Observation of correlated-photon statistics using a single detector

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ABSTRACT

Two-photon interference effects and correlated-photon statistics have usually been observed in the coincidence detection rate between two detectors. Here, we report observations of correlated-photon statistics, which are due to two-photon entanglement and interference, in the single-photon detection rate. The observed effects are explained by considering all possible photon number states that reach the detector, rather than considering just the state post-selected by the coincidence circuit.

Keywords: Quantum entanglement, spontaneous parametric down conversion, photon statistics

1. INTRODUCTION

In quantum interference experiments involving two-photon fields of spontaneous parametric down-conversion (SPDC), quantum 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 anti-correlation dip-peak experiment.[2–5]) Indeed, this would be true if the single-photon detectors available today were 100% efficient and were able to resolve incident number of photons. However, all commercially available solid-state single-photon detectors today rely on the avalanche proccess of Si or InGaAs/InP photodiodes. Therefore, even with perfect efficiency, these detectors cannot resolve photon number. This property of single-photon counting avalanche photodiodes usually does not reveal any information about the incident state: only the overall detection efficiency is reduced.

In certain cases, however, the single-detector count rate does provide information about the incident state. This was first reported in Ref. 6, where a quantum interference effect in a two-photon interferometer was employed to change the photon number distribution at a single detector. It was found that the coincidence dip associated with the photon bunching at a beamsplitter was accompanied by a dip in the single detector counting rate, as well. The observed effect can be briefly explained as follows. At the center of the coincidence dip, the photons always leave the interferometer (or the beamsplitter) together. Thus, a detector monitoring one of the output ports of the interferometer "sees" either $|0\rangle$ or $|2\rangle$, but never $|1\rangle$. ($|0\rangle$, $|1\rangle$, and $|2\rangle$ are vacuum, one-photon, and two-photon Fock states, respectively.) On the other hand, photon numbers are randomly distributed outside the region outside the coincidence dip so that all three states, $|0\rangle$, $|1\rangle$, and $|2\rangle$, are possible. If the single-photon detector is unable to resolve $|1\rangle$ and $|2\rangle$ states hence produces the same output pulse, the single-detector count rate in the coincidence dip is less than that of outside the coincidence dip, even though the mean photon number is the same in both regions.

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 the single-detector count rate. Instead, the single detector count rate reveals a dip, just as if the interferometer were 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 post-selected by the coincidence circuit. Finally, we present an experiment in which the coincidence peak or dip directly corresonds to a dip or peak in the singles rate.

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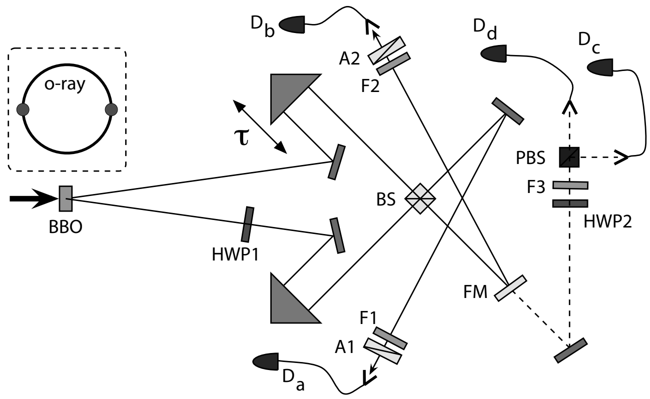

Figure 1. Outline of the experimental setup. Photon pairs from non-collinear type-I SPDC was used in this experiment. HWP1 and HWP2 are half-wave plates, BS is a non-polarizing beamspliter, PBS is a polarizing beamsplitter, FM is a flipper mirror, A1 and A2 are polarizers, and F1 $\sim$ F3 are spectral filters centered at 702.2 nm. Photons are detected by single-photon counting Si avalanche photodiodes, each of which are coupled to a multi-mode fiber.

2. EXPERIMENT WITH POST-SELECTED TWO-PHOTON STATE

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 FWHM of spectral filters F1 and F2 were 3 nm and the coincidence window for all measurements was about 3 nsec. The non-collinear 702.2 nm signal and idler photons are brought together on a beamsplitter and one arm of the interferometer can be adjusted by a computer-controlled DC motor. The non-collinear arrangement avoids the problematic second-order (of the field) interference effect reported in Ref. 6. (Manipulation of raw data is therefore not necessary in our experiment.)

