

Generation of a Two-Photon Singlet Beam

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(Received 3 September 2003; published 30 January 2004)

Controlling the pump beam transverse profile in multimode Hong-Ou-Mandel interference, we generate a “localized” two-photon singlet state, in which both photons propagate in the same beam. This type of multiphoton singlet beam may be useful in quantum communication to avoid decoherence. We show that although the photons are part of the same beam, they are never in the same plane-wave mode, which is characterized by spatial antibunching behavior in the plane normal to the propagation direction.

DOI: 10.1103/PhysRevLett.92.043602

PACS numbers: 42.50.Dv, 03.67.Hk

Entangled multiphoton polarization states are an important tool in the investigation and future implementation of quantum information protocols [1]. In the case of the polarization of two photons, the maximally entangled Bell states, given by

$$|\psi^\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2), \quad (1a)$$

$$|\phi^\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2), \quad (1b)$$

form a complete basis in four-dimensional Hilbert space. Here H and V are horizontal and vertical polarization and kets 1 and 2 represent plane-wave modes. The “triplet” states, $|\psi^\pm\rangle$ and $|\phi^\pm\rangle$, are symmetric and the “singlet” state $|\psi^-\rangle$ is antisymmetric under exchange of the two photons. To maintain their overall bosonic symmetry, photons in the singlet polarization state also display spatial antisymmetry, and cannot occupy the same plane-wave mode [2,3]. This behavior can be seen in the usual two-photon interference experiment: when two indistinguishable plane-wave photons meet at a beam splitter (BS), they leave the BS in the same port if they are in a symmetric polarization state and in opposite ports if they are in the antisymmetric $|\psi^-\rangle$ polarization state.

The antisymmetry exhibited by the singlet state leads to some interesting properties. Recently, some attention has been paid to “supersinglet” states [4]—singlet states of two or more particles. It has been shown that these states can be used to solve several problems that have no classical solutions, as well as in violations of Bell-type inequalities and in proofs of Bell’s theorem without inequalities [5]. Perhaps an even bigger potential is in the storage and transmission of quantum information. In particular, singlet states $|\psi_N^-\rangle$ formed by N two-dimensional systems—qubits—can be used to construct decoherence-free subspaces which are robust to collective decoherence [4,6,7], in which the system-environment interaction is the same for all qubits. More specifically, these states are (up to a global phase factor) invariant to any type of N -lateral unitary operation,

$$U^{\otimes N}|\psi_N^-\rangle = |\psi_N^-\rangle, \quad (2)$$

where U is a single qubit unitary operation and $U^{\otimes N}$ is given by $U \otimes U \otimes \dots \otimes U$. Hence, it is possible to avoid collective decoherence of this form by encoding quantum information in the $|\psi_N^-\rangle$ states [7]. The assumption that the decoherence is collective is generally valid as long as the physical systems representing the qubits are closely spaced as compared to the coherence length of the environment [4]. In future implementations of optical quantum communication, for example, this may not be true if the photons are not propagating in the same spatiotemporal region.

It has been shown experimentally that the two-photon state $|\psi^-\rangle \equiv |\psi_2^-\rangle$ is robust to decoherence of the form (2) [8]. Photons in the polarization state $|\psi^-\rangle$ were generated using spontaneous parametric down conversion (SPDC). Each photon was subject to a decohering environment in the form of a birefringent crystal, which introduces a frequency-dependent random phase between horizontal and vertical polarization components. To simulate a collective environment, the crystals were kept aligned so that both photons always suffered the same decoherence. In this way, it was shown that the fidelity of the $|\psi^-\rangle$ state is unaffected by the decohering crystals.

We could assure that the decoherence suffered by the $|\psi^-\rangle$ state is more likely to be collective if we could localize the two photons to within a given spatiotemporal region, such as a well-collimated beam, for example. Here we show experimentally that, using multimode Hong-Ou-Mandel (HOM) interference [9], it is possible to create a localized $|\psi^-\rangle$ polarization state, in which the two photons propagate in a single beam. In this manner, up to a scale defined by the beam width, any unitary decoherence caused by the environment is felt equally by the two photons.

