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Independent Photons and Entanglement. A Short Overview

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Operational criteria for high-visibility interference experiments involving particles emitted by two independent sources are discussed. These operational techniques enable one to entangle systems that never interacted with themselves. Such methods also enable one to perform an "event-ready" version of the Bell-type experiment and to generate Greenberger–Horne–Zeilinger particle triples, etc.

1. INTRODUCTION

It has been shown that the experimentally accessible EPR-Bell phenomena are no longer limited solely to spin or polarization correlations and to the sources discussed in the standard review papers (e.g., Clauser and Shimony, 1978). Beam entanglement Bell-type experiments have been proposed (Horne and Zeilinger, 1985; Zukowski and Pykacz, 1988; Horne *et al.*, 1989) and performed (Rarity and Tapster, 1990). Effects due to entanglement were predicted for a new type of two-particle interferometer (Franson, 1989), and subsequent experiments exhibited high-visibility fringes (see, e.g., Kwiat *et al.*, 1990; Rarity *et al.*, 1994). The phenomenon of spontaneous parametric downconversion is now the standard source for EPR-Bell experiments [first used by Ou and Mandel (1988) and Shih and Alley (1988)]. EPR states are now also obtainable for atoms (Hagley *et al.*, 1997).

This expansion of the area of EPR-Bell phenomena continues. Until recently it was commonly believed that particles producing EPR-Bell phenomena have to originate from a single source, or at least have to interact

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with each other. Yurke and Stoler (1992) were first to explicitly suggest the use of independent sources of particles in a Bell test (however, no operational requirements were given). In this paper we shall review recent advances in research aimed at understanding the operational requirements for actually performing such experiments. It is shown here that by a suitable monitoring procedure of the emissions of the independent sources one can *preselect* an ensemble of pairs of particles which reveal EPR-Bell correlations (Żukowski *et al.*, 1993).

It was shown by Greenberger *et al.* (GHZ) (1989) that the premises of the Einstein–Podolsky–Rosen argument for their claim that quantum mechanics is an incomplete theory are inconsistent when applied to entangled systems of more than two particles. However, thus far there is no experimental confirmation for the existence of such states, and even some doubts about their existence have been expressed (Home and Selleri, 1991). The technique to obtain GHZ states which will be presented here rests upon an observation that when a single particle from two independent entangled pairs is detected in a manner such that it is impossible to determine from which pair the single came, the remaining three particles become entangled (Zeilinger, 1997). This method can only be developed with a clear operational understanding of the necessary requirements to observe multiparticle interference effects for particles coming from independent sources.

In recent years new, exciting applications have been found for EPR-Bell phenomena. There has been a rapid growth of interest in quantum communication and quantum information science. It has become evident that quantum mechanics offers new possibilities for novel technological schemes, based on completely different principles than the standard ones. Applications may range from supersecure (quantum) cryptography (see, e.g., Ekert, 1991) to the possibility of constructing logical elements for (future) quantum computers (Bennett, 1995). All those applications necessarily involve independent sources of particles and multiparticle interference phenomena.

In this presentation experiments involving the phenomenon of spontaneous parametric downconversion (PDC) are used as an illustration of the requirements to obtain high visibilities of multiparticle fringes. The discussed experiments are feasible. They are not *per se gedankenexperiments*. The rapid development of the field of atomic interferometry in the future may result in new, exciting Bell experiments. However, so far, the fringe visibility of interference phenomena obtainable with atoms is much lower than in photonic experiments.

The method of entangling independently radiated photons which share no common past (Zukowski *et al.*, 1993) is essentially a preselection procedure. The selected registrations of the idler photons define the ensemble which contains entangled signal photons (see next sections). Surprisingly, such a procedure enables one to realize Bell's idea of "event-ready" detection. This approach was thought for many years to be completely unfeasible and thus no research was done in this direction (Clauser and Shimony, 1978). As mentioned earlier, the technique to obtain *entanglement swapping* can also be applied to generate three (or more) photon GHZ entanglements, or, after a modification, to observe in the laboratory quantum state teleportation [for the original idea of teleporatation see Bennet *et al.* (1993)].

In Section 2 a brief description of the parametric downconversion process is given. This is used in Section 3 to show operational methods to obtain interference effects for particles emitted by two independent sources. Section 4 contains a discussion of the possible problems that could arise due to the specific thermal-like statistics of the PDC sources. In Section 5 various interpretations of the interference effects are presented. The final section is devoted to a discussion of implications of an experiment recently performed in Innsbruck (Bouwmeester *et al.*, 1997).

2. SHORT DESCRIPTION OF THE PROPERTIES OF THE SPONTANEOUS PARAMETRIC DOWNCONVERSION PROCESS (PDC)

One can find in the literature very detailed theoretical descriptions of the PDC process. Thus, we shall only give its essential characteristics [the reader wishing to know the details is encouraged to read the lucid presentation of the theory of the process given in Hong and Mandel (1985)]. It must be stressed that laboratory observations of various characteristics of PDC radiation are in full agreement with theory.

