $\sqrt{\eta_1\eta_2}$. Besides the quantum efficiencies, two factors contribute to lower η_{12}: (a) losses in the paths from the source to the detectors, and (b) losses due to the finite size of the detectors' apertures, that is, the less-than-one pair collection efficiency. In this work we deal with the second case only; that is, η_{12} as a function of D_1, D_2 aperture areas.

According to Monken, Souto Ribeiro, and Pádua [6], if the nonlinear crystal is thin enough along the pumping direction (a few millimeters in length), the angular spectrum of the pump field is transferred to the two-photon down-converted field in an entangled way. For the quasimonochromatic case in the paraxial approximation (far field, small observation areas around the propagation directions), the following expression is a good approximation for the state generated by SPDC:

$$|\psi\rangle=|\text{vac}\rangle+\text{const}\times\int d\mathbf{q}_1\int d\mathbf{q}_2 v(\mathbf{q}_1+\mathbf{q}_2)\times\text{sinc}\left(\frac{1}{4k}|\mathbf{q}_1-\mathbf{q}_2|^2L_z\right)|1;\mathbf{q}_1\rangle|1;\mathbf{q}_2\rangle. \tag{2}$$

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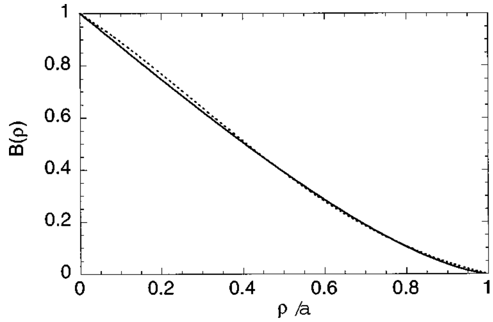

FIG. 1. Plots of expressions (7), solid line; and (8), dotted line.

$\mathbf{q}_1$ and $\mathbf{q}_2$ are the transverse components of $\mathbf{k}_1$ and $\mathbf{k}_2$ (the wave vectors of the down-converted field modes), k is the wave number of the pump field, and $v(\mathbf{q})$ is the angular spectrum of the pump field. Due to the small thickness L_z of the nonlinear crystal considered here, the sinc function in expression (2) can be regarded as constant. In this case, expression (2) leads to the interesting consequence that the transverse coincidence rate profile R_{12} maps the transverse intensity profile $I_p(\boldsymbol{\rho})$ the pump beam has *in the detection region* [6]. When $\omega_1=\omega_2=\omega_p/2$ and the two detectors are equidistant from the crystal ($z_1=z_2$), the coincidence count rate can be approximated by

$$R_{12}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2)=\text{const}\times I_p(\tfrac{1}{2}\boldsymbol{\rho}_1+\tfrac{1}{2}\boldsymbol{\rho}_2). \tag{3}$$

While R_{12} depends on the detectors' transverse positions $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$, single count rates R_1 and R_2 remain constant within the approximation assumed. For finite aperture detectors, expression (3) must be integrated in $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$ over the apertures.

Let us consider a Gaussian pump beam, with the transverse intensity profile given by

$$I_p(\boldsymbol{\rho})=I_0 e^{-2\rho^2/w^2}, \tag{4}$$

where w is the beam radius at the detection region. The coincidence rate (3) integrated over circular detectors apertures is

$$R_{12}(a)=\text{const}\times\int d\boldsymbol{\rho}_1\int d\boldsymbol{\rho}_2\mathcal{A}(\boldsymbol{\rho}_1)\mathcal{A}(\boldsymbol{\rho}_2)e^{-|\boldsymbol{\rho}_1+\boldsymbol{\rho}_2|^2/2w^2}, \tag{5}$$

where $\mathcal{A}(\boldsymbol{\rho})$ describes a circular aperture of radius a, centered at $\boldsymbol{\rho}$. Working out integral (5) one finds

$$R_{12}(a)=\text{const}\times\pi a^2\int d\rho\, B(\rho)e^{-2\rho^2/w^2}, \tag{6}$$

where

$$B(\rho)=\begin{cases}\dfrac{2}{\pi}\left[\cos^{-1}\dfrac{\rho}{a}-\dfrac{\rho}{a}\sqrt{1-(\rho/a)^2}\right] & \text{if } \rho\leqslant a,\\ 0 \quad \text{otherwise.}\end{cases} \tag{7}$$