With HWP1, A1, and A2 removed from the apparatus, the usual Shih-Alley/Hong-Ou-Mandel type coincidence dip is obtained by scanning the delay τ.[2,3] The experimental data for this measurement is shown in Fig. 2(a). Note that both the coincidence rate and the single-detector rate show dips as the delay is scanned. Note, also, that the two dips have the same widths.

The dip in the single-count rate can be understood more formally 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 $\eta+(1-\eta)\eta = 2\eta-\eta^2$. 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 (P_1 and P_2) at the output ports of the beamsplitter BS are determined entirely by the delay τ in the case considered here. If $\tau > \tau_c$, where τ_c is the coherence time of the single-photon wavepacket, 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 1, Eq.(1) yields the single-detector counting rates

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

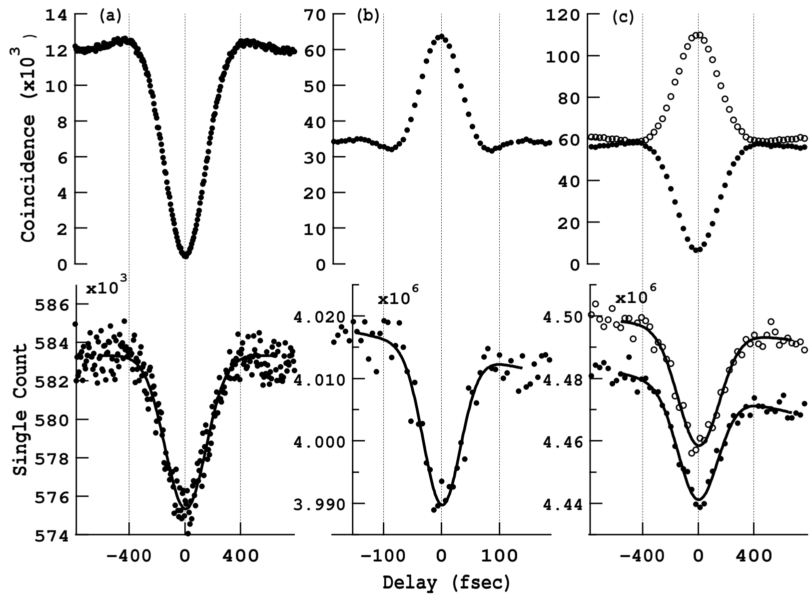

Figure 2. Experimental data for the setup shown in Fig. 1. (a) Coincidence between detectors D_a-D_b shows a dip in the count rate (measured without HWP1, A1 and A2). Note that single-detectors D_a and D_b also show dip's in the count rate. The data accumulation time is 40 seconds at each point. (b) Coincidence between detectors D_c-D_d shows a peak in the count rate. This peak confirms that two photons are bunched at the beamsplitter BS and leave the beamsplitter together at the same output port (measured without HWP1; HWP2 set at 22.5° and PBS together act as a 50/50 beamsplitter). Rather surprisingly, the single-detector count rate shows a dip. The data accumulation time is 10 seconds at each point. (c) Polarization correlation measurement with D_a and D_b (HWP1, A1 and A2 are inserted back to the setup). Coincidence peak (dip) is measured for polarizer angles A1/A2 $= 45°/-45°$ ($= 45°/45°$). Note that the single-detector count rates show dip's for both cases. The data accumulation time is 40 seconds at each point.

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 is usually regarded as the signature of the state $\frac{1}{\sqrt{2}}(|2,0\rangle + |0,2\rangle)$ exiting the beamsplitter BS. 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 beamsplitter to detectors D_c and D_d. The detectors are preceded by a halfwave plate HWP2 set at 22.5° and a polarization beamspitter PBS, which act together as a 50/50 beamsplitter. The FWHM of the spectral filter F3 was 20 nm. When $\tau = 0$, the path exiting the beamsplitter 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] (The HWP2, PBS, two detectors D_c and D_d, and the coincidence circuit act as a 'two-photon detector,' which only responds to the two-photon Fock state $|2\rangle$.)

It is indeed tempting to regard such a coincidence peak as signalling the presence of the state $|1\rangle_{D_c}|1\rangle_{D_d}$ or the presence of one photon in each output mode of the PBS. If this were true, then a peak in the single-detector counting rate would also be expected, since every two-photon Fock state $|2\rangle$ present at the output ports of the beamsplitter BS would lead to exactly one photon at each detector D_c or D_d. This is, however, not the case. Instead of a peak in the single-detector counting rate, a dip is observed just as in the case of the coincidence dip between D_a and D_b, see Fig. 2(b).