If one shines a strong, linearly polarized monochromatic laser beam, or a quasimonochromatic laser light pulse, on a suitably cut and oriented crystal endowed with a quadratic nonlinearity some pump photons spontaneously fission into pairs of photons of lower frequency (for historical reasons called signal and idler) (Fig. 1). The process is elastic, i.e., the energy of the photon field is conserved in the process. Therefore the frequencies of pump photon ω_p, signal ω_s, and idler ω_i must satisfy

$$\omega_p = \omega_s + \omega_i \tag{1}$$

(for the pulsed pump this relation still holds; however, in this case the pulse frequency is not precisely defined, and the downconverted frequencies are correlated up to the spectral width of the pulse). There is no other restriction on the frequency of the PDC photons. Thus, the spectra of the (individual) photons are extremely broad. However, the geometry of the process leads to a constructive interference of the spontaneous emissions into the so-called

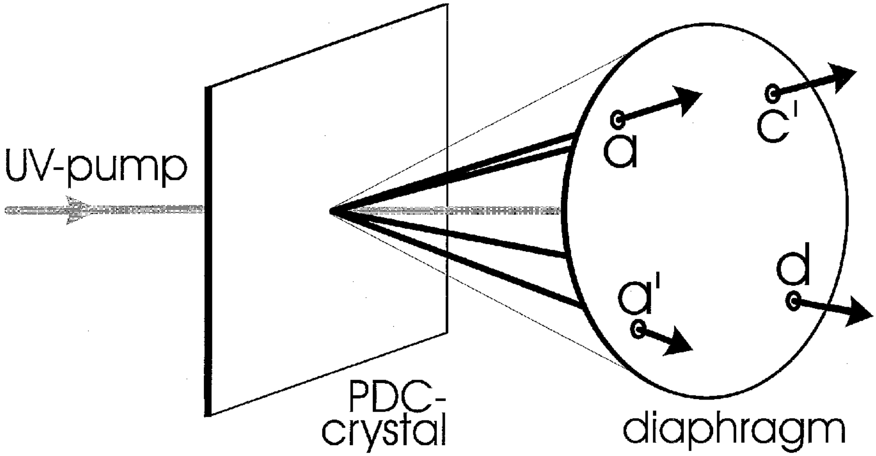

Fig. 1. Mode selection of photon pairs. A UV pump beam falling onto a crystal generates photon pairs via the spontaneous parametric downconversion (PDC) process. The directions of emission and the frequencies are determined by momentum and energy conservation laws. Photons of the same frequency are emitted into cones centered on the pump beam. Photons of one pair pass through pinholes which are symmetric with respect to the pump beam (i.e., through either a and d, or a' and c').

phase-matched directions only. The photonic wave vectors satisfy (within the crystal)

$$\mathbf{k}_p \approx \mathbf{k}_s + \mathbf{k}_i \tag{2}$$

i.e., the emissions are therefore strongly correlated directionally (again, for the pulsed case $|\mathbf{k}_p|$ is not precisely defined). Phase matching cannot occur for all frequencies and all emission directions, and thus into a given direction only specific frequencies are emitted. Knowing the frequency and the direction of an idler, we can predict with a good accuracy the corresponding parameters for the signal. The sharpness of (2) grows with the size of the crystal and of the laser beam width. If the crystal is cut in such a way that the so called type I phase matching condition is satisfied, both PDC photons are of the same polarization (crystals with quadratic nonlinearities are always non-centrosymmetric, and thus birefringent, and if the pump beam is an ordinary wave, the downconverted photons are extraordinary). Due to the phase matching condition (2) (single) photons of the same frequency are emitted into cones centered at the pump beam. By picking photons from a specially chosen cone one can have PDC radiation with both photons of equal frequency $\frac{1}{2}\omega_p$. The selection can be done by a suitable pinhole arrangement in a diaphragm behind the crystal and/or with the use of filters. Pairs of pinholes can be pierced at points on a circle, drawn on the diaphragm, and centered about the pump beam. The pinholes of each pair should be bored at points symmetric with respect to the center of the circle. If a downconversion photon passes through one of the pinholes, then the other photon will pass through the diametrically opposite pinhole. If there are two pairs of diametrically opposite pinholes, the state of the photon pair will be a superposition of passage through the two pairs of pinholes (Horne *et al.*, 1989); see Fig. 1. The state describing the coherent superposition for the pair of photons to leave the aperture system with equal probability by either the pinholes a and d or a' and c' can be written as

$$|\Psi^A\rangle = \frac{1}{\sqrt{2}}\left(|a\rangle|d\rangle + |a'\rangle|c'\rangle\right) \tag{3}$$

where, e.g., $|a\rangle$ describes a particle going through the pinhole a, etc. This state is formally equivalent to that of two spin-1/2 particles in a singlet state. However, one must have in mind that this is a highly simplified description.