For years HOM interferometry [10] (and variations) has been one of the principal methods used to observe two-photon interference. As shown in Fig. 1, two photons s and i are created by noncollinear SPDC and directed

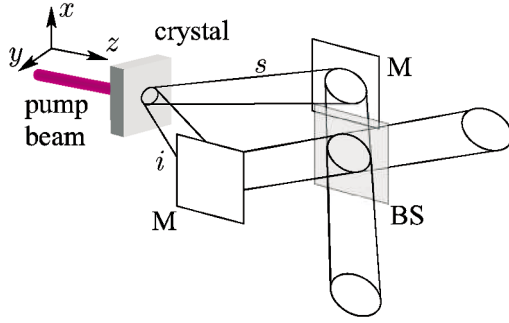


FIG. 1 (color online). HOM interferometer. Two photons created by noncollinear SPDC are directed by mirrors (M) onto a nonpolarizing 50-50 beam splitter (BS). Path lengths s and i can be made equal by the translation of one of the mirrors M.

onto a nonpolarizing 50-50 beam splitter (BS). If the optical path lengths of s and i are equal, then they interfere as described above.

Recently, Walborn *et al.* [9] showed that in a multimode treatment of HOM interference, it is necessary to take into account both the polarization and transverse spatial degrees of freedom. In multimode noncollinear SPDC, it is well known that, under certain experimental conditions, the transverse profile of the pump beam field $\mathcal{W}(x, y, z)$ is transferred to the two-photon detection amplitude as $\mathcal{W}((x_1 + x_2)/2, (y_1 + y_2)/2, Z)$ [11]. In the monochromatic approximation considered here (it is assumed that the down-converted photons have the same wavelength), the two-photon detection amplitude can be regarded as the two-photon wave function [12]. Subjecting the down-converted photons to a beam splitter, the observed HOM interference then depends upon the parity of the function $\mathcal{W}(x, y, z)$. Specifically, using a pump beam that is an odd function of the y coordinate, $\mathcal{W}(x, -y, z) = -\mathcal{W}(x, y, z)$, photons in the polarization state $|\psi^-\rangle$ leave the beam splitter in the same output port. In this case, following [9], the probability amplitude to detect *both* photons in the *same* output port is given by

$$\Psi(\mathbf{r}_1\mathbf{r}_2) \propto \mathcal{W}\left(\frac{x_1 + x_2}{2}, \frac{y_1 - y_2}{2}, Z\right) \times (\mathbf{H}_1\mathbf{V}_2 - \mathbf{V}_1\mathbf{H}_2), \quad (3)$$

where $\mathbf{r}_1 = (x_1, y_1, z_1)$ and $\mathbf{r}_2 = (x_2, y_2, z_2)$ are the coordinates of detectors D_1 and D_2 , respectively, with $z_1 = z_2 = Z$. We note that both detectors are placed in the same output port of the BS, i.e., D_1 and D_2 detect in the same spatial region. \mathbf{H} and \mathbf{V} are unit polarization vectors in the H and V directions. The $y_1 - y_2$ dependence of (3) is due to the reflection of one of the photons at the beam splitter [9]. Here it has been assumed that the 50-50 beam splitter is symmetric. In addition, we have ignored the entanglement between the polarization and wave vector due to the birefringence of the nonlinear crystal, which

can be minimized using a compensating crystal in addition to narrow band interference filters and small detection apertures in the experimental setup.

In contrast to the experiment reported in Ref. [9], here we focus our attention on the polarization and spatial properties of the two-photon beam that comes out of one of the beam splitter ports. Although photons in the $|\psi^-\rangle$ always leave through the same port, which port they leave through is random. We also note that both the spatial and polarization components of Eq. (3) are antisymmetric.

