

Observation of Two-Photon “Ghost” Interference and Diffraction

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Observations of unusual diffraction and interference by two-photon correlation measurements are reported. The signal and idler beams produced by spontaneous parametric down-conversion are sent in different directions, and detected by two distant pointlike photon counting detectors. A double slit or a single slit is inserted into the signal beam. Interference-diffraction patterns are observed in coincidences by scanning the detector in the idler beam.

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Spontaneous parametric down-conversion (SPDC) [1] is the most effective source of two-photon light, consisting of pairs of correlated photons. The essentially quantum nature of the corresponding two-photon state [2,3] has been confirmed in a number of two-photon correlation experiments [4]. This quantum feature allows us to demonstrate an unusual two-photon effect [5], which looks very strange from the classical point of view. The SPDC light beam, which consists of two orthogonal polarization components (usually called signal and idler), is split by a polarization beam splitter into two beams, and detected by two distant pointlike photon counting detectors for coincidences (see Fig. 1). A Young’s double-slit or single-slit aperture is inserted into the *signal* beam. Surprisingly, an interference or diffraction pattern is observed in the coincidence counts by scanning the detector in the *idler* beam. As will be shown, this effect is even more striking when one considers that there is no first order interference pattern behind the slits, as is discussed in this paper.

The detailed experimental setup is illustrated in Fig. 1. A cw argon laser ($\lambda = 351.1$ nm) is used to pump a 3 mm long beta barium borate (BBO) crystal to generate pairs or orthogonally polarized signal (*e*-ray of BBO) and idler (*o*-ray of BBO) photons with wavelengths $\lambda_o \cong \lambda_e \cong 2\lambda_p$. The pump beam has width 2 mm FWHM (full width at half maximum) and divergence of about 0.3 mrad. The pump beam is separated from the collinear SPDC beams by a fused quartz dispersion prism. The signal and idler beams are then separated from each other by a polarization beam-splitting Thompson prism (BS). The signal beam passes through a single- or double-slit aperture and then travels about 1 m to a photon counting detector D_1 (0.5 mm in diameter), which is fixed on the axis of the signal beam. The idler beam travels a distance of about 1.2 m from BS to the input end of a 0.5 mm diameter multimode optical fiber whose output end is coupled to another photon counting detector D_2 . The horizontal transverse coordinate x_2 of the fiber input tip is scanned by an encoder driver. In the following x_2 is referred to a “the position of the detector D_2 .” Two 702.2 nm spectral filters f_1 and f_2 with 10 nm FWHM

bandwidth are inserted in front of each detector. The output pulses of the detectors are sent to a coincidence circuit with a 1.8 nsec coincidence time window.

Figure 2 shows a typical observed double-slit interference-diffraction pattern. The period of the interference oscillations is measured to be $x_d = 2.7 \pm 0.2$ mm and the distance between the center and the minimum of the envelope is estimated to be about $x_a = 8$ mm. The theoretical values are expected to be $x_d = 2.67$ mm and $x_a = 8.4$ mm, respectively.

By curve fitting we conclude that the observed structure has a typical shape of Young’s interference-diffraction pattern

$$R_c(x_2) \propto \text{sinc}^2(x_2\pi a/\lambda z_2) \cos^2(x_2\pi d/\lambda z_2). \quad (1)$$

In Eq. (1) a and d are the slit width and slit distance of the double slit, respectively; $\lambda = 2\lambda_p$ is the center wavelength of the signal and idler. The remarkable feature here is that z_2 is the distance from the slits plane, which is in the signal beam, back through BS to the BBO

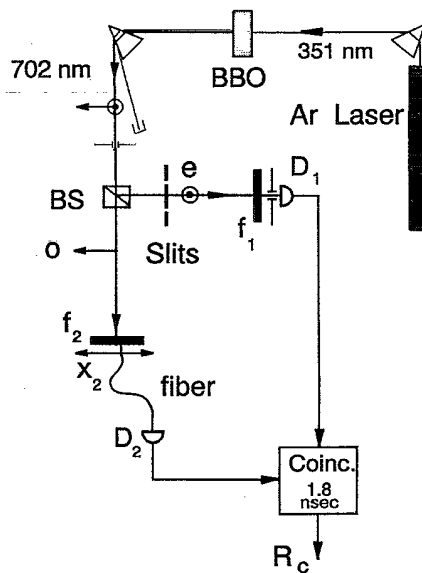


FIG. 1. Experimental setup.