In order to simplify the calculations, $B(\rho)$ will be approximated by

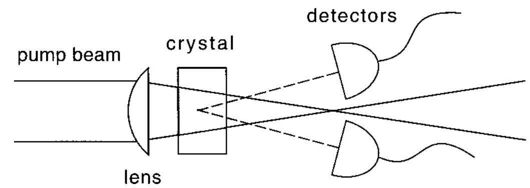

FIG. 2. Basic arrangement to increase the spatial correlation of the photon pair.

$$B(\rho)=\begin{cases}\left(1-\dfrac{\rho}{a}\right)e^{-(\rho/a)^2} & \text{if } \rho\leqslant a,\\ 0 \quad \text{otherwise.}\end{cases} \tag{8}$$

Figure 1 shows plots of expressions (7) and (8) for comparison. $R_{12}(a)$ is then

$$R_{12}(a)=\text{const}\times\pi a^2\frac{1}{1+\dfrac{w^2}{2a^2}}\left[1-\frac{\sqrt{\pi}\,\text{erf}\left(\sqrt{1+\dfrac{2a^2}{w^2}}\right)}{2\sqrt{1+\dfrac{2a^2}{w^2}}}\right]. \tag{9}$$

Since the single count rates $R_1(a)$ and $R_2(a)$ are proportional to the apertures area πa^2, the pair detection efficiency can be written as

$$\eta_{12}(a)=\frac{A}{1+\dfrac{w^2}{2a^2}}\left[1-\frac{\sqrt{\pi}\,\text{erf}\left(\sqrt{1+\dfrac{2a^2}{w^2}}\right)}{2\sqrt{1+\dfrac{2a^2}{w^2}}}\right], \tag{10}$$

where the constant A accounts for $\sqrt{\eta_1\eta_2}$ and additional absorption losses in the optical system. By inspection of expression (10), one sees that η_{12} increases with the ratio a/w and tends to saturate in A for large values of this ratio. So, if the pump beam radius at the detection region is minimized, η_{12} is maximized. This can be easily accomplished by placing a convergent lens in the pump beam, before it reaches the nonlinear crystal, focalizing it at the detection region, as shown in Fig. 2.

III. EXPERIMENT

An experiment has been carried out in order to test relation (10) in conditions normally encountered in Einstein-Podolsky-Rosen–type experiments using SPDC as a two-photon source. The setup is represented in Fig. 3. A 7-mm-long nonlinear crystal (BBO) is pumped by an Ar^+ laser. The laser operates at 351.1 nm, TEM_{00} (Gaussian profile) power-stabilized mode, with an output power of approximately 30 mW. Spontaneous type-II parametric down-conversion is generated by the nonlinear crystal, which is cut for $\lambda_1=\lambda_2=702$ nm, with output angles of approximately 4° with respect to the pumping direction.

A convergent lens L of 1-m focal length is placed in the pump beam, so that the beam waist is located at 1 m from the crystal. The measured waist is $w=0.18$ mm at $I=I_{max}/e^2$.

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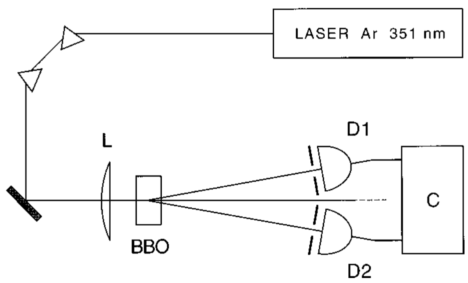

FIG. 3. Experimental setup.

Detectors D_1 and D_2 are avalanche photodiodes (APD's) operating in the photon counting mode, placed at 1 m from the crystal. In front of each detector there is an arrangement composed of a variable circular aperture, followed by an interference filter of 1-nm bandwidth, and a microscope objective focused on the APD's active area. The response of this detection system as a function of the incidence angle has been measured with the help of an attenuated laser beam, and was found to be flat over an acceptance angle of 1.0°. D_1 and D_2 are connected to single and coincidence counters C, with a resolving time of 10 ns.

