Observation of correlated-photon statistics using a single detector

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We report experimental observations of correlated-photon statistics in the single-photon detection rate. The usual quantum interference in a two-photon polarization interferometer always accompanies a dip in the single-detector counting rate, regardless of whether a dip or a peak is seen in the coincidence rate. This effect is explained by taking into account all possible photon number states that reach the detector, rather than considering just the state postselected by the coincidence measurement. We also report an interferometeric scheme in which the interference peak or dip in the coincidence corresponds directly to a peak or a dip in the single-photon detection rate.

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In interference experiments involving two-photon fields of spontaneous parametric down-conversion (SPDC), quantum interference effects are typically observed in the rate of coincidence counts between two detectors, while the single-detector count rate is expected to be featurelessly constant [1]. (A good example is the two-photon anticorrelation dip-peak experiment [2–5].) Indeed, this would be the case if the single-photon detectors available today were truly 100% efficient and were able to resolve multiphoton excitations. However, all commercially available solid-state single-photon detectors today rely on the avalanche proccess of Si or InGaAs/InP photodiodes. Therefore, even with 100% efficiency, these detectors cannot resolve the photon number. This effect usually does not reveal any information about the incident state, since it simply reduces the overall detection efficiency.

In certain cases, however, the single-detector count rate does provide information about the incident state. This was first demonstrated in Ref. [6], where a quantum interference effect in a two-photon interferometer was employed to change the photon statistics at a single detector. It was found that the coincidence dip associated with the photon bunching effect at a beam splitter was accompanied by a dip in the single-detector counting rate as well. At the center of the coincidence dip, the photons always leave the interferometer (or the beam splitter) together. Thus, a detector monitoring one of the output ports of the interferometer "sees" either $|0\rangle$ or $|2\rangle$, but never $|1\rangle$. Compared to the photon statistics outside the coincidence dip, where the two photons are randomly distributed to the detectors, a single detector sees fewer photon events in the coincidence dip, even though the mean photon number does not change. Because the detector is unable to distinguish between $|1\rangle$ and $|2\rangle$, a single-detector dip is observed.

In this paper, we first confirm the dip effect in the single-detector count rate using a different experimental setup. We also measure the single-detector count rate with the interferometer designed for a coincidence peak, rather than a dip. Somewhat surprisingly, the coincidence peak is not reflected as a peak in the single-detector count rate. Instead, the singles rate reveals a dip, as if the interferometer was aligned for a coincidence dip. This result can be explained by taking into account all possible photon number states that reach the detector, rather than just the state postselected by the coincidence measurement. Finally, we present an experiment in which the coincidence peak or dip directly corresponds to a dip or peak in the singles rate.

We consider the experimental setup shown in Fig. 1. SPDC photon pairs are generated in a 2-mm-thick type-I BBO crystal pumped with a 351.1-nm argon-ion laser. The full width at half maximum (FWHM) of the spectral filters F1 and F2 were 3 nm and the coincidence window for all measurements was about 3 nsec. The noncollinear 702.2-nm signal and the idler photons are brought together on a beam splitter and one arm of the interferometer can be adjusted by a computer-controlled dc motor. The noncollinear arrangement avoids the problematic second-order (of the field) interference effect reported in Ref. [6].

With HWP1, A1, and A2 removed from the apparatus, the usual coincidence dip is obtained by scanning the delay τ [3]. The experimental data for this measurement is shown in

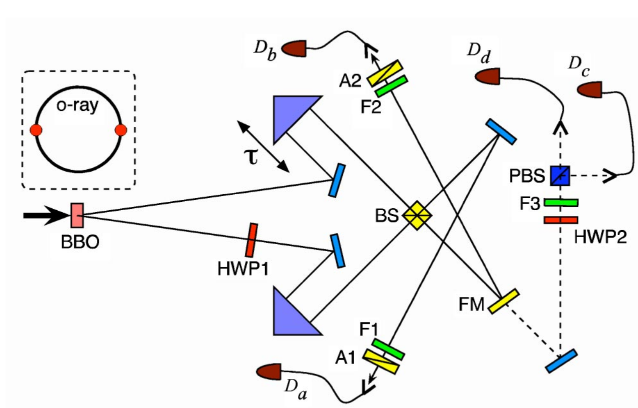

FIG. 1. Outline of the experimental setup. HWP1 and HWP2 are half-wave plates oriented at 45° and 22.5°, respectively. PBS is the polarizing beam splitter. HWP2 and PBS act together as a 50-50 beam splitter. FM is a flipper mirror, A1 and A2 are polarizers, and F1, F2, and F3 are spectral filters.

