Comparing quantum and classical correlations in a quantum eraser

A. Gogo, W. D. Snyder, and M. Beck*
Department of Physics, Whitman College, Walla Walla, Washington 99362, USA
(Received 14 February 2005; published 18 May 2005)

We have demonstrated the operation of a quantum eraser based on a polarization interferometer. Which-path information is erased not by modifying the interferometer apparatus, but instead by modifying the information obtained from measurements performed on a second beam, whose polarization is correlated with that of the interferometer beam. We compare the results obtained when the two beams are in an entangled state (quantum correlations) and in a mixed state (classical correlations). We find that classical correlations can mimic most, but not all, of the quantum-mechanical behavior.

DOI: 10.1103/PhysRevA.71.052103 PACS number(s): 03.65.Ud, 42.50.Dv, 42.65.Lm

I. INTRODUCTION

When light passes through an interferometer, the visibility of the resulting fringe pattern depends on the amount of "which-path" information available to the experimenter. If the experimenter is able to determine, by any means, which path the light takes through the interferometer then there is no interference. If the experimenter has no information about the path (and cannot even *in principle* determine which path the light took) then high visibility interference can be observed. In general partial path information leads to partial interference (visibility between 0 and 1) [1], but here we concern ourselves only with the extreme cases of high or low visibility.

In some experiments it is possible to switch between having full which-path information and having no which-path information by a subtle modification of the experimental apparatus. In cases where the which-path information is not available, the which-path information is said to be "erased," and this erasure can allow the observation of high visibility interference fringes. An interferometer with these properties is frequently referred to as a "quantum eraser." For example, a wave plate or polarizer inserted into one arm of an interferometer can be used to modify the polarization of that beam. With suitable polarization analysis after the interferometer, rotations of this wave plate or polarizer can either yield or erase which-path information, hence changing the visibility of the observed interference pattern [1–3]. However, using the criteria of Kwiat *et al.* this example does not constitute an "ideal" quantum eraser because it involves modification of the interferometer itself, as opposed to simply modifying the measurement apparatus [4].

It is also possible to perform experiments with correlated photon pairs. When using parametric downconversion, the correlated photons are known as the signal and the idler. In this case it is often possible to obtain which-path information not only from the signal beam traversing the interferometer, but also by performing appropriate measurements on the idler beam. For example, consider the case in which the polarizations of the signal and idler are perfectly correlated. If the path of the signal photon through an interferometer (or a double slit) is determined by its polarization, then a suitable measurement of the idler polarization yields full which-path information for the signal. This destroys any interference. In order to observe interference, which-path information must be erased from the idler as well as from the signal; this is done by a suitable modification of the idler measurement [5,6]. This example does constitute an ideal quantum eraser, because only the idler measurement is changed to affect the available which-path information.

Quantum erasers with geometries different from those described above have also been implemented [7–10]. Here we demonstrate ideal quantum erasure in a polarization interferometer using two different sources of polarization-correlated photon pairs: an entangled state source and a mixed state source. The signal beam traverses the polarization interferometer, while the idler beam passes through a polarization analyzer before being measured. We look for interference in the measured coincidence counts between these beams; hence interference depends not only on the properties of each individual beam, but also on the correlations between them. As described above, we must erase which-path information obtainable from the idler (as well that from the signal) in order to see interference. Our experiments are quite similar to those proposed by Kwiat and Englert [11].

We find that the visibility of the measured interference pattern does indeed depend on how the polarization of the idler beam is analyzed; this is true for both the entangled-state and the mixed-state sources. However, we find that the results obtained with these two sources are not identical in all respects. For the entangled-state source we find that interference is lost when which-path information for the signal beam can be obtained by measuring the polarization of the idler beam. For our mixed-state source which-path information is never available; the lack of an interference pattern when using this source is due to the inability to separate two overlapping interference patterns which are out of phase with each other [11].