Let us now discuss a more quantitative description of the PDC radiation for the case when the pump field is pulsed and for a more realistic description of the frequency filtering (which is the result of the photon momentum selection by the pinholes, and may still be enhanced by frequency filters). The description again will be an approximate one; however, it will contain the other basic characteristics of the PDC radiation which are absent in (3). The following assumptions will be made: (i) the probability of a multiple emission from a single PDC is low; (ii) the laser pulse is not too short, i.e., the nonmonochromaticity of the pulse will not blur too much the strong angular correlation of the emissions (due to the effective energy and momentum conservation within the crystal). Thus, the photons still can be described as emitted in specified, very well defined directions.

The state of the photon *pair* emerging from the source A (plus the filtering system) can be approximated by

$$\begin{aligned} |\Psi^A\rangle &= |\psi_{ad}\rangle + |\psi_{a'c'}\rangle \\ &= \int d\omega_1\, d\omega_2\, d\omega_0\, \Delta(\omega_0 - \omega_1 - \omega_2) g(\omega_0) \\ &\quad \times \left(f_a(\omega_1) f_d(\omega_2)|\omega_1; a\rangle|\omega_2; d\rangle \right. \\ &\quad \left. + f_{a'}(\omega_1) f_{c'}(\omega_2)|\omega_1; a'\rangle|\omega_2; c'\rangle\right) \end{aligned} \tag{4}$$

where, e.g., the ket $|\omega; e\rangle$ describes a single photon of frequency ω in the beam e, the function g represents the spectral content of the pulse, and f_e is the transmission function of the filtering in the beam e (a pinhole and/or a filter). The function Δ is sharply peaked at the origin and describes the phase-matching condition. One can approximate it by the Dirac delta.

If one introduces objects like, e.g., $|t; b\rangle = (1/\sqrt{2\pi}) \int d\omega\, e^{i\omega t}|\omega; b\rangle$, then the amplitude, e.g., to detect a photon at time $t_{x'}$ by a detector monitoring the beam x' and another one at time $t_{y'}$ by a counter in the beam y', provided the initial photon state was, say, $|\psi_{xy}\rangle$, can be written as $A_{xy}(t_{x'}, t_{y'}) = (\langle t_{x'}; x'|\langle t_{y'}; y'|)|\psi_{xy}\rangle$. The elementary amplitudes of the detection process have now a simple, intuitively appealing form

$$A_{xy}(t_x, t_y) = \frac{1}{\sqrt{2\pi}} \int dt\, G(t) F_x(t_x - t) F_y(t_y - t) \tag{5}$$

where the functions denoted by uppercase letters are the Fourier transforms: $H(t) = (1/\sqrt{2\pi}) \int d\omega\, e^{i\omega t} h(\omega)$, for $h = f$ or g. The convolution of the filter functions in (5) reveals one of the basic properties of the PDC radiation: the time correlation between the detection of the idler and the corresponding signal photon is entirely determined by the bandwidth of the detection system. This implies, for example, that in the limit of no filtering, when the functions $F(t)$ are approaching $\delta(t)$, the time correlation is absolutely precise. However, just a single filter will blur this correlation to around the inverse of the filter's bandwidth, $1/\Delta\nu$, i.e., the coherence time of the filtered radiation. The function $G(t)$ represents the temporal shape of the laser pulse and its presence in the formula simply indicates that (barring retardation) the signal and idler can be produced only when the pulse is present in the crystal.

3. NONCLASSICAL HIGHER ORDER INTERFERENCE OF PARTICLES ORIGINATING FROM TWO INDEPENDENT SOURCES

Yurke and Stoler (1992) suggested that interfering particles from independent sources may give rise to nonclassical correlations. It was shown later that the interference between particles produced by independent sources is observable only if the origin of the particles cannot longer be inferred (Zukowski *et al.*, 1993). We shall describe here the procedure to do this (Zukowski *et al.*, 1995).