This rather unexpected result can be understood by considering conditional probabilities at the second beamsplitter HWP2-PBS set, which acts as a 50/50 beamsplitter. The probabilities that zero, one, and two photons are incident on, for example, detector D_c are

$$\begin{aligned} P_0 &= P_{b0}P_{00} + P_{b1}P_{10} + P_{b2}P_{20}, \\ P_1 &= P_{b0}P_{02} + P_{b1}P_{11} + P_{b2}P_{21} = P_{b1}P_{11} + P_{b2}P_{21}, \\ P_2 &= P_{b0}P_{02} + P_{b1}P_{12} + P_{b2}P_{22} = P_{b2}P_{22}, \end{aligned} \tag{3}$$

where, as defined above, P_{b0}, P_{b1}, and P_{b2} are the probabilities that zero, one, and two photons leave the first beamsplitter BS, respectively. The conditional probabilities P_{ij} are defined as the probabilities that j photons will exit port c of the second beamsplitter (HWP2-PBS set or a 50/50 beamsplitter), given i incident photons. These conditional probablities are independent of the delay τ and are summarized in Table 1. With these quantities, Eq. (1) yields

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

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 beamsplitter, it should not be assumed that the output state is $|1\rangle_{D_c}|1\rangle_{D_d}$. In this case, there are clearly instances in which the two photons exit the second beamsplitter (HWP2-PBS set or a 50/50 beamsplitter) via the same port. This also means that a 50/50 beamsplitter, two single-photon counting detectors, and a coincidence circuit work as a 'two-photon detector' but the two-photon detection efficiency is limited at maximum value of 50% (when all other components are considered ideal).

Let us now consider the case in which the coincidence peak-dip may be observed in a single apparatus: HWP1 rotates the polarization of one of the photons by 90° and polarizers A1 and A2 are inserted in front of the detectors D_a and D_b. Note that this is a typical Bell-experiment setup. When $\tau = 0$, polarizer settings of $A1/A2 = 45°/45°$ result in a null in the coincidence rate, while settings of $A1/A2 = 45°/-45°$ result in a coincidence peak.[2,4,5] This is because the coincidence measurement post-selects the output state of the beamsplitter to be a polarization-entangled two-photon state:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|H\rangle_a|V\rangle_b - |V\rangle_a|H\rangle_b).$$

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 dip's in both cases.

As before, correct understanding of these results requires a full consideration of all possible photon number states that reach the detector, rather than just the states post-selected by the coincidence measurement. Let us first consider what happens at the first beamsplitter BS. Since the two input photons are orthogonally polarized, they exit the beamsplitter 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 A1 and A2. At the polarizers A1 and A2 (±45° oriented), single photons are passed only half the time, again, regardless of the delay. On the other hand, when two photons are present before the polarizers A1 or A2, the photon number distribution after the polarizers depends on the delay τ. Note that this two-photon presence is usually ignored in two-photon correlation or polarization-entanglement measurement done by the coincidence circuit which post-selects the states with only one photon

Table 1. Summary of probabilities that a particular output port contains zero, one, and two photons when two incident photons have the same polarization.

At Beamsplitter BS		Conditional probabilities at D_c (D_d)		
$\tau > \tau_c$	$\tau = 0$	Probability independent of τ		
$P_{b0} = 1/4$	$P_{b0} = 1/2$	$P_{00} = 1$	$P_{10} = 1/2$	$P_{20} = 1/4$
$P_{b1} = 1/2$	$P_{b1} = 0$	$P_{01} = 0$	$P_{11} = 1/2$	$P_{21} = 1/2$
$P_{b2} = 1/4$	$P_{b2} = 1/2$	$P_{02} = 0$	$P_{12} = 0$	$P_{22} = 1/4$

in each output modes of the beamsplitter BS. As we shall see below, the dip in the single-detector count rate is due to these usually ignored terms.

These usually ignored two-photon terms are $|H\rangle_a|V\rangle_a$ and $|V\rangle_a|H\rangle_b$ in modes a and b before the polarizers. The two photons (orthogonally polarized) scatter randomly for $\tau > \tau_c$, while quantum interference occurs when $\tau = 0$. In the latter case ($\tau = 0$), the two photons are either both blocked or both passed at the polarizer A1 or A2. With these probabilities, which are summarized in Table 2, 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 $|1\rangle_a|1\rangle_b$ exiting the beamsplitter. Indeed, in the Bell-state generation scheme, the orthogonally polarized photons always exit the beamsplitter in random fashion. When the photons exit the beamsplitter BS 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 reached each detector because only $|1\rangle_a|1\rangle_b$ state has been post-selected by the coincidence circuit. The coincidence count rate when $\tau = 0$ is higher than that of $\tau > \tau_c$ because of the the polarization entanglement between the two photons. Photons, however, do not always exit the beamsplitter BS via different ports. These other cases, in which the photons exit the beamsplitter 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 $|1\rangle_a|1\rangle_b$ term, but also the terms which lead to photons at only one detector. As mentioned above, these terms are $|H\rangle_a|V\rangle_a$ and $|V\rangle_a|H\rangle_b$.