II. EXPERIMENT

A. Entangled state

The experimental apparatus for measurements using an entangled-state source is depicted in Fig. 1. We use a pair of

*Electronic address: beckmk@whitman.edu

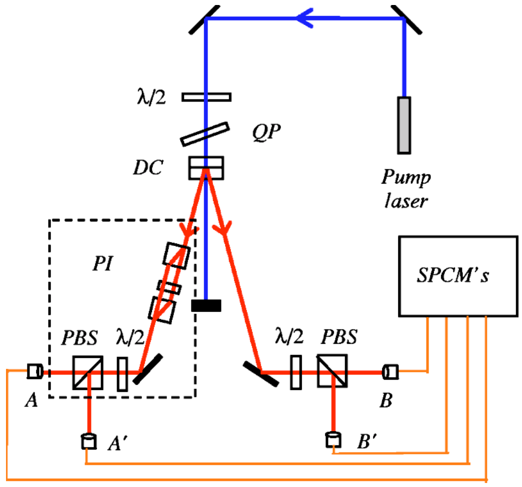

FIG. 1. (Color online) The experimental arrangement of a quantum eraser with polarization entangled photons. Here $\lambda/2$ denotes a half wave plate, QP denotes the quartz plate, DC denotes the downconversion crystals, PI denotes the polarization interferometer, SPCM's denotes the single-photon counting modules, and PBS denotes a polarizing beamsplitter.

0.5-mm-thick BBO crystals, each cut for type-I downconversion. They are stacked back-to-back, with their crystal axes oriented at 90° with respect to each other [12,13]. The first crystal converts vertically polarized pump photons into horizontally polarized signal and idler, while the second crystal converts horizontally polarized pump photons into vertically polarized signal and idler. The crystals are pumped using a 50-mW, 405-nm laser diode polarized at 45° in order to pump both crystals. The half wave plate, $\lambda/2$, and the quartz plate (QP) in front of the downconversion crystals are used to adjust the pump polarization, and the relative phase between the horizontal and vertical polarizations. The downconverted light is collected by lenses and focused into multimode fibers which are used to direct the light to single-photon counting modules (SPCM's). The SPCM's have RG780 filters in front of them, which pass the downconverted light but block scattered pump photons. Further details about our experimental apparatus can be found in Ref. [14].

Our source produces photon pairs in the polarization entangled state,

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|H,H\rangle + |V,V\rangle), \quad (1)$$

where H refers to a horizontally polarized photon, and V refers to a vertically polarized photon [12,13]. Any given photon has a 50/50 chance of being either horizontally or vertically polarized. However, if one photon of a pair, for example, the idler, is found to be horizontally polarized then we know that the second (signal) photon will also be horizontally polarized. The correlations between the two beams as expressed in the entangled state of Eq. (1) are purely quantum mechanical, and cannot be mimicked by any local hidden variable theory (i.e., by any strictly classical theory). We have verified that our source produces true quantum correlations by performing a test of a Bell inequality, and finding a 30 standard deviation violation of local realism [12,13].

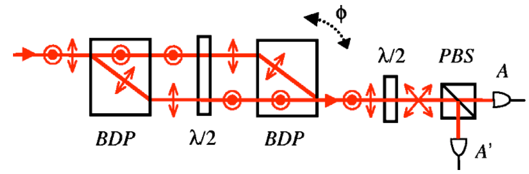

FIG. 2. (Color online) The polarization interferometer, with the polarization of the individual beams labeled (⊙ indicates vertical polarization and ↕ indicates horizontal polarization). Here BDP denotes a beam displacing prism.

The polarization interferometer is shown in Fig. 2. A beam displacing prism (BDP) (simply a piece of birefringent calcite) splits the beam into vertically and horizontally polarized components, with the horizontally polarized piece walking off. A half wave plate flips the polarizations, so that a second BDP causes the two polarizations to walk back together. Upon exiting this BDP the beams are overlapped, but do not yet interfere because they have orthogonal polarizations. A second $\lambda/2$ plate rotates both polarizations by 45° so that they interfere on the polarizing beamsplitter (PBS). The pathlength difference (relative phase) between the two arms is adjusted by rotating the second BDP.

As discussed in Sec. I, interference can only occur if the signal photon takes both paths through the interferometer. If this photon is known to take either one path or the other then no interference will occur. Since the path of the signal photon is determined if its polarization is known to be either horizontal or vertical, there will be no interference if it is possible to determine that the signal photon is horizontally or vertically polarized.