Figure 2 shows the generic configuration for obtaining interference effects for pairs of particles originating from two independent sources. Assume that the sources in Fig. 2, A and B, each spontaneously emits a pair of particles in an entangled state (all particles are supposed to be identical) at nearly the same moment of time. Suppose, for example, that the states of the pairs are $|\Psi^A\rangle = (1/\sqrt{2})(|a\rangle|d\rangle + |a'\rangle|c'\rangle)$ for source A and $|\Psi^B\rangle = (1/\sqrt{2})(|b'\rangle|d'\rangle + |b\rangle|c\rangle)$ for source B (the letters represent beams taken by the particles in Fig. 1, and $\langle e|f\rangle = \delta_{ef}$). The beams x and x', where $x = a$, b, c, or d, are mixed by 50–50 beamsplitters. The unitary transformation performed by such a device is given, e.g., for the beams a by $|a\rangle =$

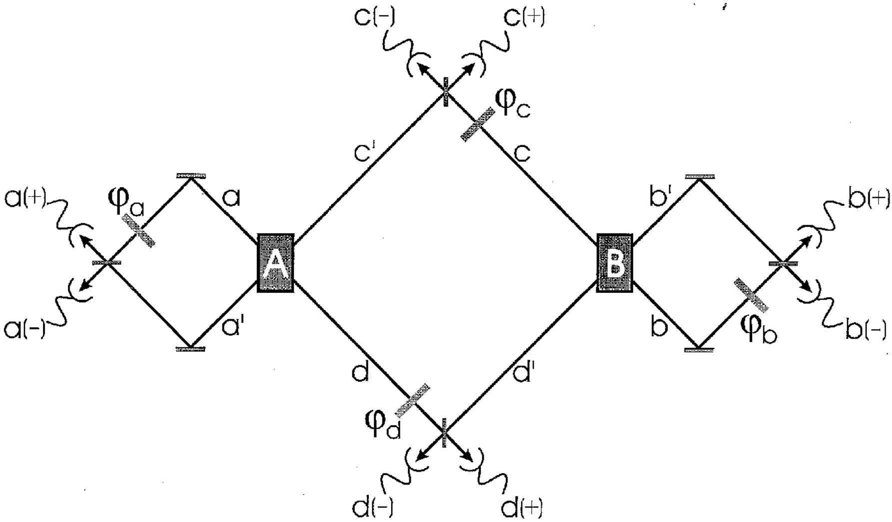

Fig. 2. Generic layout for interference of photons from independent PDC sources A and B. The symbols are explained in the text.

$(1/\sqrt{2})(|a(+)\rangle + i|a(-)\rangle)$ and $|a'\rangle = (1/\sqrt{2})(|a(-)\rangle + i|a(+)\rangle)$. Behind the beamsplitters we place pairs of detectors which observe the output ports $x(\pm)$. In all unprimed beams one has a phase shifter (which changes the phase by ϕ_x).

One should first notice here that the detector stations differ in their role. Stations $a(\pm)$ and $b(\pm)$ observe radiation coming from one source only. However, this is not so for stations $d(\pm)$ and $c(\pm)$. For example, if a *single* particle is detected by $d(+)$, its origin may be uncertain. If one could not determine which source produced the particle which activated the detectors, say $d(+)$ and $c(+)$, then four-particle interference effects may occur. Assume that detectors $a(+)$ and $b(+)$ also fired. Simultaneous firings of the four detectors can exhibit interference effects provided the two contributing processes, namely, (1) detection of the particles from source A in $d(+)$ and $a(+)$, and detection of the particles from B in $c(+)$ and $b(+)$, and (2) detection of the particles from source A in $c(+)$ and $a(+)$, and detection of the particles form B in $d(+)$ and $b(+)$, are totally indistinguishable. To ensure that this is indeed so, we must arrange our experiment in such a way that all knowledge of the sources of the photons registered in $c(+)$ and $d(+)$ is erased.

Thus, a more detailed description of the experimental setup is needed. The two sources of entangled states are two PDC crystals pumped by one pulsed laser in such a way that the pulses enter both crystals always simultaneously. We assume that the time separation between two pulses is much larger than all other time scales of the experimental process (i.e., we shall study the physics of PDC radiation generated by a single pump pulse). We shall omit all retardation effects from our description (tacitly assuming, where necessary, equal optical paths). Also we assume that we pick the PDC radiation with frequencies close to $\frac{1}{2}\omega_p^o$ (where, ω_p^o is the central frequency of the pulse).

Suppose that the four PDC photons are detected coincidentally (within a few nanosecond window), one in each of the detectors $a(+)$, $b(+)$, $c(+)$, and $d(+)$. The origins of the photon at $c(+)$ and $d(+)$ must be unknown. However, one could, in principle, determine that photon detected at $d(+)$ came from crystal A (B) by noting the near simultaneity of the detection of photon $d(+)$ and one of the photons at $a(+)$ or $b(+)$ (recall the property of the PDC radiation: the detection times of a pair are extremely well correlated). To ensure that the source of photons is unknowable, the two crystals can be pumped by pulses of durations, say, τ, and the photons should be detected behind a filtering system (to be called later simply a filter) whose inverse of the bandwidth (coherence time) exceeds τ by an order of magnitude. Then, the temporal separation of true PDC pairs spreads to around 10τ and thereby prevents any possibility of identifying the source of the photon at $d(+)$ and its partner photon by comparison of their arrival times. However, if the detections at, say, $b(+)$ and $c(+)$ are strictly time correlated, one still concludes that the photons came from one crystal. Yet, one can again put another filter of coherence time exceeding τ in front of the detector station $c(\pm)$. Now, the which-way information is completely erased. We can then expect high-visibility four-particle fringes. Note that no filtering is required in front of the detection stations $a(\pm)$ and $b(\pm)$. The above method of erasing the information of the origin of the photons at $d(+)$ and $c(+)$ also precludes the possibility of inferring the source of the photon from the frequency correlations (1). The conditions specified above imply that the frequency of the photons reaching $d(+)$ is better defined than the pumping pulse frequency, and it is the spread of the latter which limits the frequency correlations of the idler–signal pair coming from one source.

