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New High-Intensity Source of Polarization-Entangled Photon Pairs

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We report on a high-intensity source of polarization-entangled photon pairs with high momentum definition. Type-II noncollinear phase matching in parametric down conversion produces true entanglement: No part of the wave function must be discarded, in contrast to previous schemes. With two-photon fringe visibilities in excess of 97%, we demonstrated a violation of Bell's inequality by over 100 standard deviations in less than 5 min. The new source allowed ready preparation of all four of the EPR-Bell states.

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Entangled states of quantum particles highlight the nonseparability and nonlocality of quantum mechanics most vividly. A great number of experiments have investigated the production of entangled states of photons, particularly for use in tests of Bell's inequalities [1–3]. Recently, a whole wealth of curious and/or potentially useful applications of entangled states was proposed, from quantum communication, including cryptography [4] and transfer of two bits of information in one photon [5], to quantum teleportation [6] and "entanglement swapping" [7], to quantum computation [8].

Although entanglement in any degree of freedom is usually equally good in principle, polarization is often much easier to deal with in practice, due to the availability of high efficiency polarization-control elements and the relative insensitivity of most materials to birefringent thermally induced drifts. Unfortunately, as has been pointed out by several authors [9–12], no adequate source of polarization-entangled states has hitherto been reported. In particular, besides low brightness and difficulty in handling, the atomic cascade sources [1,2] suffer a degrade of the polarization correlations when the two photons are not emitted back to back (due to the recoil of the atom) [9]. This also results in a reduced collection efficiency for the pair. Nearly all previous experiments employing photons from parametric down conversion [3] have actually produced *product* states—they approximated an entangled state by post-selecting only *half* of the total state detected [13]. For example, one directs two orthogonally polarized photons onto a beam splitter, but considers only those cases where they leave via different output ports.

Three methods to avoid this problem by means of two down-conversion crystals have been proposed [10,14], but not yet carried out. Here we present a much simpler technique, relying on noncollinear type-II phase matching. The desired polarization-entangled state is produced *directly* out of a single nonlinear crystal [BBO (beta-barium borate) in our experiment], with no need for extra beam splitters or mirrors and no requirement of discarding detected pairs to observe nonlocal correlations. Verifying the correlations produced by the novel source, we have observed strong violations of Bell's inequalities (modulo the typical auxiliary assumptions), in some cases by more than 100 standard deviations. Using two extra birefringent elements, one can easily produce any of the four orthogonal "EPR-Bell states" [15].

To date, most of the experiments with photons from spontaneous parametric down conversion have used type-I phase matching, in which the correlated photons have the same polarization [16]. There, for the case of degenerate emission, a pair of photons with equal wavelength emerge on a cone [17], which is centered on the pump beam and whose opening angle depends on the angle θ_{pm} between the crystal optic axis and the pump. With type-II phase matching, the down-converted photons are emitted into *two* cones [10], one ordinary polarized, the other extraordinary polarized [17]. In the collinear situation the two cones are tangent to one another on exactly one line, namely, the pump beam direction [18]. If θ_{pm} is decreased, the two cones will separate from each other entirely. However, if the angle is *increased*, the two cones tilt toward the pump, causing an intersection along two lines (see Fig. 1) [19–21]. Along the two directions ("1" and "2"), where the cones overlap, the light can be essentially described by an entangled state:

$$|\psi\rangle = (|H_1, V_2\rangle + e^{i\alpha}|V_1, H_2\rangle)/\sqrt{2}, \qquad (1)$$

where H and V indicate horizontal (extraordinary) and vertical (ordinary) polarization, respectively. The relative phase α arises from the crystal birefringence, and an overall phase shift is omitted.

Using an additional birefringent phase shifter (or even slightly rotating the down-conversion crystal itself), the value of α can be set as desired, e.g., to the values 0 or π. (Somewhat surprisingly, a net phase shift of π may be obtained by a 90° rotation of a *quarter* wave plate in one of the paths.) Similarly, a half wave plate in one path can be used to change horizontal polarization to vertical and vice versa. One can thus very easily produce any of the four EPR-Bell states,

$$|\psi^{\pm}\rangle = (|H_1, V_2\rangle \pm |V_1, H_2\rangle)/\sqrt{2},$$
$$|\phi^{\pm}\rangle = (|H_1, H_2\rangle \pm |V_1, V_2\rangle)/\sqrt{2}, \qquad (2)$$

which form the complete maximally entangled basis of the two-particle Hilbert space, and which are important in many quantum communication and quantum information schemes.

