Observation of correlated-photon statistics using a single detector

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Abstract: We report an experimental observation of correlated-photon statistics using a single detector. The usual coincidence dip in a two-photon polarization interferometer is accompanied by a dip in single-photon detection rates. Surprisingly, a dip in the singles rate is also observed when the interferometer is aligned for a coincidence peak, or anti-dip.
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In interference experiments involving two-photon fields of spontaneous parametric down-conversion (SPDC), the coincidence counts between two detectors exhibit quantum effects while the single-detector count rate is expected to be featurelessly constant. The two-photon anti-correlation dip is a well-known example. Recently, it was reported that the single-detection rate shows a dip when the two-photon anti-correlation dip occurs in the coincidence counts [1]. The dip in the singles rate can be attributed to the detector's inability to distinguish a single-photon event from a two-photon event.

In this paper, we first confirm the dip effect in the singles rate using a different experimental setup. We then measure the singles rate after the interferometer is aligned for a coincidence peak (i.e., $|1,1\rangle$) instead of coincidence dip (i.e., $\frac{1}{\sqrt{2}}(|2,0\rangle + |0,2\rangle)$). Interestingly, the singles rate shows the same dip even though the coincidence rate shows a peak. 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.

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 702.2 nm signal and idler photons are emitted non-collinearly and are selected by a set of pinholes before being brought together on a beamsplitter. One arm of the interferometer can be adjusted by a computer-controlled DC motor. The non-collinear setup avoids the problematic first-order modulation seen in [1]. We first performed the usual coincidence dip experiment by scanning the delay τ (HWP1, A1, and A2 were removed for this measurement). The experimental data for this measurement are shown in Fig. 1(a). The measured visibility of the coincidence dip is about 94%. The singles rates of detectors D1 and D2 show a dip with the same width as that of the coincidene dip.

The dip in the single-count rate for this measurement can be understood as follows. Suppose η is the single-photon detection efficiency. In the presence of two photons, the probability that the detector will register a count can be written as $\eta + (1-\eta)\eta = 2\eta - \eta^2$. The overall singles rate can then be expressed as $R \propto p_1\eta + p_2(2\eta - \eta^2)$, where p_1 and p_2 are the probabilities for the single-photon and two-photon events, respectively. If $\tau > \tau_c$, where τ_c is the coherence time of the single-photon wavepacket, there are four possible events at the output: (i) both photons reflected, (ii) both photons transmitted, (iii) both photons end up at D1, and (iv) both photons end up at D2. Since all these possible events have the same probabilities, $p_0 = 1/4$ ($|0\rangle$ in D1), $p_1 = 1/2$ ($|1\rangle$ in D1), and $p_2 = 1/4$ ($|2\rangle$ in D1). On the other hand, if $\tau = 0$, amplitudes (i) and (ii) cancel each other due to quantum interference. In this case, $p_0 = 1/2$, $p_1 = 0$, and $p_2 = 1/2$. Then, the single-counting rates are $R(\tau > \tau_c) \propto \eta - \frac{1}{4}\eta^2$ and $R(\tau = 0) \propto \eta - \frac{1}{2}\eta^2$. These equations show that a dip in single rates should accompany a dip in the coincidence rate.

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 D3 and D4. The detectors are preceded by a half-wave plate and a polarization beamsplitter, which act together as a 50-50 beamsplitter. The FWHM of the spectral filter F3 was 20 nm. When $\tau = 0$, the path existing the beamsplitter BS contains either zero or two phohtons, since this delay corresponds to the center of the coincidence dip for detectors D1 and D2. With a higher probability of finding two photons in the exit path