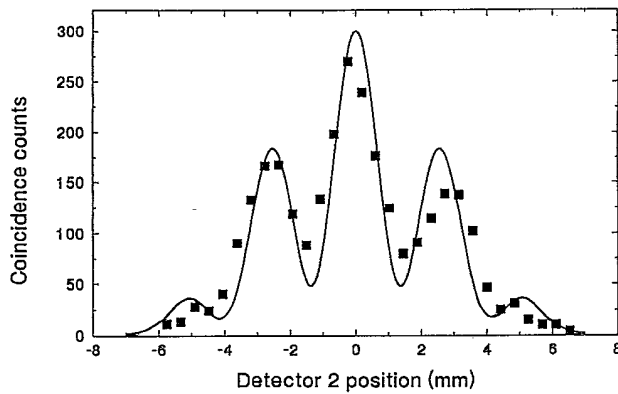


FIG. 2. Two-photon double-slit “ghost” interference-diffraction pattern: the dependence of the coincidences (per 400 sec) on the position of detector D_2 , which counts the idler photons, while the signal photons pass through a double-slit with $a = 0.15$ mm and $d = 0.47$ mm. The theoretical curve is calculated from Eq. (1), corrected for the finite size of the detectors and the pump profile.

crystal and then along the idler beam to the scanning fiber tip of detector D_2 (see Fig. 1).

Even though the interference-diffraction pattern is observed in coincidences, the single detector counting rates are both observed to be constant when scanning detector D_1 or D_2 . Of course it seems reasonable not to have any first order interference diffraction in the single counting rate of D_2 , which is located in the “empty” idler beam. Of interest, however, is the absence of the first order interference-diffraction structure in the single counting rate of D_1 , which is behind the double slit. This is mainly due to the divergence of the SPDC beam ($\gg \lambda/d$). In other words, the “blurring out” of the first order interference fringes is due to the considerably large angular propagation uncertainty of a single SPDC photon.

Furthermore, if D_1 is moved to an unsymmetrical point, which results in unequal distances to the two slits, the interference-diffraction pattern is observed to be simply

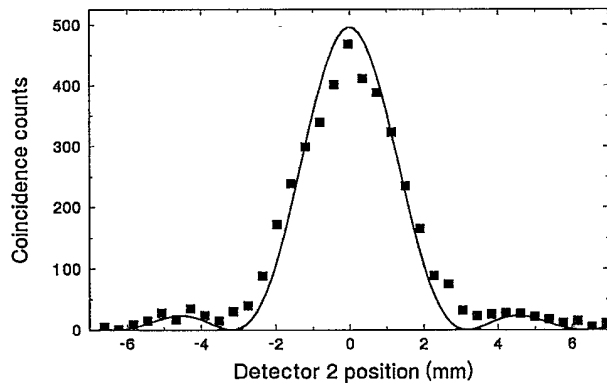


FIG. 3. Two-photon diffraction pattern: coincidence counts (per 400 sec) vs the idler photon detector position. A single slit of width $a = 0.4$ mm is in the signal beam. The theoretical curve is calculated from Eq. (9).

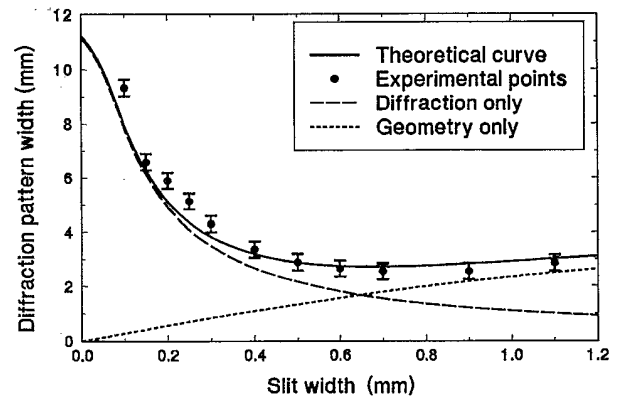


FIG. 4. The diffraction pattern width vs the slit width. The calculated curve (solid line) takes into account the corrections for finite size of the detectors, the Gaussian pump profile and non-far-field corrections, which become important for wider slits. No fitting parameters were used. The dashed (dotted) line shows the expected purely diffraction (geometrical) width, limited by the pump profile.

shifted from the current symmetrical position to one side of x_2 . We still observe the same interference pattern in the coincidences (same period, shape, and counting rate), except for a phase shift.

Figure 3 shows a typical single-slit diffraction pattern, and in Fig. 4 the dependence of the measured diffraction pattern width (FWHM) on the slit width a is shown.