The birefringent nature of the down-conversion crystal complicates the actual entangled state produced, since the ordinary and the extraordinary photons have different velocities inside the crystal, and propagate along different directions even though they become collinear outside the crystal (an effect well known from calcite prisms, for example). The resulting longitudinal and transverse walk-offs between the two terms in the state (1) are maximal for pairs created near the entrance face, which consequently acquire a relative time delay $\delta T = L(1/u_o - 1/u_e)$ (L is the crystal length, and u_o and u_e are the ordinary and extraordinary group velocities, respectively) and a relative lateral displacement $d = L \tan\rho$ (ρ is the angle between the ordinary and extraordinary beams inside the crystal). If $\delta T > \tau_c$, the coherence time of the down-conversion light, then the terms in (1) become, in principle, distinguishable by the order in which the detectors would fire, and no interference will be observable. Similarly, if d is larger than the coherence width, the terms can become partially labeled by their spatial location.

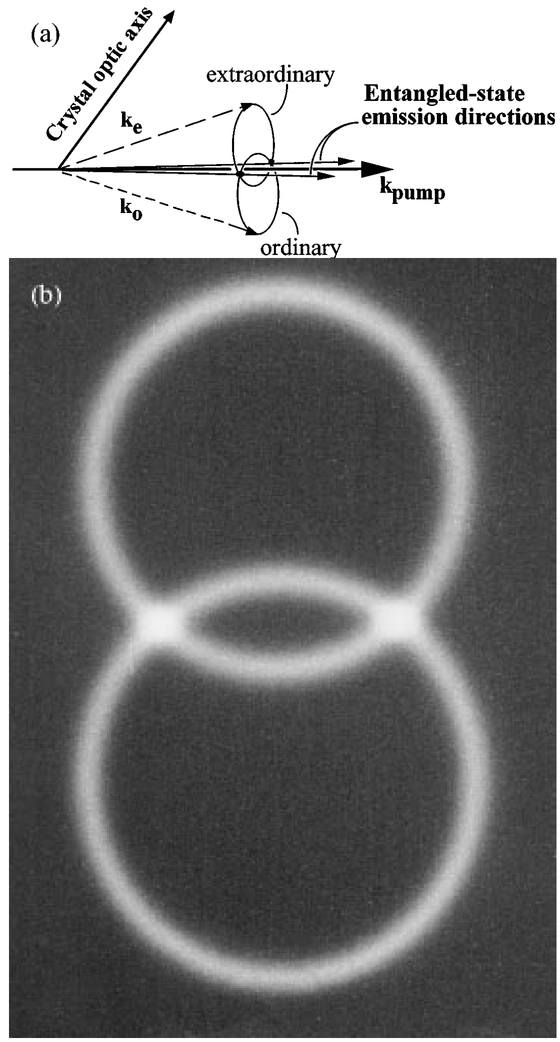

FIG. 1. (a) Spontaneous down-conversion cones present with type-II phase matching. Correlated photons lie on opposite sides of the pump beam. (b) A photograph of the down-conversion photons, through an interference filter at 702 nm (5 nm FWHM). The infrared film was located 11 cm from the crystal, with no imaging lens. (Photograph by M. Reck.)

Because the photons are produced coherently along the entire length of the crystal, one can *completely* compensate for the longitudinal walk-off [23]—after compensation, interference occurs pairwise between processes where the photon pair is created at distances $\pm x$ from the middle of the crystal. The ideal compensation therefore uses two crystals, one in each path, which are identical to the down-conversion crystal, but only half as long. If the polarization of the light is first rotated by 90° (e.g., with a half wave plate), the retardations of the o and the e components are exchanged and complete temporal indistinguishability is restored ($\delta T = 0$) [24]. The same method provides the optimal compensation for the transverse walk-off effect as well [25].