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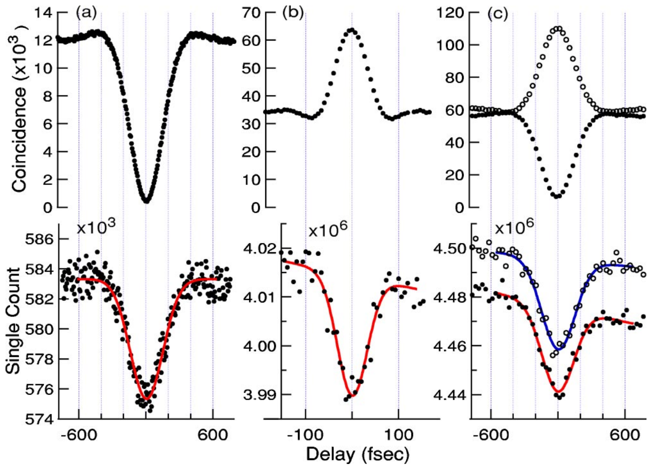

FIG. 2. Experimental data. (a) D_a-D_b coincidence dip: 40 sec. for each point. (b) D_c-D_d coincidence: 10 sec. for each point. (c) Polarization correlation measurement with D_a and D_b. Coincidence peak (dip) is measured for polarizer angles A1/A2 $=45°/-45°(=45°/45°)$. 40 sec. for each point.

Fig. 2(a). Note that both the coincidence rate and the single-detector rate show dips as the delay is scanned. Also, note that the two dips have the same widths. The dip in the single-count rate can be understood more clearly as follows. If η is the single-photon detection efficiency, then the probability of a detection event in the presence of two photons is given by $\eta+(1-\eta)\eta=2\eta-\eta^2$ [6]. The overall single-detector counting rate can then be written as

$$R\propto P_1\eta+P_2(2\eta-\eta^2), \tag{1}$$

where P_1 and P_2 are the probabilities that one and two photons, respectively, are incident on the detector.

The photon statistics at the output ports of the beam splitter are determined entirely by the delay τ in this case. If $\tau>\tau_c$, where τ_c is the coherence time of the single-photon wave packet, incident photons simply scatter independently, resulting in four possible events at the output: (i) both photons reflected, (ii) both photons transmitted, (iii) both photons end up at D_a, and (iv) both photons end up at D_b. Since each of these events is equally likely, the probabilities that a particular output port, D_a or D_b, contains zero, one, and two photons are $P_{b0}=1/4$, $P_{b1}=1/2$, and $P_{b2}=1/4$. If, on the other hand, $\tau=0$, quantum interference causes amplitudes for (i) and (ii) to sum to zero [2–5]. In this case, $P_{b0}=1/2$, $P_{b1}=0$, and $P_{b2}=1/2$. With these probabilities, which are summarized in Table I, Eq. (1) yields the single-detector counting rates

$$R(\tau>\tau_c)\propto\eta-\tfrac{1}{4}\eta^2,\quad R(\tau=0)\propto\eta-\tfrac{1}{2}\eta^2. \tag{2}$$

The above result clearly shows that a dip in the singles rate is expected to accompany a dip in the coincidence rate between detectors D_a and D_b.

The coincidence dip in this case can be regarded as the signature of the state $(1/\sqrt{2})(|2,0\rangle+|0,2\rangle)$ exiting the beam splitter. When $\tau=0$, each detector receives either zero photons or two photons, but never one photon. Consider now the case in which a peak is observed in the coincidence rate. This is accomplished in our setup by removing the flipper mirror, thus directing one output of the beam splitter to detectors D_c and D_d. The detectors are preceded by a half-wave plate and a polarization beam splitter, which act together as a 50-50 beam splitter. The FWHM of the spectral filter F3 was 20 nm. When $\tau=0$, the path exiting the beam splitter (BS) contains either zero or two photons, since this delay corresponds to the center of the coincidence dip for detectors D_a and D_b. With a higher probability of finding two photons in the exit path (1/2 for $\tau=0$ vs 1/4 for $\tau>\tau_c$), a coincidence peak is observed between D_c and D_d, as shown in Fig. 2(b) [7].