To explain the observed effects we consider a simple quantum model. In type II SPDC a pair of orthogonally polarized photons is generated by a pump beam. The two-photon state of SPDC is an entangled states [2,3]. The photons that belong to one pair satisfy the phase matching conditions: $\omega_s + \omega_i = \omega_p$, $\mathbf{k}_s + \mathbf{k}_i = \mathbf{k}_p$ [1]. The transverse components of the wave vectors matching condition

$$k_s \sin \alpha'_s = k_i \sin \alpha'_i \quad (2)$$

is the key for understanding these effects (here α'_j is the internal scattering angle relative to the pump wave vector \mathbf{k}_p direction; $j = s$ or i). The output scattering angles α_j are determined by the Snell's law. Combining Eq. (2) and the Snell's relations, we have

$$\omega_s \sin \alpha_s = \omega_i \sin \alpha_i \quad (3)$$

or $\alpha_s = \alpha_i$ when $\omega_s = \omega_i$. All angles α_j are measured relative to the pump direction. Thus in the degenerate case the signal and idler photons, belonging to one pair, are emitted at equal, yet opposite, angles. In other words, for each single photon of the pair the propagation direction has a considerably large uncertainty. However, the measurement of the exit angle of either photon determines the exit angle of its conjugate twin brother with unit probability. This important peculiarity selects the only possible paths in Fig. 5(a), when one photon passes through the double-slit aperture while the

other gets to D_2 . We can simply treat the crystal as a “geometrical reflection” mirror, see Fig. 5. The full range of possible scattering angles $\alpha_s = \alpha_i$ is about ± 30 mrad as determined by the spectral filters bandwidth, the BBO dispersion, and the phase matching conditions.

The coincidence counting rate R_c is determined by the probability P_{12} of detecting a pair of photons by detectors D_1 and D_2 simultaneously. For SPDC, P_{12} is proportional to the square of the second order correlation function $\langle E_2^{(+)} E_1^{(+)} \rangle$ of the fields at points D_1 and D_2 (it thus plays the role of the two-photon’s effective wave function):

$$P_{12} = \langle E_1^{(-)} E_2^{(-)} E_2^{(+)} E_1^{(+)} \rangle = |\langle E_2^{(+)} E_1^{(+)} \rangle|^2. \quad (4)$$

In Eq. (4) $\langle \dots \rangle \equiv \langle \Psi | \dots | \Psi \rangle$, and $|\Psi\rangle$ is the four-mode state vector of the SPDC field:

$$|\Psi\rangle = |\text{vac}\rangle + \epsilon [a_s^\dagger a_i^\dagger \exp(i\varphi_A) + b_s^\dagger b_i^\dagger \exp(i\varphi_B)] |\text{vac}\rangle, \quad (5)$$

where $\epsilon \ll 1$ is proportional to the pump field (classical) and the nonlinearity of the crystal, φ_A and φ_B are the phases of the pump field at A and B , a_j^\dagger (b_j^\dagger) are the photon creation operators for the upper (lower) mode in Fig. 5(b) ($j = s, i$). In terms of the Copenhagen interpretation one can say that the interference is due to the uncertainty in the birth place (A or B in Fig. 5) of a photon pair.

In Eq. (4) the fields at the detectors are given by

$$\begin{aligned} E_1^{(+)} &= a_s \exp(ikr_{A1}) + b_s \exp(ikr_{B1}), \\ E_2^{(+)} &= a_i \exp(ikr_{A2}) + b_i \exp(ikr_{B2}), \end{aligned} \quad (6)$$

where r_{Aj} (r_{Bj}) are the optical path lengths from region A (B) along the upper (lower) path to the j th detector. Substituting Eqs. (5) and (6) into Eq. (4),

$$\begin{aligned} R_c \propto P_{12} &= \epsilon^2 |\exp(ikr_A + i\varphi_A) + \exp(ikr_B + i\varphi_B)|^2 \\ &\propto 1 + \cos[k(r_A - r_B)], \end{aligned} \quad (7)$$

where we assume $\varphi_A = \varphi_B$ in the second line of Eq. (7) (although this is not a necessary condition to see the interference pattern, the transverse coher-

ence of the pump beam at A and B is crucial). In Eq. (7) we defined the overall optical lengths between the detectors D_1 and D_2 along the upper and lower paths [see Fig. 5(b)]: $r_A \equiv r_{A1} + r_{A2} = r_{C1} + r_{C2}$, $r_B \equiv r_{B1} + r_{B2} = r_{D1} + r_{D2}$, where r_{Ci} and r_{Di} are the path lengths from the slits C and D to the i th detector.