The experimental setup is shown in Fig. 2. The 351.1 nm pump beam (150 mW) originated in a single-mode argon ion laser, followed by a dispersion prism to remove

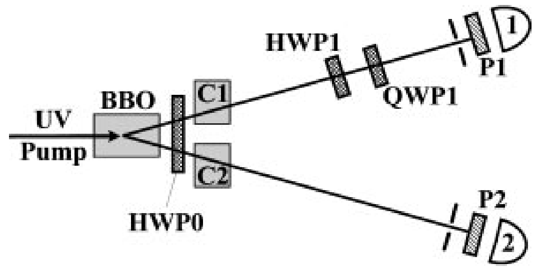

FIG. 2. Schematic of one method to produce and select the polarization-entangled state from the down-conversion crystal. The extra birefringent crystals C1 and C2, along with the half wave plate HWP0, are used to compensate the birefringent walk-off effects from the production crystal. By appropriately setting half wave plate HWP1 and quarter wave plate QWP1, one can produce all four of the orthogonal EPR-Bell states. Each polarizer P1 and P2 consisted of two stacked polarizing beam splitters preceded by a rotatable half wave plate.

unwanted laser fluorescence. Our 3 mm long BBO crystal (from Castech-Phoenix) was nominally cut at $\theta_{\text{pm}} = 49.2°$ to allow collinear degenerate operation when the pump beam is precisely orthogonal to the surface. The optic axis was oriented in the vertical plane, and the entire crystal tilted (in the plane containing the optic axis, the surface normal, and the pump beam) by 0.72°, thus increasing the effective value of θ_{pm} (inside the crystal) to 49.63°. The two cone-overlap directions, selected by irises before the detectors, were consequently separated by 6.0°. Each polarization analyzer consisted of two stacked polarizing beam splitters preceded by a rotatable half wave plate. The detectors were cooled silicon avalanche photodiodes operated in the Geiger mode. Coincidence rates $C(\theta_1, \theta_2)$ were recorded as a function of the polarizer settings θ_1 and θ_2.

In our experiment the transverse walk-off d (0.3 mm) was small compared to the coherent pump beam width (2 mm), so the associated labeling effect was minimal. However, it was necessary to compensate for longitudinal walk-off, since the 3.0 mm BBO crystal produced $\delta T = 385$ fs, while τ_c [determined by the collection irises and interference filters (centered at 702 nm, 5 nm FWHM)] was about the same. As discussed above, we used an additional BBO crystal (1.5 mm thickness) in each of the paths, preceded by a half wave plate to exchange the roles of the horizontal and vertical polarizations.

Under these conditions, we attained a maximum coincidence fringe visibility (as polarizer 2 was rotated, with polarizer 1 fixed at −45° [26]) of (97.8 ± 1.0)%, indicating the high quality of the source. Appropriately orienting the wave plates in path 1, we produced all four EPR-Bell states and observed the expected correlations (Table I, Fig. 3).

As is well known, the high-visibility sinusoidal coincidence fringes in such an experiment imply a violation of a suitable Bell inequality. In particular, according to the inequality of Clauser, Horne, Shimony, and Holt (CHSH) [27], $|S| \leq 2$ for any local realistic theory, where

TABLE I. The four EPR-Bell states, the associated coincidence rate predictions, and the measured value of the parameter S.

EPR-Bell state	$C(\theta_1, \theta_2)$	S [a]
$\lvert\psi^+\rangle$	$\sin^2(\theta_1 + \theta_2)$	-2.6489 ± 0.0064
$\lvert\psi^-\rangle$	$\sin^2(\theta_1 - \theta_2)$	-2.6900 ± 0.0066
$\lvert\phi^+\rangle$	$\cos^2(\theta_1 - \theta_2)$	2.557 ± 0.014
$\lvert\phi^-\rangle$	$\cos^2(\theta_1 + \theta_2)$	2.529 ± 0.013

[a] Data for the $|\phi^\pm\rangle$ states were taken with a single compensating crystal, data for the $|\psi^\pm\rangle$ states with a compensating crystal in each path (see text).

$$S = E(\theta_1, \theta_2) + E(\theta_1', \theta_2) + E(\theta_1, \theta_2') - E(\theta_1', \theta_2'), \tag{3a}$$

and $E(\theta_1, \theta_2)$ is given by [28]

$$\frac{C(\theta_1, \theta_2) + C(\theta_1^\perp, \theta_2^\perp) - C(\theta_1, \theta_2^\perp) - C(\theta_1^\perp, \theta_2)}{C(\theta_1, \theta_2) + C(\theta_1^\perp, \theta_2^\perp) + C(\theta_1, \theta_2^\perp) + C(\theta_1^\perp, \theta_2)}. \tag{3b}$$

The measured value of S is a figure of merit for the quality of the actual entangled state produced from the crystal. Therefore, for each of the four EPR-Bell states we took extensive data for the settings [29] $\theta_1 = -22.5°$, $\theta_1^\perp = 67.5°$; $\theta_1' = 22.5°$, $\theta_1'^\perp = 112.5°$; and $\theta_2 = -45°$, $\theta_2^\perp = 45°$; $\theta_2' = 0°$, $\theta_2'^\perp = 90°$. The CHSH inequality was strongly violated in all cases; see Table I.