It is tempting to regard such a peak as signaling the presence of state $|1,1\rangle$. If this were true, then a peak in the single-detector counting rate would also be expected, since every photon pair emission would lead to exactly one photon at each detector. However, this is not the case. Instead of a peak in the single-photon counting rate, a dip is observed just as in the case of the coincidence dip between D_a and D_b. This rather unexpected result can be explained by considering conditional probabilities at the second beam splitter. The probabilities that zero photons, one photon, and two photons are incident on, for example, detector D_c are

$$P_0=P_{b0}P_{00}+P_{b1}P_{10}+P_{b2}P_{20},$$

$$P_1=P_{b0}P_{01}+P_{b1}P_{11}+P_{b2}P_{21}=P_{b1}P_{11}+P_{b2}P_{21},$$

$$P_2=P_{b0}P_{02}+P_{b1}P_{12}+P_{b2}P_{22}=P_{b2}P_{22}, \tag{3}$$

where, as defined above, P_{b0}, P_{b1}, and P_{b2} are the probabilities that zero photons, one photon, and two photons leave the first beam splitter, respectively. The conditional probabilities P_{ij} are defined as the probabilities that j pho-

TABLE I. Summary of probabilities that a particular output port contains zero photons, one photon, and two photons for the three distinct experimental conditions considered in this paper. BG refers to the background random probabilities which occurs when $\tau>\tau_c$. At BS stands for at beam splitter.

Two photons have the same polarization					Two photons are orthogonally polarized					Deterministic case (Fig. 3)		
At beam splitter		Conditional probability at D_c (D_d)			At BS	Probability at D_a (D_b) with $\pm45°$ polarizer				BG	Dip	Peak
$\tau>\tau_c$	$\tau=0$	Probability independent of τ			Probability independent of τ			$\tau>\tau_c$	$\tau=0$	$\tau>\tau_c$	$\tau=0$	$\tau=0$
$P_{b0}=\frac{1}{4}$	$P_{b0}=\frac{1}{2}$	$P_{00}=1$	$P_{10}=\frac{1}{2}$	$P_{20}=\frac{1}{4}$	$P_{b0}=\frac{1}{4}$	$P_{00}=1$	$P_{10}=\frac{1}{2}$	$P_{20}=\frac{1}{4}$	$P_{20}=\frac{1}{2}$	$P_0=\frac{1}{4}$	$P_0=\frac{1}{2}$	$P_0=0$
$P_{b1}=\frac{1}{2}$	$P_{b1}=0$	$P_{01}=0$	$P_{11}=\frac{1}{2}$	$P_{21}=\frac{1}{2}$	$P_{b1}=\frac{1}{2}$	$P_{01}=0$	$P_{11}=\frac{1}{2}$	$P_{21}=\frac{1}{2}$	$P_{21}=0$	$P_1=\frac{1}{2}$	$P_1=0$	$P_1=1$
$P_{b2}=\frac{1}{4}$	$P_{b2}=\frac{1}{2}$	$P_{02}=0$	$P_{12}=0$	$P_{22}=\frac{1}{4}$	$P_{b2}=\frac{1}{4}$	$P_{02}=0$	$P_{12}=0$	$P_{22}=\frac{1}{4}$	$P_{22}=\frac{1}{2}$	$P_2=\frac{1}{4}$	$P_2=\frac{1}{2}$	$P_2=0$

tons will exit port c of the second beam splitter, given i incident photons. These conditional probablities are independent of the delay τ and are summarized in Table I. With these quantities, Eq. (1) yields

$$R(\tau>\tau_c)\propto \tfrac{1}{2}\eta-\tfrac{1}{16}\eta^2,\quad R(\tau=0)\propto \tfrac{1}{2}\eta-\tfrac{1}{8}\eta^2. \tag{4}$$

Here, we clearly see that a dip in the single-detector counting rate should occur even in this case. Thus, while a coincidence detection signals one photon in each output port of the second beam splitter, it should not be assumed that the output state is $|1,1\rangle$. In this case, there are clearly instances in which the two photons exit the second beam splitter (HWP2-PBS set) via the same port.