We illustrate this lack of interference in Fig. 3, where we plot the measured number of coincidence counts between the A and B detectors, N_{AB}, as a function of the pathlength difference between the two arms of the interferometer. The $\lambda/2$ plate in the idler beam is oriented so that horizontally polarized photons are detected at B, and vertically polarized photons are detected at B'. If a horizontally polarized idler photon is detected at B, for example, then the polarization correlations inherent in the state $|\psi\rangle$ indicate that the signal photon must be also be horizontally polarized. In this case we know which path the signal photon took through the in-

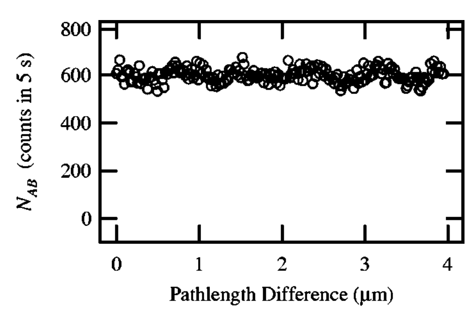

FIG. 3. The measured number of coincidence counts N_{AB} as a function of the pathlength difference between the two arms of the interferometer. Here the source is in an entangled state, and detector B measures horizontally polarized idler photons.

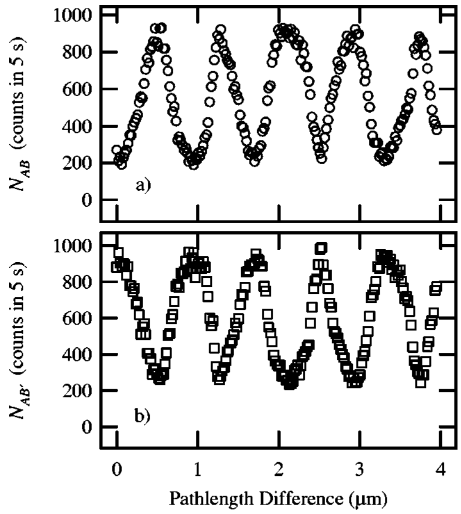

FIG. 4. The measured number of coincidence counts [N_{AB} in (a), and $N_{AB'}$ in (b)] as a function of the pathlength difference between the two arms of the interferometer. Here the source is in an entangled state, and detector B measures +45° polarized idler photons, while detector B' measures −45° polarized idler photons.

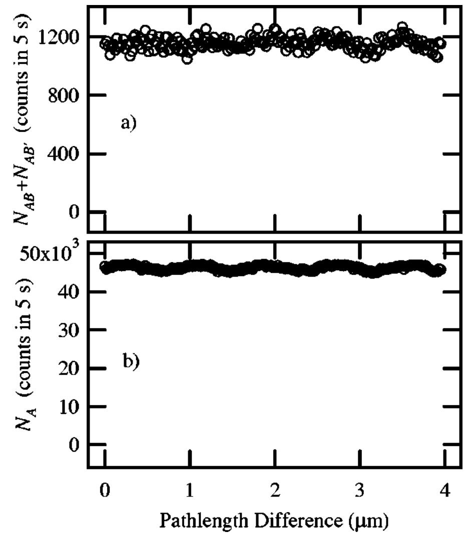

FIG. 5. (a) The sum of the measured number of coincidence counts $N_{AB}+N_{AB'}$ as a function of the pathlength difference between the two arms of the interferometer. Here the source is in an entangled state, and detector B measures +45° polarized idler photons, while detector B' measures −45° polarized idler photons. (b) The singles count rate N_A under the same conditions.

terferometer, and no interference will be observed. By measuring the outputs of detector A in coincidence with B, we can see whether or not these photons will produce an interference pattern. In Fig. 3 we see that there is essentially no interference [15].

How then can we see interference? Because of the correlations between the signal and the idler, potential which-path information must be erased from *both* beams. To do this we orient the $\lambda/2$ plate in the idler beam so that +45° linearly polarized idler photons are detected at B, and −45° linearly-polarized idler photons are detected at B'. With this orientation a detection at B, for example, yields no information about whether the idler photon (and hence the signal photon) was vertically or horizontally polarized. This effectively erases which-path information about the signal photon. We expect to see interference if we look at coincident detections between B and A. This interference is shown in Fig. 4(a), and represents evidence of quantum erasure.