For one of the Bell inequality measurements (ψ^+), a larger collection iris allowed us to accumulate the statistics necessary for a 102 standard deviation violation in less than 5 min. In particular, we were able to use elliptical collection irises (1.5 m from the crystal) with a horizontal opening of 3 mm, and a vertical opening of 10 mm, and still see visibilities of 95%. Therefore this source is more

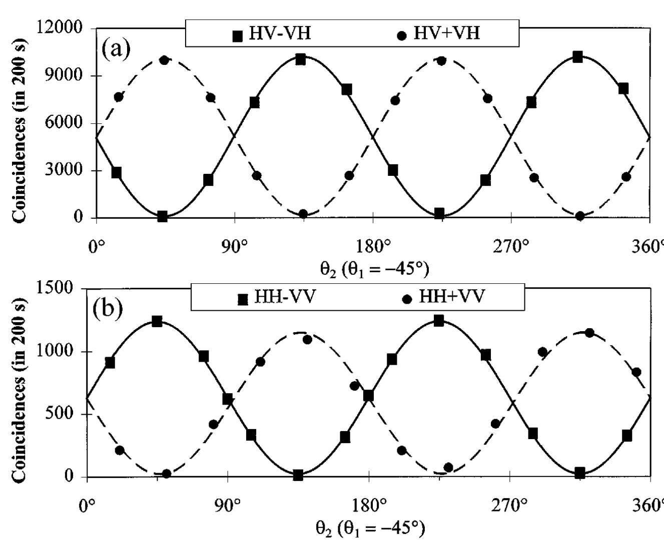

FIG. 3. Coincidence fringes for states (a) $(|H_1, V_2\rangle \pm |V_1, H_2\rangle)/\sqrt{2}$; (b) $(|H_1, H_2\rangle \pm |V_1, V_2\rangle)/\sqrt{2}$. The difference in the counting rates for the two plots is due to different collection geometries.

than an order of magnitude brighter than previous sources for polarization-entangled photons, with coincidence rates greater than 1500 s^{-1}. The high net detection efficiency ($> 10\%$) is an important step towards a loophole-free Bell-inequality experiment [9,10]. However, to achieve the requisite efficiency, it will almost certainly be necessary to employ a spatial-filtering scheme to take advantage of the momentum correlations of the photons.

Our source has a number of distinct advantages. As indicated above, it seems to be relatively insensitive to larger collection irises, an important practical advantage, and possibly crucial for a loophole-free test. In addition, due to its simplicity, the present scheme was much quicker to align than other down-conversion setups, and was remarkably stable. One of the reasons is that phase drifts are not detrimental to a polarization-entangled state unless they are *birefringent*, i.e., polarization dependent—this is a clear benefit over momentum-entangled or energy-time-entangled states. Moreover, one can, in fact, transform polarization-entangled states into momentum- or energy-time entangled states [12,30].

For these reasons, we expect that our technique will find immediate application in many experiments requiring a stable source of easily controllable entangled states of two particles, in particular, experiments on quantum communication, including quantum cryptography [4], encoding more than one bit of information in a photon [5], teleportation [6], "entanglement swapping" [7], and in the new field of quantum computation [8]. We believe that this source will significantly facilitate such experiments, as well as investigations of the foundations of quantum mechanics, even in student laboratories.

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[19] As θ_{pm} is increased to 90°, the two cones each become centered on the pump, and, in fact, overlap exactly. While this seems desirable, the actual down-conversion efficiency in a uniaxial crystal such as BBO varies as $\cos^2(\theta_{pm})$ [22], so that no down conversion takes place at this setting.

[20] A detailed calculation for vector phase matching in BBO [P. G. Kwiat, Ph. D. thesis, University of California at Berkeley, 1993] shows that the precise overlap only occurs *outside* the crystal, as a result of Snell's law at the exit face (assumed normal to the pump beam direction).

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[25] However, for a sufficiently long crystal, the o and e rays can separate by more than the coherence width of the pump beam, and it is then not possible to completely compensate the effects of walk-off.

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