It should also be pointed out that, in contrast to the case in which the photons have the same polarizations when they reach the beamsplitter [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 $\frac{1}{\sqrt{2}}(|2,0\rangle+|0,2\rangle)$, after the polarizers A1/A2= 45°/45°. The state reaching the detectors, after the polarizers, 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 beamsplitter via different ports toward identically oriented polarizers (polarizer settings for a coincidence dip), only one of the two photons will reach the detectors and as a result, no coincidence can be registered.

It is also interesting to note that the dip in the single-detector count 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.

Table 2. Summary of probabilities that a particular output port contains zero, one, and two photons when two incident photons are orthogonally polarized. BS is the beamsplitter.

At BS	Probability at D_a (D_b) after $\pm 45°$ polarizer			
	Probability independent of τ		$\tau > \tau_c$	$\tau = 0$
$P_{b0} = 1/4$	$P_{00} = 1$	$P_{10} = 1/2$	$P_{20} = 1/4$	$P_{20} = 1/2$
$P_{b1} = 1/2$	$P_{01} = 0$	$P_{11} = 1/2$	$P_{21} = 1/2$	$P_{21} = 0$
$P_{b2} = 1/4$	$P_{02} = 0$	$P_{12} = 0$	$P_{22} = 1/4$	$P_{22} = 1/2$

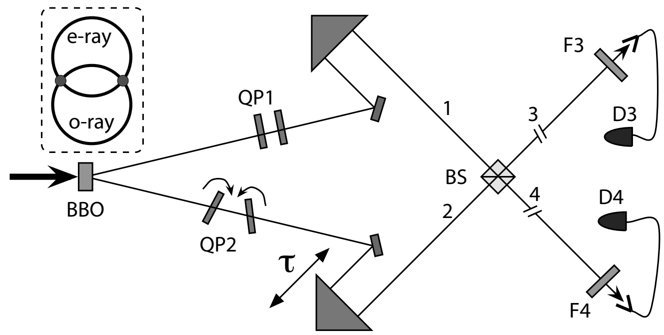

Figure 3. Outline of experimental setup which is used to generate postselection-free two-photon states $|1,1\rangle$ and $\frac{1}{\sqrt{2}}(|2,0\rangle + |0,2\rangle)$. In this case, the coincidence dip and peak are reflected in the single-detector count rates as well. Unlike the experimental setup shown in Fig. 1, non-collinear type-II SPDC is used in this experiment. QP1 and QP2 are quartz phase plates (optic axes oriented vertically), each of which are 600μm thick.

3. EXPERIMENT WITH POSTSELECTION-FREE TWO-PHOTON STATE

An obvious drawback to the Bell-state generation scheme of the type shown in Fig. 1 is that it is not possible to deterministically generate (or switch between) the states $\frac{1}{\sqrt{2}}(|2,0\rangle + |0,2\rangle)$ and $|1,1\rangle$. If it were possible to generate these states without relying on post-selective 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 thus 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 $\frac{1}{\sqrt{2}}(|2,0\rangle + |0,2\rangle)$, 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) and with probabilities summarized in Table 3, the single-detector counting rates would be

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

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).

Fig. 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 central wavelength of 390 nm and pulse durations of approximately 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 are interested in the photons emitted into the intersections of the two

Table 3. Summary of probabilities that a particular output port contains zero, one, and two photons for the experimental setup shown in Fig. 3. The first column shows the background random probabilities which occurs when $\tau > \tau_c$. The next two column show the probabilities at the coincidence dip and at the coincidence peak.