Let us now consider the case in which the coincidence peak dip may be observed in a single apparatus: HWP1 rotates the photon polarization by 90° and polarizers are inserted in front of the detectors D_a and D_b. [This is a typical Bell-experiment setup.] When $\tau=0$, polarizer settings of $A1/A2=45°/45°$ result in a null coincidence rate, while settings of $A1/A2=45°/-45°$ result in a coincidence peak [2,4,5]. The experimental data for these measurements are shown in Fig. 2(c). The coincidence measurements show the expected peak and dip, while the single-count measurements, once again, yield dips in both cases.

As before, these results can be understood by taking into account all possible photon number states at the detector, rather than just the states postselected by the coincidence measurement. Since the two input photons are orthogonally polarized, they exit BS independently, regardless of the delay τ. Therefore, $P_{b0}=1/4, P_{b1}=1/2$, and $P_{b2}=1/4$ in both modes a and b before the polarizers. At the polarizer ($\pm 45°$ oriented), single photons are passed only half the time, regardless of the delay. When two photons are incident, however, the result depends on the delay τ. The orthogonally polarized photons scatter randomly for $\tau>\tau_c$, while quantum interference occurs when $\tau=0$. In the latter case, the two photons are either both blocked or both passed at the polarizer. With these probabilities, which are summarized in Table I, Eqs. (1) and (3) yield the same overall single-detector counting rates as given in Eq. (4), which predict a dip in the single-detector rate, regardless of whether the coincidence shows a peak or a dip.

As in the previous case, the presence of a coincidence peak does not indicate the state $|1,1\rangle$ exiting the beam splitter. Indeed, in the Bell-state generation scheme, the orthogonally polarized photons always exit the beam splitter in a random manner. When the photons exit the beam splitter via different ports and a coincidence is registered with orthogonally oriented polarizers (polarizer settings for a coincidence peak), it is certainly the case that one photon reaches each detector. Because of the polarization entanglement between the two photons, the rate at which coincidences are registered is higher when $\tau=0$. It is not the case, however, that the photons always exit via different ports. These other cases, in which the photons exit the beam splitter together, do not lead to coincidences, but they do contribute to the singles rates. Therefore, the complete description of the state reaching the detectors must include not only the $|1,1\rangle$ term, but also the terms which lead to photons at only one detector.

It should also be pointed out that, in contrast to the case in which the photons have the same polarizations when they reach the beam splitter [this setup leads to the experimental data shown in Fig. 2(a)], the presence of a coincidence dip in a Bell-sate generation scheme does not indicate the state $(1/\sqrt{2})(|2,0\rangle+|0,2\rangle)$. The state reaching the detectors must also include the terms $|1,0\rangle$ and $|0,1\rangle$. These terms are present because the polarization entanglement ensures that, for the cases in which the photons exit the beam splitter via different ports toward identically oriented polarizers (polarizer settings for a coincidence dip), only one of the two photons will reach the detectors.

It is also interesting to note that the dip in the singles rate is due to a quantum interference effect that differs from the effect leading to the interference features in the coincidence rate. In the latter case, coincidence detection collapses the two-photon state to a polarization-entangled state (the terms $|2,0\rangle$ and $|0,2\rangle$ do not lead to coincidences). The coincidence rate for this entangled state depends on the (relative) orientations of the two polarizers. The interference observed in the singles rate is different not only because only a single polarizer is required, but also because the terms discarded in coincidence detection become important. The singles rate is independent of τ when single photons reach the polarizer, but when two photons are present, photon bunching occurs when $\tau=0$, i.e., the photons are passed or blocked as a pair at the $\pm 45°$ polarizer.

An obvious drawback to the Bell-state generation scheme is that it is not possible to deterministically generate (or switch between) the states $(1/\sqrt{2})(|2,0\rangle+|0,2\rangle)$ and $|1,1\rangle$. If it was possible to generate these states without relying on postselective measurements, then photon pairs with well-known quantum states would be available for further processing or for use in other applications. Unlike the schemes discussed so far, such a method would be characterized by single-detector counting rates that would differ for the coincidence peak and dip. That is, the state $(1/\sqrt{2})(|2,0\rangle+|0,2\rangle)$, which would yield no coincidences, would lead to probablities $P_0=1/2$, $P_1=0$, and $P_2=1/2$ for a single detector. Meanwhile, the state $|1,1\rangle$ would yield only coincidences and would lead to single-detector probabilities of $P_0=0$, $P_1=1$, and $P_2=0$. According to Eq. (1), the single-detector counting rates would be

$$R_{peak}(\tau=0)\propto \eta,\quad R_{dip}(\tau=0)\propto \eta-\tfrac{1}{2}\eta^2, \tag{5}$$

for these two cases. Thus, the singles rate would mirror the coincidence rate, i.e., it would increase (decrease) in the presence of a coincidence peak (dip).