One can estimate the maximal visibility expected for the interference process described above. We shall still work within the earlier simplifying assumptions (the specific problems associated with the emission statistics of the PDC sources will be discussed in the next section).

The amplitude of the four-photon detection at, say, detectors $a(+)$, $b(+)$, $c(+)$, and $d(+)$ at times t_a, t_b, t_c, and t_d is proportional to

$$e^{i(\phi_a+\phi_b+\phi_c+\phi_d)}A_{ad}(t_a, t_d)A_{cb}(t_c, t_b) + A_{b'd'}(t_b, t_d)A_{a'c'}(t_a, t_c) \tag{6}$$

where ϕ_i, $i = a, b, c, d$, is the local phase shift in the given beam. To get the overall probability of the process one has to integrate the square of the modulus of the amplitude over the detection times (the time resolution of the detectors is of the order of nanoseconds, which is much longer than the coherence times of the filters and the width of pump pulse, and therefore the integrations over time can be extended to infinity).

Now, if one assumes that the filters in beams leading to a single detector station are identical, and that the functions have the structure

$$F_f(t) = e^{-(1/2)\omega_p^o t}\left|F_f(t)\right|, \qquad G(t) = e^{-\omega_p^o t}\left|G(t)\right|$$

where ω_p^o is the central frequency of the pulse, then the four-particle interference fringes in the joint probability to have counts in the four detectors behave as

$$1 - V(4)\cos\left(\sum_{x=a,b,c,d} \phi_x\right)$$

and the visibility $V(4)$ is given by

$$V(4) = \frac{\int d^4t \left|A_{ad}(t_a, t_d)A_{bc}(t_b, t_c)A_{b'd'}(t_b, t_d)A_{a'c'}(t_a, t_c)\right|}{\int d^4dt \left|A_{ad}(t_a, t_d)A_{bc}(t_b, t_c)\right|^2} \tag{7}$$

where $d^4t = dt_a\, dt_b\, dt_c\, dt_d$.

If one specifies, for simplicity, all the functions as Gaussians exp $[-\frac{1}{2}(\omega - \Omega)^2/\sigma^2]$, where Ω is the midfrequency and σ the width, the formula for the visibility reads

$$V(4) = \left(\frac{2\sigma_p^2}{2\sigma_p^2 + \sigma_a^2\sigma_c^2/(\sigma_p^2 + \sigma_a^2 + \sigma_c^2) + \sigma_a^2\sigma_d^2/(\sigma_p^2 + \sigma_a^2 + \sigma_d^2)}\right)^{1/2} \tag{8}$$

where σ_p is the spectral width of the pulse, σ_f, $f = a, b, c, d$, is the width of the filter in the given beam, and we assume that $\sigma_a = \sigma_b$. If one removes the filters in beams a, a' and b, b', the formula simplifies to

$$V(4) = \left(\frac{2\sigma_p^2}{2\sigma_p^2 + \sigma_c^2 + \sigma_d^2}\right)^{1/2} \tag{9}$$

i.e., narrow filters in paths a, a' and b, b' are not necessary to obtain high visibility. The other filters always should be sufficiently narrow.

4. THE INFLUENCE OF PHOTON STATISTICS

The visibility estimated above of the four-particle fringes in the setup of Fig. 2 can be seriously impaired by the statistical properties of the emission process. The statistics of a single beam of a downconverter is of a thermal type. The full second-quantized description of the state of idler–signal pairs emerging via a pair of (perfectly phase matched) pinholes is approximately given by

$$|\psi\rangle = N^{-1}\sum_{m=0}^{\infty} z^m|m, s\rangle|m, i\rangle \tag{10}$$

where z is a number dependent on the strength of the pump field, $|m, s\rangle$ ($|m, i\rangle$) denotes an m-photon state in the signal (idler) mode, and N is the normalization constant. The effective temperature of the idler (or signal) field (which is described by a reduced density matrix) can be obtained by expressing $|z|^2$ as