Background $\tau > \tau_c$	At the dip $\tau = 0$	At the peak $\tau = 0$
$P_0 = 1/4$	$P_0 = 1/2$	$P_0 = 0$
$P_1 = 1/2$	$P_1 = 0$	$P_1 = 1$
$P_2 = 1/4$	$P_2 = 1/2$	$P_2 = 0$

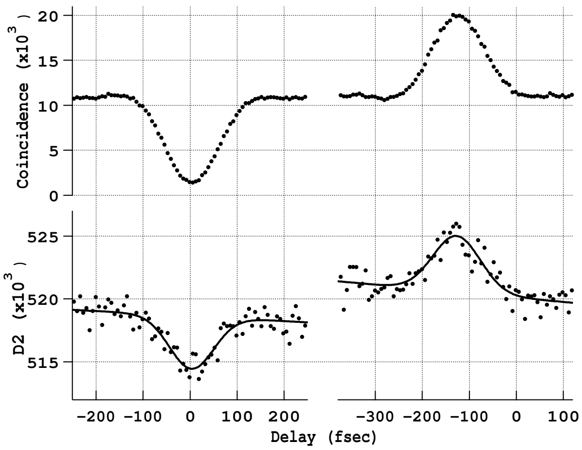

Figure 4. Experimental data for the setup shown in Fig. 3. No polarizers are used to observe the high-visibility quantum interference reported in this figure. The coincidence peak-dip visibility is about 87%. The single-detector count rate mirrors the coincidence dip and peak. Data accumulation time is 10 second each point.

cones. These two spatial modes make up the two input ports of an ordinary beamsplitter. 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 $\frac{1}{\sqrt{2}}(|2,0\rangle + |0,2\rangle)$ simply by tilting the quartz plates QP2. Detailed discussions of the interferometer can be found elsewhere.[8]

In order to understand how the desired state can be generated with this experimental setup, it is instructive to compare this setup to other two-photon interference experiments. As in many of the previous works, each of the beamsplitter inputs contains exactly one photon. An important difference, however, is the exact form of the input state. Whereas all previous two-photon experiments involved a single two-photon state, the input state for our experiment is actually a superposition of two two-photon states. Recall that the photon pairs of interest are emitted into the overlapping regions of the o-ray and e-ray cones, i.e.,

$$|\psi\rangle = \mathcal{F}(\omega_e, \omega_o)|V\rangle_1|H\rangle_2 + e^{i\varphi}\mathcal{F}(\omega_o, \omega_e)|H\rangle_1|V\rangle_2,$$

where $\mathcal{F}(\omega_e, \omega_o)$ is the two-photon joint spectrum function.

This seemingly subtle change to the input state is critical to the observed interference effect, for this superposition now provides two pathways for a given detection outcome. Suppose, for example, that detector D3 registers a horizontally polarized photon, while D4 registers a vertically polarized photon. There are two ways that this may happen: the photons are emitted as $|H\rangle_1|V\rangle_2$ and are both reflected at the beamsplitter; or the photons are emitted as $|V\rangle_1|H\rangle_2$ and are both transmitted. As long as the interferometer is properly adjusted, these two pathways are indistinguishable, even though the photons themselves are very different. If the two arms of the interferometer are identical, the amplitudes have the same sign and constructive interference (coincidence peak) is observed. The phase may be adjusted for destructive interference (coincidence dip) by changing the amount of birefringent material in one arm by a small amount. The coincidence peak therefore corresponds to photon number state $|1\rangle_{D_3}|1\rangle_{D_4}$ and the coincidence dip corresponds to the photon-number−path entangled state $\frac{1}{\sqrt{2}}(|2\rangle_{D_3}|0\rangle_{D_4} + |0\rangle_{D_3}|2\rangle_{D_4})$. It is important to note that post-selection of states have not been done here. Another important feature of this scheme is that no polarizers are necessary to observe quantum interference even though the signal-idler pair is orthogonally polarized. Because of these two features just mentioned above, the single-detector count rate should mirror, see eq.(5), the coincidence rate in the experimental setup shown in Fig. 3.

The experimental results are shown in Fig. 4. With QP2 normal to the beam path, a coincidence peak was observed, while an orientation of approximately 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 $\frac{1}{\sqrt{2}}(|2\rangle_{D_3}|0\rangle_{D_4} + |0\rangle_{D_3}|2\rangle_{D_4})$ or in the state $|1\rangle_{D_3}|1\rangle_{D_4}$, depending on the phase setting of QP2.

4. 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 post-selective. As a result, a dip in the single detector counting rate was observed regardless of whether a dip or peak was seen in the coincidence rate in a typical two-photon interferometer. We also presented an interference experiment in which two-photon number states can be prepared in a deterministic fashion. 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. Our results suggests that even though current single-photon counting avalanche photodiodes are unable to resolve photon numbers, they may still be used to distinguish between post-selective and non-postselective quantum states: making a such distinction experimentally is not possible with the usual coincidencce correlation measurement.

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