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# Ultrabright source of polarization-entangled photons

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Using the process of spontaneous parametric down-conversion in a two-crystal geometry, we have generated a source of polarization-entangled photon pairs that is more than ten times brighter, per unit of pump power, than previous sources, with another factor of 30 to 75 expected to be readily achievable. We have measured a high level of entanglement between photons emitted over a relatively large collection angle, and over a 10-nm bandwidth. As a demonstration of the source capabilities, we obtained a 242-$\sigma$ violation of Bell's inequalities in less than three minutes, and observed near-perfect photon correlations when the collection efficiency was reduced. In addition, both the degree of entanglement and the state purity should be readily tunable.
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Entangled states of multiparticle systems are arguably the quintessential feature of quantum mechanics [1]. In addition to their central role in discussions of nonlocal quantum correlations [2], they form the basis of quantum information, and enable such phenomena as quantum cryptography [3], dense coding [4], teleportation [5], and quantum computation [6]. At present, the most accessible and controllable source of entanglement arises from the process of spontaneous parametric down-conversion in a nonlinear optical crystal. Here we describe a proposal for, and experimental realization of, an ultrabright source of polarization-entangled photon pairs, using *two* such nonlinear crystals. Because nearly every pair of photons produced is polarization entangled, the total flux of emitted polarization-entangled pairs should be hundreds of times greater than is achievable with the best previous source, for comparable pump powers. The improved technique has the added advantage that the degree of entanglement and the purity of the state may be readily tunable, heretofore impossible.

It is now well known that the photons produced via the down-conversion process share nonclassical correlations [7]. In particular, when a pump photon splits into two daughter photons, conservation of energy and momentum lead to entanglements in these two continuous degrees of freedom [8]. Yet conceptually, the simplest examples of entangled states of two photons are the *polarization*-entangled ''Bell states''

$$|H_1,V_2\rangle \pm |V_1,H_2\rangle, \quad |H_1,H_2\rangle \pm |V_1,V_2\rangle, \tag{1}$$

where $H$ and $V$ denote horizontal and vertical polarization, respectively, and for convenience we omit the normalization factor $(1/\sqrt{2})$. For instance, $HV-VH$ is the direct analog of the spin singlet considered by Bell [2]. To date there have been only two methods for producing such polarization-entangled photon pairs, and each has fairly substantial limitations. The first was an atomic cascade—a two-photon decay process from one state of zero angular momentum to another. The resulting photons *do* display nonclassical correlations (they were used in the first tests of Bell's inequalities [9,10]), but the correlations decrease if the photons are not emitted back-to-back, as is allowed by recoil of the parent atom.

This problem was circumvented with parametric down-conversion, since the emission directions of the photons are well-correlated. In several earlier experiments down-conversion photon pairs of *definite* polarization were incident on a beam splitter, and nonclassical correlations observed for those *postselected* events in which photons traveled to different output ports [11]. However, the photons were actually created in polarization *product* states.

A source of truly polarization-entangled photons was realized using down-conversion with type-II phase matching, in which the photons are produced with (definite) orthogonal polarizations [12]. For two particular emission directions, however, the correlated photons are produced in the state $HV+VH$; additional birefringent elements in one or both beams allow the formation of all four Bell states. This source has been employed to demonstrate quantum dense coding [13], teleportation [14], a postselection-free test of Bell's inequality for energy and time variables [15], a test of Bell's inequality (for polarization variables) free of the usual rapid-switching loophole [16], and most recently, the generation of entangled states of *three* photons [17]. Coincidence count rates of up to $\sim$2000 $s^{-1}$ (for a 3-mm-thick BBO crystal and a 150-mW pump) have been observed with this source, while maintaining an acceptable level of entanglement.