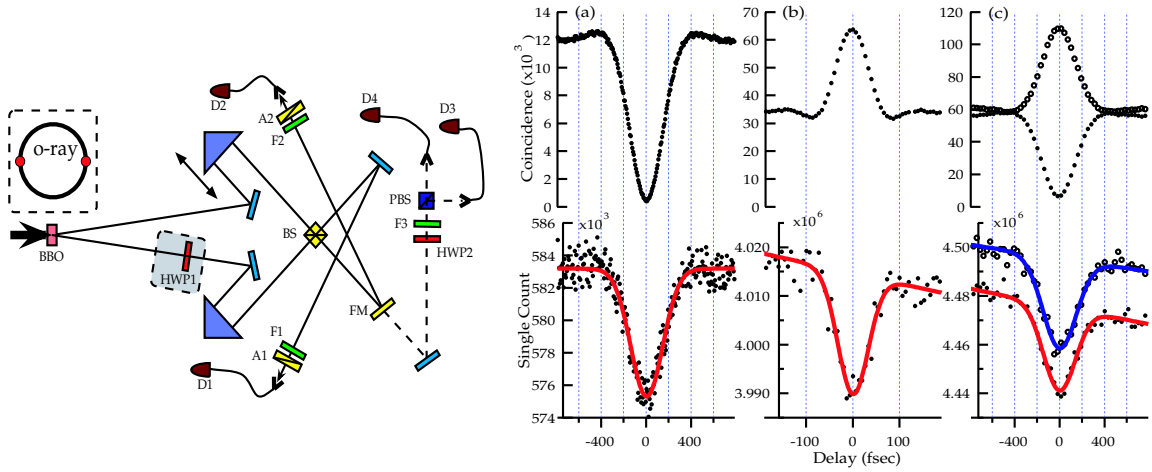

Fig. 1. Outline of experimental setup. HWP1 and HWP2 are $\lambda/2$ plates oriented at 45° and 22.5° respectively. FM is a flipper mirror. With FM flipped down and HWP1 removed, we measure the photon bunching effect using D3 and D4. As shown in (b), the D3-D4 coincidence peak accompanies a dip in the single rate.

(1/2 for $\tau = 0$ vs 1/4 for $\tau > \tau_c$), a coincidence peak is observed between D3 and D4, as shown in Fig. 1(b).

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-counting rate, a dip is observed just as in the case of the coincidence dip between D1 and D2. This rather unexpected result can be explained by considering conditional probabilities at the second beam splitter. When the conditional probabilites are taken into consideration [2], the single-counting rate is expected to be $R(\tau > \tau_c) \propto \frac{1}{2}\eta - \frac{1}{16}\eta^2$ and $R(\tau = 0) \propto \frac{1}{2}\eta - \frac{1}{8}\eta^2$. 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 $|1,1\rangle$. In this case, there are clearly instances in which the two photons exit the second beamsplitter (HWP2-PBS set) via the same port.

Let us now consider the singles rate in a typical Bell-state generation scheme. The apparatus is modified by inserting a waveplate HWP1 in one arm of the interferometer to rotate the polarization. With properly oriented polarizers preceding the detectors, it is possible to generate either a peak or a dip in the coincidence rate. When $\tau = 0$, setting the polarizer angles to $A1/A2 = 45°/45°$ results in a coincidence null, while the settings $A1/A2 = 45°/-45°$ result in a coincidence maximum. It is common to think of the coincidence dip and peak as signatures of the states $\frac{1}{\sqrt{2}}(|2,0\rangle + |0,2\rangle))$ and $|1,1\rangle$, respectively. If this were the case, we would expect singles rates of $R(\tau = 0) \propto \eta$ for the peak and $R(\tau = 0) \propto \eta - \frac{1}{2}\eta^2$ for the dip. With a background rate of $R(\tau > \tau_c) \propto \eta - \frac{1}{4}\eta^2$, the singles rate associated with the coincidence peak would be peaked at $\tau = 0$. The experimental data show, however, that this is not the case. As seen in Fig. 1(c), the coincidence measurements shows the expected dip and peak. However, the single-count measurements show dips for both cases. This result suggests that the states reaching the detector are different than $\frac{1}{\sqrt{2}}(|2,0\rangle + |0,2\rangle))$ and $|1,1\rangle$. Indeed, when all conditional probabilities are calculated [2], the singles rates are found to be $R(\tau > \tau_c) \propto \frac{1}{2}\eta - \frac{1}{16}\eta^2$ and $R(\tau = 0) \propto \frac{1}{2}\eta - \frac{1}{8}\eta^2$, which predict a dip in the single-detector count rat, regardless of whether the coincidence shows a peak or a dip.

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References

1. K.J. Resch, J.S. Lundeen, and A.M. Steinberg, Phys. Rev. A **63**, 020102 (2001).
2. Y.-H. Kim and W.P. Grice, Phys. Rev. A **67**, 065802 (2003).