Figure 3 shows the outline of the apparatus used to generate the above-mentioned two-photon number states. A 3-mm-thick type-II BBO crystal is pumped by an ultrafast pulse with a central wavelength of 390 nm and pulse durations of $\approx$120 fsec. Pairs of photons with center wavelengths of 780 nm emerge from the crystal into two separate cones, one belonging to the e-ray (V polarized) and the other belonging to the o-ray (H polarized) of the crystal. Here, we

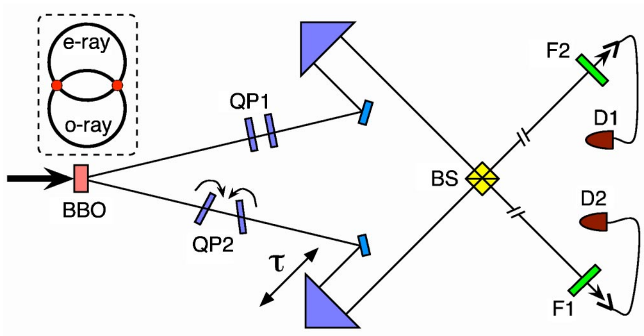

FIG. 3. Outline of experimental setup.

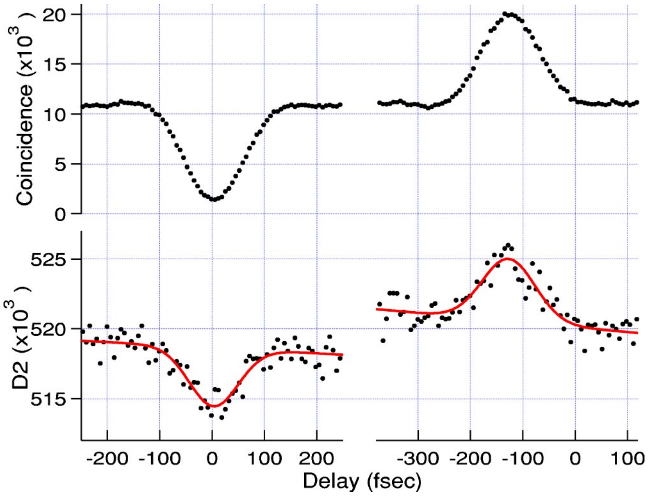

FIG. 4. Experimental data. Data accumulation time is 10 sec. The coincidence peak-dip visibility is about 87%.

are interested in the photons emitted into the intersections of the two cones. These two spatial modes make up the two input ports of an ordinary beam splitter. The FWHM of the spectral filters F1 and F2 was 20 nm. With the interferometer properly balanced, it is possible to switch between the two states $|1,1\rangle$ and $1/\sqrt{2}(|2,0\rangle+|0,2\rangle)$ simply by tilting the quartz plates QP2. Detailed discussions of the interferometer can be found elsewhere [8,9].

The experimental results are shown in Fig. 4. With QP2 normal to the beam path, a coincidence peak was observed, while an orientation of $\approx 23.5°$ produced a coincidence dip. Unlike the experiments described earlier, the coincidence features in this experiment are reflected in the single-detector counting rates, shown in the lower portion of Fig. 4. This suggests that all the photons reaching the detectors are either in the state $(1/\sqrt{2})(|2,0\rangle+|0,2\rangle)$ or in the state $|1,1\rangle$, depending on the phase setting of QP2.

In summary, we have reported the experimental observation of various photon statistics observed in single-photon detection rates in different quantum interferometric schemes. The observed dip in the single-detector counting rate is the combined result of quantum interference and the inability of the detectors to distinguish two-photon excitations from single-photon excitations. In addition, we showed that two-photon number states prepared in a typical two-photon interferometer are postselective. As a result, a dip in the single-detector counting rate was observed, regardless of whether a dip or a peak was seen in the coincidence rate in a typical two-photon interferometer. We concluded with an interference experiment in which two-photon number states can be prepared in a deterministic manner. This was confirmed by observing a correspondence in the peak and dip in single-detector counting rates with the peak and dip in coincidence rates.

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