Nevertheless, the source brightness is still very limited because the photons are polarization entangled only along two special directions. Using a *two*-crystal geometry, we have constructed a source in which *all* pairs of a given color are entangled, and we expect that this should extend to most, if not all, of the spectral down-conversion output, i.e., to cones corresponding to different colors [18]. Consider two adjacent, relatively thin, nonlinear crystals, operated with type-I phase matching [Fig. 1(a)]. The identically cut crystals are oriented with their optic axes aligned in perpendicular

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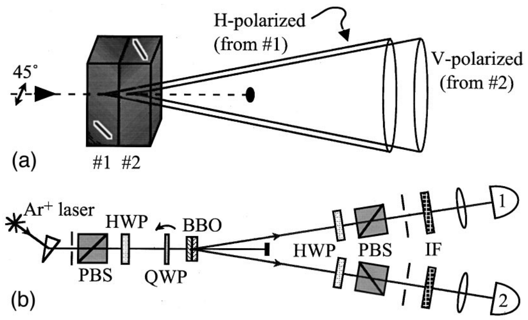


FIG. 1. (a) Method to produce polarization-entangled photons from two identical down-conversion crystals, oriented at 90° with respect to each other; i.e., the optic axis of the first (second) lies in the vertical (horizontal) plane. (b) Experimental setup to pump and characterize the source.

planes; i.e., the first (second) crystal's optic axis and the pump beam define the vertical (horizontal) plane. With a vertically polarized pump beam, due to the type-I coupling, down-conversion will only occur in crystal 1, where the pump is extraordinary polarized—the resulting down-conversion light cones will be horizontally polarized. Similarly, with a horizontally polarized pump, down-conversion will only occur in the second crystal, producing otherwise identical cones of vertically polarized photon pairs. A 45°-polarized pump photon will be equally likely to down-convert in either crystal (neglecting losses from passing through the first), and these two possible down-conversion processes are *coherent* with one another, as long as the emitted spatial modes for a given pair of photons are indistinguishable for the two crystals [19]. Consequently, the photons will automatically be created in the state $HH+e^{i\phi}VV$. $\phi$ is determined by the details of the phase matching and the crystal thickness, but can be adjusted by tilting the BBO crystals themselves (but this changes the cones' opening angles), by imposing a birefringent phase shift on one of the output beams, or by controlling the relative phase between the horizontal and vertical components of the *pump* light.

Figure 1(b) shows the experimental setup used to produce and characterize the correlated photons. The ~2-mm-diam pump beam at 351.1 nm was produced by an $Ar^+$ laser, and directed to the two crystals after passing through: a dispersion prism to remove unwanted background laser fluorescence; a polarizing beam splitter (PBS) to give a pure polarization state; a rotatable half-wave plate (HWP) to adjust the angle of the linear polarization; and a second, tiltable wave plate for adjusting $\phi$. The nonlinear crystals themselves were BBO $(8.0\times 8.0\times 0.59\,\text{mm})$, optic axis cut at $\theta_{pm}=33.9°$. For this cut the degenerate-frequency photons at 702 nm are emitted into a cone of half-opening angle 3.0°. For most of the data presented here, interference filters (IFs) centered at 702 nm [full width at half maximum (FWHM) ≈5 nm] were used to reduce background and select only these (nearly) degenerate photons; the maximum transmission of these filters was ~65%.

The polarization correlations were measured using adjustable polarization analyzers, each consisting of a PBS preceded by an adjustable HWP (for 702 nm). After passing through adjustable irises, the light was collected using 35-mm-focal-length doublet lenses, and directed onto single-