$$|z|^2 = \exp\left(-\frac{\hbar\omega}{kT_{\text{eff}}}\right) \tag{11}$$

One can obtain the state (10) by taking the Heisenberg-picture input–output relations for the PDC radiation modes. In the approximate interaction Hamiltonian one assumes that the pump field is treated as classical and described by a complex amplitude v_o (this approach also tacitly assumes that the pump is not depleted during the interaction). The annihilation operators of the output modes $a_i(T)$ for the idler field and $a_s(T)$ for the signal field (where T is the interaction time) can be expressed in term of the operators at $T = 0$ in the following way:

$$\begin{aligned} e^{i(1/2)\omega_p^o T}a_s(T) &= \cosh K\, a_s(0) - ie^{i\theta}\sinh K\, a_i^{\dagger}(0) \\ e^{i(1/2)\omega_p^o T}a_i(T) &= \cosh K\, a_i(0) - ie^{i\theta}\sinh K\, a_s^{\dagger}(0) \end{aligned} \tag{12}$$

where $K = g|v_o|T$, $v_o = |v_o|e^{i\theta}$, and g is the coupling strength. The relation between z of (10) and the parameter K is given by $|z| = \tanh(K)$.

Thus (under the assumption of exactly equal pump powers), this description suggests that the chance that the two sources emit two pairs is exactly equal to the chance for a double emission (two pairs) from a given source. This latter type of emission could in principle lead to unwanted effects which could lower the visibility of the four-particle fringes. As we shall see below, this danger can be avoided by limiting the pump power. Fortunately, the limit is not too restrictive, and we can expect high visibilities at very high pump powers. Also, it is immediately clear that for low pump intensities the state can be approximated by truncating the series in the formula (10) to the first terms.

To estimate the effects of the statistics, one should calculate the rate of the correlated counts at the four detectors, and the calculation should take into account the full description of the state (10). As only a rough estimate is needed, we shall use here the simplest description. We shall assume that the probability of a detector to click is proportional to the number of photons present in the mode monitored by the detector, i.e.,

$$P(a(+), b(+), c(+), d(+)) \approx C \langle : n_{a(+)}(T) n_{b(+)}(T) n_{c(+)}(T) n_{d(+)}(T) : \rangle \tag{13}$$

where $n_x(T) = a_x^\dagger(T) a_x(T)$ is the Heisenberg picture photon number operator in mode x after the interaction time T. The usual mode transformation algebra for the passive devices (beamsplitters and phaseshifters) has to be applied:

$$a_{x(+)} = \frac{1}{\sqrt{2}} (e^{i\phi_x} a_x - i a_x') \tag{14}$$

for $x = a, b, c, d$. In turn, for each source the idler–signal couples [coupled by the Heisenberg-picture equation (12)] are in the primed and umprimed beams, i.e., the idler–signal pairs are in modes a and d, and a' and c' for source A, and in b and c, and b' and d' for source B. After some algebraic manipulations the final formula for the visibility of the detection rate (13) is

$$V(K) = \frac{\cosh^4(K)}{8 \sinh^4(K) + 6 \cosh^2(K) \sinh^2(K) + \cosh^4(K)} \tag{15}$$

Conclusion: The visibility will be above 50% (which is the threshold for sinusoidal *three*-particle interferometric fringes to have solely nonclassical interpretation) if

$$|z|^2 < (\sqrt{17} - 3)/8 \approx 0.140 \tag{16}$$

In simple terms, one can expert quite high visibility if the ratio of the probability of *each pulse* to produce a single downconverted pair to the probability of not producing anything is less then 14%. Thus this threshold is at quite high pump powers.

5. INTERPRETATIONS. FUNDAMENTAL QUESTIONS

The interferometric configuration of Fig. 2 can find very many applications in research on the foundations of quantum physics. Each of these applications may, through a real experiment, answer some puzzling questions. Here are two of them:

- The first question is obviously related to all that was said earlier. Can one perform multiparticle higher order interference experiments for *particles* originating from independent sources (rather than for intense fields—e.g., interference experiments involving two superposed laser beams, or attenuated coherent fields)?

The presented theory supports a positive answer. We have presented the experiment in such a way that the same laser pumps both crystals. But there is no fundamental obstacle to having two independent lasers and gating the experiment in such way that only the emissions from pulses arriving simultaneously at the crystals are fed into the interferometers. The earlier experiments involving interference of light originating from independent sources involved states (essentially the coherent ones) for which the particle interpretation is doubtful even at very low intensity [for a review, see Paul (1986)]. One should also add that the two PDC sources of the experiment of Ou *et al.* (1990) cannot be thought of as independent (the relative phase of the pumping fields must be held fixed for the interference to occur).

- There is an old question posed already by Bell: can one have an "event-ready detectors" test of Bell's inequalities? Again the answer is positive.

The way to obtain the answer to the second question is to treat the whole complex of the two sources A and B (laser plus two crystals) and the detection stations $d(\pm)$ and $c(\pm)$ as a compound event-ready source for a Bell test.

