Ultra-bright source of polarization-entangled photons

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Entangled states of multiparticle systems are arguably the quintessential feature of quantum mechanics. In addition to their central role in discussions of nonlocal quantum correlations, they form the basis of quantum information, and enable such phenomena as quantum cryptography, dense coding, teleportation, and quantum computation. 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 new technique has the added advantage that the degree of entanglement and the purity of the state may be readily tunable.

It is now well known that the photons produced via the down-conversion process share nonclassical correlations. 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. Yet conceptually, the simplest examples of entangled states of two photons are the polarization-entangled “Bell states”:

$$|H_1, V_2\rangle \pm |V_1, H_2\rangle ; |H_1, H_2\rangle \pm |V_1, V_2\rangle ,$$

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.

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), 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 beamsplitter, and nonclassical correlations observed for those post-selected events in which photons traveled to different output ports. 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. 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, teleportation, a post-selection-free test of Bell’s inequality for energy and time variables, a test of Bell’s inequality (for polarization variables) free of the usual rapid-switching loophole, and most recently, the generation of GHZ states of three photons. Coincidence count rates of up to ~ 2000s$^{-1}$ (for a 3-mm thick BBO crystal and a 150mW 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. Consider two adjacent, relatively thin, nonlinear crystals, operated with type-I phase-matching (Fig. 1a). The identically-cut crystals are oriented with their optic axes aligned in perpendicular 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. 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 1b shows the experimental setup used to produce and characterize the correlated photons. The ~2mm-diameter pump beam at 351.1nm 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 beamsplitter (PBS) to give a pure polarization state; a rotatable half waveplate (HWP) to adjust the angle of the linear polarization; and a second, tiltable waveplate for adjusting $\phi$. The nonlinear crystals themselves were BBO (8.0 x 8.0 x 0.59 mm), optic axis cut at $\theta_{pm} = 33.9^\circ$. For this cut the degenerate-frequency photons at 702nm are emitted into a cone of half-opening angle 3.0°. For most of the data presented here, interference filters (IF) centered at 702nm (FWHM ~ 5nm) 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 702nm). After passing through adjustable irises, the light was collected using 35mm-focal length doublet lenses, and directed onto single-photon detectors — silicon avalanche photodiodes (EG&G #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 2a 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 $-45^\circ$, and the other was varied by rotating the HWP in path 2. As expected, the coincidence rate displayed sinusoidal fringes with nearly perfect visibility ($V = 99.6 \pm 0.3\%$ with “accidental” coincidences subtracted; 98.8 ± 0.2% with them included), while the singles rate was much flatter ($V < 3.4\%$).
The visibility then stayed essentially constant at this effectively collects a larger portion of the same cone. The dimension of the aperture was varied using the iris size; a width 3.5 mm was added after each iris, and the vertical opening of apertures, located 1 m from the BBO crystals. We measured the visibility as a function of the size of the collection apertures, located 1 m from the BBO crystals.

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. 3a), 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. 3b), 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 \(^{-1}\), a \times 10 increase over the previous type-II source (which used a BBO crystal 2.5 times longer). 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.

We believe this to be the highest purity entangled state ever reported. The collection irises for this 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 2b 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 [2], the other two 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.

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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 \textit{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 \[24\].

Moreover, we can also create arbitrary (partially-) mixed states of the type \(\cos^2\theta|H_1,H_2\rangle|H_2,H_1\rangle + \sin^2\theta|V_1,V_2\rangle|V_2,V_1\rangle\). We need only impose on the pump beam a polarization-dependent time delay which 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 “hyper-entangled” \[23\], and it has been shown that such states may benefit certain experiments in quantum information \[15,23\].

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 non-locality in standard undergraduate physics labs.

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