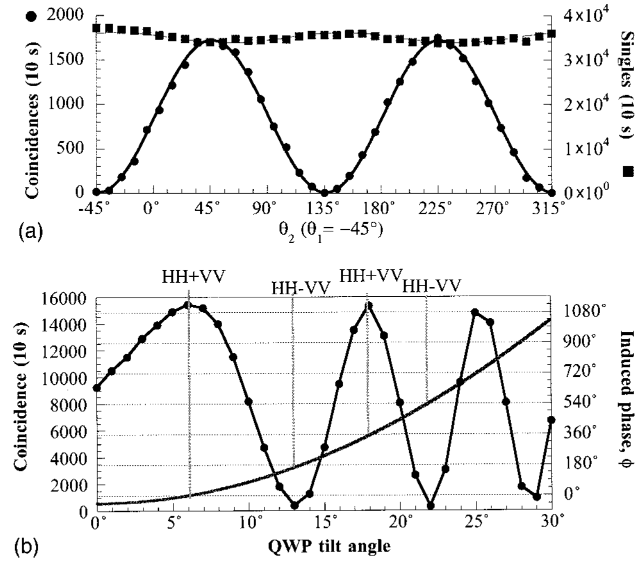


FIG. 2. (a) Measurements of the polarization entanglement. The polarization analysis of photon 2 was varied, while that of photon 1 was at −45°. The rate at detector 2 (squares, right axis) is essentially constant; i.e., the photons are individually nearly unpolarized, while the coincidence rate (circles, left axis) displays the expected quantum-mechanical correlations. The solid curve is a best fit, with visibility $V=99.6\pm0.3\%$. (b) Coincidences as the relative phase $\phi$ was varied by tilting the wave plate just before the crystal; both photons were analyzed at 45°. The solid curve is the calculated phase shift for our 2-mm-thick zero-order quartz quarter-wave plate, adjusted for the residual phase shift from the BBO crystals themselves.

photon detectors—silicon avalanche photodiodes (EG&G No. SPCM's), with efficiencies of ~65% and dark count rates of order 100 $s^{-1}$. The outputs of the detectors were recorded directly ("singles") and in coincidence, using a time-to-amplitude converter and single-channel analyzer. A time window of 7 ns was found sufficient to capture the true coincidences. Typical "accidental" coincidence rates were negligible ($<1\ s^{-1}$).

Figure 2(a) shows data demonstrating the extremely high degree of polarization entanglement achievable with our source. The state was set to $HH-VV$; the polarization analyzer in path 1 was set to −45°, and the other was varied by rotating the HWP in path 2. As expected, the coincidence rate displayed sinusoidal fringes with nearly perfect visibility ($V=99.6\pm0.3\%$ with "accidental" coincidences subtracted; $98.8\pm0.2\%$ with them included), while the singles rate was much flatter ($V<3.4\%$) [20]. We believe this to be the highest purity entangled state ever reported. The collection irises for these data were both only 1.76 mm in diameter—the resulting collection efficiency (the probability of collecting one photon *conditioned* on collecting the other) is then ~10%.

To experimentally verify that we could set $\phi$ by changing the ellipticity of the pump light, the quarter-wave plate (zero order, at 351 nm) before the crystals was tilted about its optic axis (oriented vertically), thereby varying the relative phase between horizontal and vertical polarization components [21]. Figure 2(b) shows the coincidence rate with both analyzers at 45°. For $\phi=0$, $\pi$ the states $HH\pm VV$ are produced. Just as with the previous type-II source [12], the other two

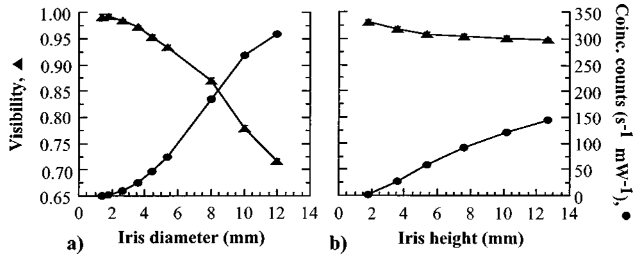


FIG. 3. For the state $HH-VV$, plots of the fringe visibility (triangles, left axis) and normalized coincidence counts (circles, right axis) versus collection aperture size. In (a) circular irises were used, showing a dropoff in visibility with increasing iris size; in (b) effective vertical *slits* (with fixed horizontal width 3.5 mm) produced a much slower reduction in visibility.