If the optical paths from the fixed detector D_1 to the two slits are equal, i.e., $r_{C1} = r_{D1}$, and if $z_2 \gg d^2/\lambda$ (which is true for this experiment), then $r_A - r_B = r_{C2} - r_{D2} \equiv x_2 d/z_2$, and Eq. (7) can be written as

$$R_c(x_2) \propto \cos^2(x_2 \pi d / \lambda z_2). \quad (8)$$

Equation (8) has the form of standard Young’s double-slit interference pattern. Here again $z_2 = 1.8$ m is the unusual distance described above.

There are two conclusions that can be drawn from Eq. (8): (i) A two-photon interference pattern can be observed in coincidences by scanning D_2 in the transverse direction of one beam, even though the Young’s double-slit aperture is in the other beam. (ii) The interference pattern is the same as one would observe on a screen in the plane of D_2 , if D_1 is replaced by a pointlike light source and the SPDC crystal by a reflecting mirror.

To calculate the ghost diffraction effect of a single slit such as is shown in Fig. 3, we need an integral of the effective two-photon wave function over the slit width

$$\begin{aligned} R_c(x_2) &\propto \left| \int_{-a/2}^{a/2} dx_0 \exp[-ikr(x_0, x_2)] \right|^2 \\ &\equiv \text{sinc}^2(x_2 \pi a / \lambda z_2), \end{aligned} \quad (9)$$

where $r(x_0, x_2)$ is the distance between points x_0 and x_2 , x_0 belongs to the slit’s plane, and the inequality $z_2 \gg a^2/\lambda$ is assumed.

Repeating the above calculations, the combined interference-diffraction coincidence counting rate for the double-slit case is given by Eq. (1), which was already obtained by a fitting of experimental data.

In the above calculations we assume that the pump beam is a plane wave and the crystal’s transverse dimension is infinite. If instead a Gaussian pump beam profile is considered, Eq. (1) must be multiplied by a Gaussian function $G(x_2, \sigma z_2/z_0)$:

$$R_c(x_2) \propto G(x_2, \sigma z_2/z_0) \text{sinc}^2(x_2 \pi a / \lambda z_2) \cos^2(x_2 \pi d / \lambda z_2), \quad (9)$$

where σ is the Gaussian width of the pump beam and z_0 is the distance between the slit plane and the crystal ($z_0 = 32.5$ cm). Furthermore, if the finite size of the detectors and the divergence of the pump are also taken into account by a convolution, the interference visibility will be reduced. These factors have been taken into account in the theoretical plots in Figs. 2 and 4.

The above simple model is consistent with the experimental results. The measured interference oscillation periods and diffraction pattern widths agree with the theoretical predictions within reasonable experimental errors.

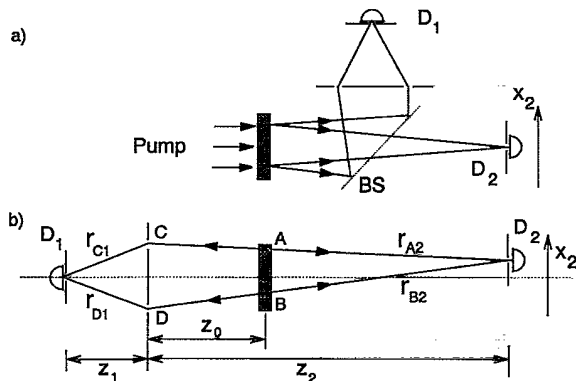


FIG. 5. Simplified experimental scheme (a) and its “unfolded” version (b).

The reported experimental data are all direct measurements without any “noise reduction” such as accidental coincidences subtraction, normalization to the pump or signal power, etc.

To summarize, this experiment is very close to the original *gedankenexperiment* of Einstein, Podolsky, and Rosen [3], where the measurement of a spatial observable of one particle determines the spatial observable for the other particle with unit probability. In our experiment each photon of a pair generated in SPDC propagate with a considerably large angular uncertainty. However, if one of them is detected at a certain direction, its conjugate twin brother must have been propagating in a defined certain direction. Thus they may be said to be entangled in *space*.

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Note added.—After the submission of this paper we learned that a two-photon diffraction experiment was also performed by Zeilinger’s group by using an optical grating. We would like to thank A. Zeilinger for bringing this to our attention [6].

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