Figure 2 shows the experimental setup. At the output of the argon laser ($\lambda_p = 351$ nm), we inserted a thin (~ 150 μm) glass laminate halfway into the Gaussian profile pump beam and adjusted the angle in order to achieve a π phase difference between the two halves of the beam. This produces a transverse profile that is an odd function of the horizontal y coordinate. A photograph of the beam intensity profile in the detection region (~ 3 m from the glass laminate) is shown in the inset of Fig. 2. Because of the spatial filtering due to propagation of the beam, this profile presents just one central minimum. In the far-field region, this beam is similar to the first-order Hermite-Gaussian beam HG_{01} .

This beam is used to pump a 2-mm thick nonlinear crystal (BBO) cut for degenerate type II phase matching. The crystal is adjusted to generate polarization-entangled

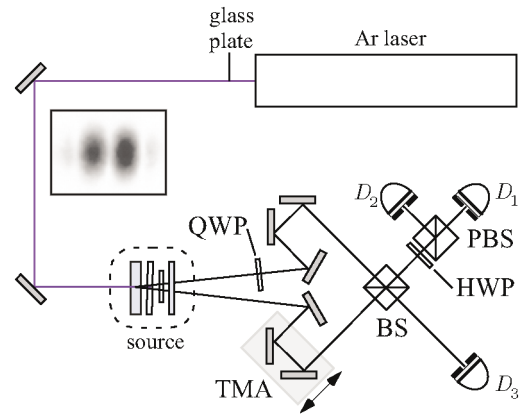


FIG. 2 (color online). Experimental setup. A glass plate is placed halfway into the beam and adjusted to create π phase difference between the two halves, creating a profile that is an odd function of the y coordinate. The inset shows a photograph of the pump profile in the detection region. A 2-mm-long nonlinear crystal (BBO) is pumped by an argon laser generating twin photons in crossed cones. The “source” in figure is composed of the nonlinear crystal, 1 mm compensating crystal, UV filter and half wave plate as in [13]. QWP is a quarter wave plate used to change the state from $|\psi^+\rangle$ to $|\psi^-\rangle$. BS is a 50/50 beam splitter. The trombone mirror assembly (TMA), mounted on a computer-controlled motorized stage, is used to adjust the path length difference. The polarizing beam splitter (PBS) and half-wave plate (HWP) are used to detect photons in the same output of the BS. D_1 , D_2 , and D_3 are photodetectors.

photons ($\lambda \sim 702$ nm) using the crossed-cone source as reported in [13]. The output state of this source is controlled by adjusting the angle of the compensating crystal to be the $|\psi^+\rangle$ polarization state. With a quarter-wave plate (QWP) in one of the paths, the relative phase can be manipulated in order to change from the polarization state $|\psi^+\rangle$ to $|\psi^-\rangle$ [13]. A trombone mirror assembly (TMA) is mounted on a motorized translational stage to adjust the path-length difference of the interferometer. The photons are directed onto a beam splitter (BS). D_1 , D_2 , and D_3 are EG&G SPCM 200 photodetectors equipped with interference filters (1 nm FWHM centered at 702 nm) and 3 mm circular detection apertures. A computer was used to register coincidence and single counts.

With the BS removed, we used polarization analyzers (not shown in Fig. 2) consisting of a half-wave plate (HWP) and polarizing beam splitter (PBS) to test the quality of the $|\psi^-\rangle$ polarization state generated by the crystal. We did this by observing the usual polarization interference [13]: one polarizer was kept fixed at 0° or 45° while the other was rotated. We observed interference curves with visibilities greater than 0.97 ± 0.01 in both cases, implying a high degree of polarization entanglement, i.e., a high quality $|\psi^-\rangle$ state.