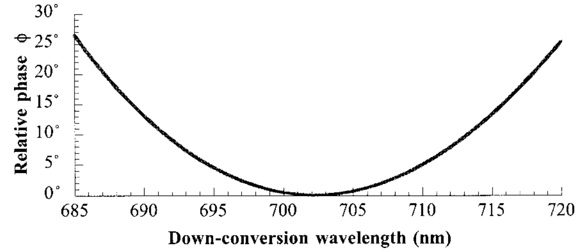


FIG. 4. A calculation of the relative phase $\phi$, as a function of the wavelength, of one of the down-conversion photons. An overall phase offset has been suppressed for clarity.

Bell states $HV\pm VH$ may be prepared simply by inserting a half-wave plate in one of the arms to exchange $H$ and $V$ polarization.

To characterize the source robustness and brightness, we measured the visibility as a function of the size of the collection apertures, located 1 m from the BBO crystals. Opening these apertures increases the aforementioned collection efficiency. In the first set of data [Fig. 3(a)], circular irises were used; the visibility decreased somewhat as the iris size increased, while the coincidence rate (normalized by the input pump power) increased. In the second set of measurements [Fig. 3(b)], a vertical slit of width 3.5 mm was added after each iris, and the vertical dimension of the aperture was varied using the iris size; this effectively collects a larger portion of the same cone. The visibility then stayed essentially constant at ~95%, but the coincidence rate still increased. At the maximum opening (limited by our collection lens), we observed over 140 coincidences per second per milliwatt of pump power. For 150-mW pump power, this implies a coincidence rate of 21,000 $s^{-1}$ [22], a $\times 10$ increase over the previous type-II source (which used a BBO crystal 2.5 times longer [12]). Note that this iris size still only accesses ~8% of the down-conversion cone. Given the symmetry of the arrangement, we expect strong entanglement over the entire cone, implying a total polarization-entangled pair *production* rate (over the 5-nm bandwidth) of about 10,000 $s^{-1}\,mW^{-1}$, where we have divided out the filter transmissions and detector efficiencies.

As a final demonstration of the source, a measurement of Bell's inequality was performed with the 5-nm interference filters replaced by 10-nm-wide filters (centered at 702 nm), the UV pump power increased to 60 mW, and the irises were set at $3.5\times 12.7$ mm. The coincidence rates were recorded for 16 combinations of analyzer settings ($\theta_1=0,90°,-45°,45°$; $\theta_2=-22.5°,67.5°,22.5°,112.5°$). Following [10], these may be combined to yield a value for the parameter $S=2.7007\pm 0.0029$, where according to any local realistic theory $|S|\leqslant 2$ (and the maximum according to quantum mechanics is $2\sqrt{2}$). Due to the very high coincidence count rates obtained for this measurement, over 10 000 $s^{-1}$, the necessary statistics for this 242-$\sigma$ violation were obtained in only 160 s.

We have thus far only considered photons belonging to a single cone of colors, though the arguments should apply to every such cone, even for down-converted photons with nondegenerate frequencies. However, due to dispersion in the nonlinear crystals, the relative phase $\phi$ will in general depend on the particular wavelength pairs being considered [23]. Figure 4 shows the results of a numerical calculation of $\phi$ (modulo 360°), as a function of the wavelength of one of the down-conversion photons, for our particular crystals. For all detected down-conversion photons to be described by essentially the *same* polarization-entangled state, the bandwidth of acceptance needs to be restricted, the crystal thicknesses reduced, or a special birefringent compensation element included. We see that an acceptable range of phase variation ($\phi\leqslant 26°$, the value for which fringe visibility $V=\cos\phi\geqslant 0.9$) is maintained for a bandwidth of 30 nm, assuming no other visibility-degrading effects come into play. Scaling our earlier 5-nm bandwidth result, we thus expect a total output over the entire cones making up this bandwidth of ~60,000 $s^{-1}\,mW^{-1}$. This is ~300 times brighter than the polarization-entangled photon-pair production rates obtainable with the previous down-conversion scheme [12] (and 750 times brighter if scaled by the crystal thickness).