The phases ϕ_c and ϕ_d should be kept fixed at, say, zero. Now, if the two detectors $c(+)$ and $d(+)$ fire simultaneously (i.e., within the time around one pulse), this event can have its origin in the two sources emitting two entangled states: $|\Psi^A\rangle = (1/\sqrt{2})(|a\rangle|d\rangle + |a'\rangle|c'\rangle)$ for source A and $|\Psi^B\rangle = (1/\sqrt{2})(|b'\rangle|d'\rangle + |b\rangle|c\rangle)$ for source B (see Section 3). As mentioned earlier, the interferometric setup is designed in such a way that one cannot distinguish the origin of the photons at $c(+)$ and $d(+)$. Therefore the simultaneous firing of the two detectors effectively collapses the state of the two photons into $|\Psi^{d(+)c(+)}\rangle = (1/\sqrt{2})(|c\rangle|d\rangle + |c'\rangle|d'\rangle)$, which in turn effectively collapses the state of the two (remaining) photons, which are on their way to the detector stations $a(\pm)$ and $b(\pm)$, into $|\Psi^{\text{swap}}\rangle = (1/\sqrt{2})(|a\rangle|b\rangle + |a'\rangle|b'\rangle)$. In this way the entanglement gets swapped and now entwines the photons that were not entangled initially. Of course the state $|\Psi^{\text{swap}}\rangle$ is a perfect one for performing a Bell test. The two local observation stations are now the fragments of the full four-particle interferometer. The full device should be topologically transformed in such a way that the detection stations $a(\pm)$ and $b(\pm)$ together with the beamsplitters and the phase shifters ϕ_a and ϕ_b should be as far away as possible from each other (this could enable one to perform a delayed-choice version of the experiment). The dichotomic observable measured at, e.g., station $a(\pm)$ is defined in the following way: a click at $a(+)$ is associated with the eigenvalue $+1$, and a click at $a(-)$ is associated with the eigenvalue -1. The corresponding eigenstates are $(1/\sqrt{2})(e^{i\phi_a}|a\rangle + i|a'\rangle)$ and $(1/\sqrt{2})(ie^{i\phi_a}|a\rangle + |a'\rangle)$.

The firings at $c(+)$ and $d(+)$ preselect the entangled pairs for the Bell-type experiment. The ensemble of the entangled pairs is operationally defined [one can therefore operationally define nondetection events at stations $a(\pm)$ and $b(\pm)$].

The entanglement swapping process may not always occur. One may have firings at $d(+)$ and $c(+)$ caused by a double emission at a single PDC source (see Section 4). However, this would never (at low pump rates) lead to simultaneous registrations at stations $a(\pm)$ and $b(\pm)$. Such a "wrong" event will happen at only one of the stations (where, by the way, altogether two photons will be registered). A "wrong" event at, say, station $a(\pm)$ would immediately imply no click at the other station $b(\pm)$, i.e., such events are, in a way, EPR correlated, and thus are of a fundamentally different nature than the usual problems with low detection efficiency of the detection. What is even more important: If the detectors $d(+)$ and $c(+)$ fire and we do not observe any photons at $a(+)$, then we know with certainty that, whatever is the setting of ϕ_b, we shall register two photons at the other station (we discuss now the idealized case by assuming that we have perfect detectors, and we employ methods to distinguish a two-photon registration from a single-photon registration at one detector). This very strong property enables one to find a method of incorporating such "wrong" events into the Bell theorem [see Popescu *et al.* (1997), where it was shown that one can indeed show contradiction between local realism and the quantum prediction for experiments where "wrong" events of this type are observed].

Also, one should note that high visibilities in the discussed experiment do not require any filtering of the photons on their way to the detection stations $a(\pm)$ and $b(\pm)$ (where the interference effects due to entanglement swapping are observed; see Fig. 2). It is the radiation on the way to $c(\pm)$ and $d(\pm)$ that suffers all the losses due to the filtering. The Bell pair for the two-particle interference at $a(\pm)$–$b(\pm)$ is preselected by the coincident firing events at $d(+)$ and $c(+)$. Thus, the experiment is done under conditions which do not involve any additional obstacles for high collection efficiencies (except the trivial usual ones, like detection inefficiency or misalignments, etc.) for the particles involved in the Bell-type interference phenomena (see, e.g., Zukowski *et al.*, 1993).

The interpretation of the interferometric configuration as a device for performing an "event-ready" Bell test via the use of the method of entanglement swapping provides answers to some other questions:

- Is the phenomenon of entanglement confined only to particles originating from one source, or at least interacting with each other at a certain stage? Definitely no.

- Can one entangle particles that share no common past and are spatially separated? Yes. Notice that the photons cannot exist before the pulse–crystal interaction.