Putting the BS in place and removing the polarization analyzers, we measured the usual HOM interference curve in coincidence detections at the output ports (detectors D_1 and D_3 in Fig. 2) by scanning the TMA. With the glass plate removed we observed interference curves with visibilities $\mathcal{V}_{\text{HOM}} = 0.92 \pm 0.01$, indicating good spatial overlap at the BS. With the glass plate placed in the laser beam (odd pump profile) and using photons in the $|\psi^-\rangle$ polarization state, the visibility was $\mathcal{V}_{\text{HOM}} = 0.82 \pm 0.01$. The decrease in visibility was most likely due to two reasons. First, the alignment of the HOM interferometer is noticeably more sensitive when an odd pump beam is used [9]. Second, there is a slight loss in the intensity of the portion of the pump beam that passes through the glass laminate, which creates a small distinguishability in the fourth-order interference.

Next, we placed a polarization analyzer (a HWP and PBS) in one output of the BS and detected coincidences at the two output ports of the PBS, so that detectors D_1 and D_2 (Fig. 2) always detect orthogonal polarizations. The HWP was set so the analyzer detected in the H/V or $+/-$ bases, where $\pm = 1/\sqrt{2}(H \pm V)$. We scanned the path-length difference and performed HOM interference measurements, however, this time coincidences were registered at detectors D_1 and D_2 . The results are shown in Fig. 3. Error bars in all figures correspond to photon counting statistics [12]. Using the $|\psi^-\rangle$ state, we observe constructive interference at detectors D_1 and D_2 in both the H/V [Fig. 3(a)] and $+/-$ bases [Fig. 3(b)]. Observing constructive interference in both detection bases is characteristic of the $|\psi^-\rangle$ state, since it is the only antisym-

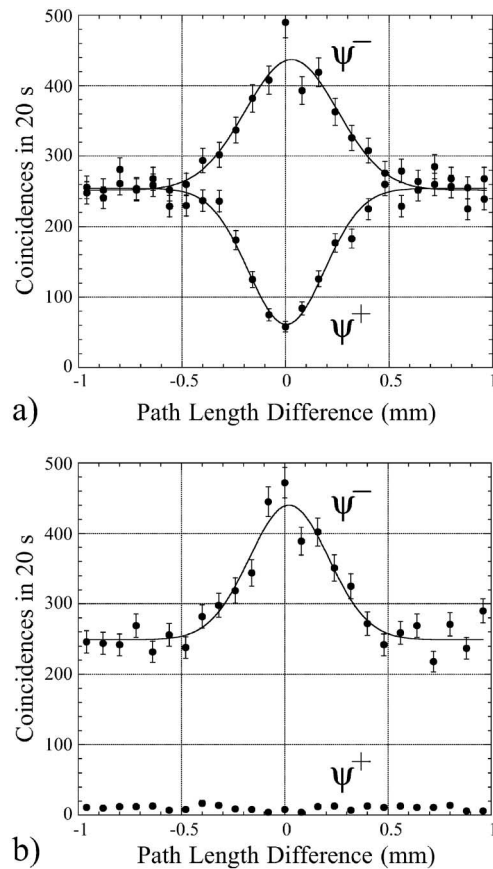


FIG. 3. Detections in the same output port of the BS. (a) Detections in the H/V basis. The visibility of the state $|\psi^-\rangle$ is $\mathcal{V} = 0.73 \pm 0.05$. The visibility of the state $|\psi^+\rangle$ is $\mathcal{V} = 0.76 \pm 0.02$. (b) Detections in the $+/-$ basis. The visibility of the state $|\psi^-\rangle$ is $\mathcal{V} = 0.76 \pm 0.05$. There are no coincidences of the state $|\psi^+\rangle$ in this basis.

metric two-photon polarization state and is invariant to bilateral rotation [4]. In this respect, one can regard the HWP as a special case of a decoherence environment. Comparatively, using the polarization state $|\psi^+\rangle$, and detecting in the H/V basis, we observe an interference “dip” [Fig. 3(a)]. However, in the $+/-$ basis [Fig. 3(b)], we observe no coincidences, since in this basis the $|\psi^+\rangle$ state is proportional to $(|+\rangle_1|+\rangle_2 - |-\rangle_1|-\rangle_2)$.