Another remarkable feature of this source is that it may be used to produce ''non-maximally-entangled'' states, i.e., states of the form $HH+\epsilon VV$, $|\epsilon|\neq 1$, simply by rotating the pump polarization—for a pump polarized at angle $\theta$ to the vertical, $\epsilon=\tan\theta$. Such states have been shown to be useful in reducing the required detector efficiencies in loophole-free tests of Bell's inequalities [24]. They are also central to certain gedanken experiments demonstrating the nonlocality of quantum mechanics *without* the need for inequalities [25], and enlarge the accessible Hilbert space of quantum states. To our knowledge, this source is the first one to enable preparation of such states, at *any* rate of production [26].

Moreover, we can also create arbitrary (partially) mixed states of the type

$$\cos^2\theta|H_1,H_2\rangle\langle H_2,H_1|+\sin^2\theta|V_1,V_2\rangle\langle V_2,V_1|.$$

We need only impose on the pump beam a polarization-dependent time delay that is greater than the pump coherence time (for mixed states) or comparable to it (for partially mixed states) [27].

Finally, as indicated earlier, the down-conversion photon pairs are automatically entangled in energy and momentum as well. Hence, for our two-crystal scheme, the photons are actually simultaneously entangled in all degrees of freedom. We call such a state ''hyperentangled'' [28], and it has been shown that such states may benefit certain experiments in quantum information [15,29]. A more complete discussion of the production and characterization of these general quantum states (nonmaximally entangled, mixed and partially mixed, and hyperentangled) will be presented elsewhere [30].

In summary, using spontaneous down-conversion in a very simple two-crystal geometry, we have demonstrated a tunable source of polarization-entangled photon pairs. Because the entanglement exists over the entire cones of emitted light, this source is much brighter than previous ones, allowing a tremendous Bell inequality violation in only minutes. Such brightness is completely necessary for some applications (like quantum cryptography to a satellite), and very advantageous for others (like teleportation, which requires two pairs of entangled photons, and hence scales as the *square* of the source intensity). Due to its simplicity and robustness, this source should benefit many ongoing pursuits using correlated photons pairs, and may even permit the inclusion of tests of nonlocality in standard undergraduate physics laboratories.

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[18] A related method using *separated* crystals was proposed [L. Hardy, Phys. Lett. A **161**, 326 (1992)] and confirmed experimentally [T. J. Herzog *et al.*, Phys. Rev. Lett. **75**, 3034 (1995)]. Yet again, only along specific spatial modes are the desired entangled states produced, and the systems require interferometric stability. See also, Burlakov *et al.*, Phys. Rev. A **56**, 3214 (1997), who discuss adjacent crystals, but without polarization correlations.

[19] Based on a simple geometrical argument, the spatial overlap will be high if $\theta_{dc}L/D \ll 1$, with cone opening angle $\theta_{dc}$, crystal thickness $L$, and pump beam diameter $D$. The constraint on transverse walkoff in the crystals is similar if we replace $\theta_{dc}$ by the walkoff angle $\rho$ (typically $\approx 4°$).

[20] Some of the singles rate net polarization may be due to an unexpectedly high background fluorescence from the BBO crystals, nearly one-third of the true singles rate.

[21] Contrary to popular belief, such a zero-order wave plate, consisting of two perpendicularly oriented multiorder quartz plates does *not* have reduced tilt sensitivity [see P. D. Hale and G. W. Day, Appl. Opt. **27**, 5146 (1988)].

[22] Significantly, this is roughly the minimum rate for quantum cryptography in an earth-to-satellite configuration [W. T. Buttler *et al.*, Phys. Rev. Lett. **81**, 3283 (1998)].

[23] $\phi$ also depends on the *azimuthal* angle of production—photons produced in crystal 1 are extraordinarily polarized in crystal 2, so the refractive index depends on direction; however, for us the total azimuthal variation in $\phi$ was negligible, 0.017°. It could in any event be eliminated entirely by adding a compensation crystal identical in size and orientation to crystal 2.

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[27] We recently realized such an effect using an unbalanced Mach-Zehnder interferometer with polarizing beam splitters to produce a tunable (partially) mixed state of polarization of single photons [P. D. D. Schwindt, P. G. Kwiat, and B.-G. Englert (unpublished)].

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