The premises of the Einstein, Podolsky, and Rosen (1935) argument to show incompleteness of quantum mechanics are inconsistent when applied to maximally entangled states of at least three particles. The natural source of three-particle entanglements, three-photon positronium annihilation, is a rare event, and the polarizations of the γ-rays are difficult to measure. Also, one could think of a higher order spontaneous downconversion process involving cubic nonlinearity in a crystal's polarizability. However, both processes share (almost) complete unpredictability of the directions of emission (this makes the count rates very low). Since 1989, many other sources have been proposed, but thus far no experiment has been performed (for example, Wódkiewicz *et al.*, 1993; Cirac and Zoller, 1994; Haroche, 1995; Sleator and Weinfurter, 1995; Laloë, 1995; Gerry, 1996; Pfau, *et al.*, 1996). So another question emerges:

- Is there an experimentally feasible method to observe GHZ entangled particle triples and their correlations?

The studied interferometric configuration provides a method for generating three-particle entanglement out of only *two* pairs of entangled photons (Zeilinger *et al.*, 1997). Consider the arrangement of Fig. 2. Again imagine that both sources emit two entangled pairs. Suppose that one and only one of the four particles is detected by $d(+)$, and no particle is detected at $d(-)$. The other six beams enter the three-particle GHZ interferometer [which again can be obtained by a topological distortion of the device of Fig. 2: one has to place the detector stations $a(\pm)$, $b(\pm)$, and $c(\pm)$ together with their local beamsplitters and phaseshifters very far away from each other]. Because of the beamsplitter, the trigger particle at $d(+)$ could have come from either source A or B. If it came from A, its companion must be in beam a, and the pair from B must be in beams b and c. Thus, the state of the triple of remaining particles is $|a\rangle|b\rangle|c\rangle$. If, on the other hand, the trigger particle [at $d(+)$] came from source B, its companion must be in beam b' and the pair from A must be in beams a' and c'. Thus, if the trigger particle came from B, the state of the remaining triple is $|a'\rangle|b'\rangle|c'\rangle$.

Now, as the procedure of emission and selection of the four photons in our device is such that one *cannot ever know, not even in principle*, which source produced the trigger event, then the other photons, as they enter the three-particle interferometer, will be in a superposition of the two states mentioned above, i.e., in the GHZ state

$$\frac{1}{\sqrt{2}}(|a\rangle|b\rangle|c\rangle + e^{i\phi}|a'\rangle|b'\rangle|c'\rangle) \tag{17}$$

where the relative phase ϕ depends on the positions of various elements of the full setup and ϕ_d.

The principal aim of such experiment will be to show the existence of GHZ states. However, there are seemingly some complications. For example, the trigger detector may fire if (a) only one downconversion occurred, or (b) two downconversions occurred in one crystal. Case (a) can be rejected; two of the detector stations will show no counts. Case (b) can also be rejected; either station $a(\pm)$ or $b(\pm)$ will exhibit no counts. In other words, all triple counts observed in the three-particle interferometer are GHZ triples (of course, for low pump levels). As mentioned earlier, three-particle fringes in such a device cannot have a classical model if they possess visibility higher than 50% [the critical visibilities for such experiments are discussed in Belinskii and Klyshko (1993), Żukowski (1993), and Żukowski and Kaszlikowski (1997)].

Finally, we note that an extension of these schemes would enable us to answer the question of observability of four-particle correlations specific to the four-particle GHZ state. Simply, the pattern of correlations in the full four-particle interferometer of Fig. 2 reveals the features of GHZ correlations (the visibility, in principle, can be close to 1). Note, however, that here the state is not prepared, but that the correlations are observed by a destructive selection at the detectors.

6. THE BEGINNING OF AN EPILOGUE

While this paper was being written, the first experiments of the type presented here were performed.

The first one (Bouwmeester *et al.*, 1997) was a laboratory realization of the teleportation idea (Bennett *et al.*, 1992). The interferometric configuration was slightly different, but the techniques to obtain high visibility were based on the very idea of hiding the origin of the particles by using pump pulses of time widths shorter than the coherence times of the filtered radiation (see previous sections). The obtained visibility (around 70%) was high enough to exclude any interpretation of the experiment based upon the classical theory of electromagnetism (for details concerning the observed phenomenon of quantum teleportation, see the original work).

Finally, the first observation of entanglement swapping (again based on the ideas presented here) was done in November 1997, and will be reported in a forthcoming publication. In the first run of the experiment, two particle fringes of visibility 65% were observed.

The success of these experiments permits one to be very optimistic about the possibility of observing GHZ phenomena using the discussed methods. Also, the much more involved three-source scheme of an event-ready preparation of GHZ triples (Żukowski *et al.*, 1995) seems now to be at the border of feasibility.

Finally, we mention that the methods presented here can find applications in future quantum networks (Bose *et al.*, 1998) and in devices for distributed quantum computation.

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