Single and coincidence counts were recorded in sampling times of 100 s, for detector aperture radii $a_1 = a_2$ varying from 0.2 to 1.5 mm in steps of 0.1 mm, and for 2.0 mm. The pair detection efficiency η_{12} was calculated using Eq. (1), after subtraction of dark counts and accidental coincidences. For comparison purposes, the same measurements were repeated without the lens in the pump beam. In this case, the measured pump beam radius in the detectors' region at 1 m from the crystal was $w = 1.35$ mm.

IV. RESULTS AND CONCLUSION

Figure 4 shows plots of η_{12} versus a for the two experimental situations. Expression (10) was fit to the two data sets by a nonlinear least-squares-fitting routine, with parameters A and w. The fitting values of $A = 0.14$ in the first case and $A = 0.15$ in the second case are compatible with the nominal values of η_1 and η_2 of about 0.4 specified by the manufacturer, combined with a maximum transmittance of 0.45 for the Gaussian-profile interference filters, plus some additional losses in the microscope objectives. The fitting values for w are 0.21 mm for the first experiment (with the converging lens in the pump beam) and 1.41 mm for the second experiment (no lens in the pump beam). Both values are in good agreement with direct measurements of w: 0.18 and 1.35 mm, respectively.

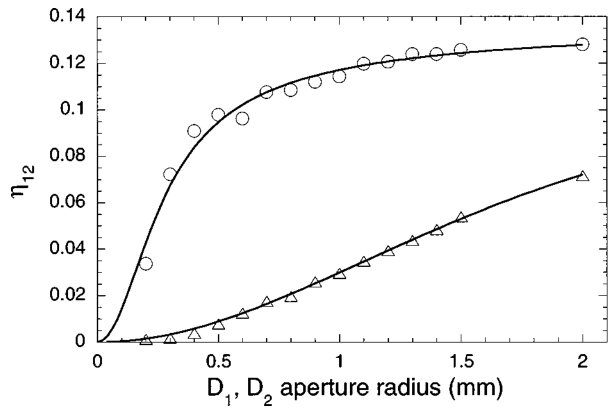

FIG. 4. Measurements of $R_{12}/\sqrt{R_1 R_2}$ with sampling times of 100 s. ○, pump beam focused; △, pump beam in free propagation. The solid curves at least-squares fits of expression (10) with parameters A and w.

Figure 4 shows a clear improvement in the pair detection efficiency when the pump beam is focused. For example, for $a = 1$ mm, about 84% of the photon pairs reach the active detection area in the first experiment (pump beam focused), whereas only 21% do it in the second case (pump beam in free propagation). By extrapolating the graph in Fig. 4 with expression (10), one sees that an aperture radius of 6.4 mm would be required to attain 84% pair collection efficiency in the second experiment. Considering that the background count rate is proportional to the detector aperture area, the first experiment has a gain of about 40 in the signal-to-noise ratio with respect to the second.

In conclusion, we have shown that the control of the fourth-order correlation between the conjugate fields generated by spontaneous parametric down-conversion through the pump beam can be used to optimize the pair collection efficiency in two-photon EPR-type experiments. This control is possible without introducing additional optics in the two-photon field. Besides, small aperture detectors can be employed, minimizing the background count level. We have also presented a theoretical model to describe the process, in good agreement with experimental data. Although the low quantum efficiency problem still remains, the detection loophole can be partially closed by the method described in this work.

ACKNOWLEDGMENTS

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[1] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 777 (1935).

[2] For reviews, see D. Home and F. Selleri, Riv. Nuovo Cimento **14**, 9 (1991); J. F. Clauser and A. Shimony, Rep. Prog. Phys. **41**, 1881 (1978).

[3] Z. Y. Ou and L. Mandel, Phys. Rev. Lett. **61**, 50 (1988); Y. H. Shih and C. O. Alley, *ibid.* **61**, 2921 (1988); J. R. Torgerson, D. Branning, C. H. Monken, and L. Mandel, Phys. Rev. A **51**, 4400 (1995); Phys. Lett. A **204**, 323 (1995).

[4] E. Santos, Phys. Rev. A **46**, 3646 (1992).

[5] P. H. Eberhard, Phys. Rev. A **47**, R747 (1993).

[6] C. H. Monken, P. H. Souto Ribeiro, and S. Pádua, Phys. Rev. A **57**, 3123 (1998).