It is interesting to examine this experiment from the point of view of symmetry. In order for the wave packets of the two twin photons to occupy the same spatiotemporal region, the total biphoton wave function must be symmetric. In this symmetrization, all degrees of freedom must be considered. In the case of the $|\psi^-\rangle$ polarization state with an odd pump beam profile, overall bosonic symmetry requires that photons pairs are found in the same output port of the BS. However, because of the antisymmetry of the transverse spatial component, which is provided by the odd pump beam together with the reflection of one photon at the beam splitter, the photons are spatially separated in the y direction and

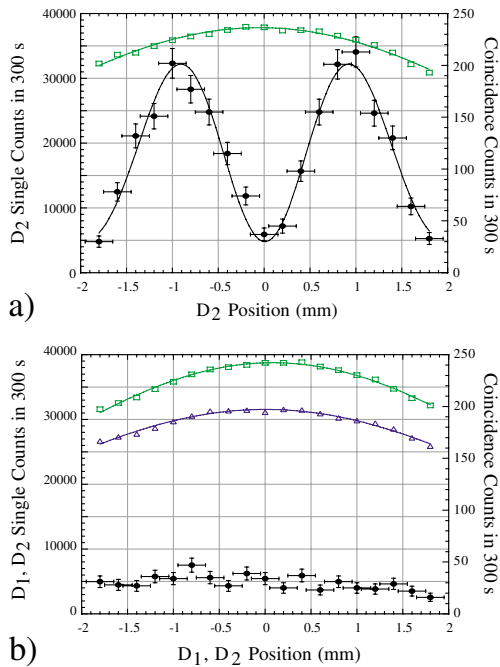


FIG. 4 (color online). \triangle : D_1 single counts; \square D_2 single counts; \bullet : Coincidences. Horizontal error bars correspond to the width of detection slits. (a) Coincidence counts with D_1 fixed at “0” and D_2 scanned horizontally. (b) D_1 and D_2 scanned together, always detecting in the same position.

thus do not occupy the same plane-wave mode. Interestingly enough, this characteristic guarantees that the singlet beam exhibits spatial antibunching, a quantum effect with no classical analog [14,15].

To investigate this aspect of the singlet beam, both detectors were equipped with $0.3 \text{ mm} \times 3 \text{ mm}$ vertical detection slits and aligned to the same spatial region as in [14]. The TMA was set at the interference maximum (“0” in Fig. 3). Figure 4(a) shows the coincidence counts when detector D_1 is fixed at “0” and D_2 is scanned in the horizontal y direction. There is a coincidence minimum at the origin where D_1 and D_2 are detecting at the same position. The solid line is a curve fit as in [14]. Figure 4(b) shows results when the two detectors are scanned together in the same sense—always detecting in the same position—in which they always detect a coincidence minimum. The residual coincidence detections at the minima are due to the width of the detection slits. In Ref. [14], the two photons were in a singlet polarization state after the birefringent double slit, but they did not constitute a beam. The measurements shown above (Fig. 4), however, are not of a fourth-order interference pattern that exhibits spatial antibunching in a detection region, but rather measurements of the transverse profile of a two-photon spatially antibunched singlet beam. It is worth noting that while the singlet beam is necessarily spatially antibunched, spatial antibunching can also be achieved

with symmetric polarization states and an even pump beam [16].

Although the photons never occupy the same plane-wave mode, it is important to stress that the individual photons are indistinguishable in all degrees of freedom (spatially, temporally, polarization, frequency, etc.). This guarantees that the decoherence felt by this type of localized state is collective up to the width of the two-photon beam.

Here we have taken a first step in creating a localized multiphoton state that is more resistant to decoherence. Using multimode Hong-Ou-Mandel interference, we have generated a two-photon singlet beam, which forms a unidimensional decoherence-free subspace. We expect to use these same techniques to create singlet beams of more than two photons, which could be used to encode and transmit quantum information in a higher-dimensional decoherence-free channel [17]. We have also shown that the singlet beam is inherently nonclassical, exhibiting spatial antibunching in the transverse plane.

The authors acknowledge financial support from the Brazilian agencies CNPq and CAPES.

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