Another way to understand why interference is observed for this setting of the wave plate in the idler beam is to note the following. An interesting property of the entangled state $|\psi\rangle$ of Eq. (1) is that it *remains* entangled in the basis consisting of +45 and −45° polarized photons:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|+45,+45\rangle + |-45,-45\rangle). \tag{2}$$

So, for example, if we measure the idler photon to be polarized along the +45° axis, the signal photon is projected onto a state with +45° polarization. This +45° polarized signal photon will take both paths through the interferometer, and will then interfere with itself.

Note further that a detection at B' indicates that the idler (signal) photon must be polarized at −45°. In this case the signal photon should interfere with itself as well; however, the fringe pattern for this polarization is 180° out of phase with respect to that obtained from a +45° polarized photon. Because these fringes are 180° out of phase, they are sometimes referred to as *antifringes*. These antifringes are shown in Fig. 4(b). Note that the fringes and antifringes do not come from the two output ports of the interferometer. They come from the same output port, but are conditioned upon different polarization states of the idler photon.

If we add the number of AB and AB' coincidences, $N_{AB}+N_{AB'}$, the interference is lost, as is seen in Fig. 5. Why is the interference lost in this case? We realize that by adding the AB and AB' coincidences, we have effectively removed the polarization information from the idler beam measurement—it is as if we simply had a single detector in the idler beam, with no polarization analysis. This yields no information about the polarization of the signal photon in the interferometer, so one might expect interference. However, interference is not seen in this case because one could *in principle* place a polarizer in front of the idler detector to learn the polarization. In order to see interference there must be no way (even in principle) to determine the polarization. The only way to *guarantee* that the polarization information is erased is to arrange B and B' to detect +45 and −45° polarizations, and then to perform that measurement. If this measurement is not explicitly carried out there always remains an in principle method of determining the polarization. We illustrate this point further in Fig. 5(b), where we show the raw counts on detector A, N_A, taken at the same time as the data shown in Figs. 4 and 5(a). These raw counts show no interference, because for these counts the which-path information for the signal is in principle available from a measurement performed on the idler beam.

B. Mixed state

Before we discuss the details of our experiments with a mixed state source, it is useful to consider which mixed states we expect to exhibit interference. In analogy to Eq. (1) we first consider the mixed state given by the density operator

$$\hat{\rho}_{HV} = \frac{1}{2}(|H,H\rangle\langle H,H| + |V,V\rangle\langle V,V|). \quad (3)$$

It is straightforward to see that the mixed state of Eq. (3) will never exhibit interference. The superposition of the entangled state $|\psi\rangle$ means that the signal photon contains both horizontal *and* vertical polarizations; it can take both paths through the interferometer and exhibit interference. However, a signal photon in the state $\hat{\rho}_{HV}$ has either horizontal *or* vertical polarization; it never takes both paths. Photons in this state will never exhibit interference.

Now consider the mixed state $\hat{\rho}_{45}$, which is given by the density matrix

$$\hat{\rho}_{45} = \frac{1}{2}(|+45,+45\rangle\langle +45,+45| + |-45,-45\rangle\langle -45,-45|). \quad (4)$$

It is important to note that $\hat{\rho}_{45}$ is not simply obtained by changing the basis of $\hat{\rho}_{HV}$; it is an entirely different state. This is in contrast to the entangled state $|\psi\rangle$, as Eqs. (1) and (2) represent the same state expressed in different bases. A signal photon in the state $\hat{\rho}_{45}$ has polarization +45° or −45°, so it *always* takes both paths through the interferometer. In this mixed state we thus have the potential to see interference.

In order to generate the state $\hat{\rho}_{45}$ experimentally, we place a liquid crystal variable retarder (LCVR) in the pump beam. The retardance of this LCVR is varied by applying a voltage to it. This retarder is configured so that for one applied voltage the pump polarization entering the downconversion crystals is vertical, producing pairs of signal and idler photons in the state $|H,H\rangle$ which emerge from one of the crystals. For a different voltage the pump polarization is horizontal, producing pairs of photons in the state $|V,V\rangle$ which emerge from the other crystal. We alternate back and forth between these two pump polarizations at 1 Hz, and average over a 5-s time interval to sample both polarization states. The state of the signal and idler photons leaving the downconversion crystals thus approximates $\hat{\rho}_{HV}$. We convert $\hat{\rho}_{HV}$ to $\hat{\rho}_{45}$ by inserting half wave plates in the signal and idler beams immediately after they leave the downconversion crystal. These wave plates are oriented to rotate horizontal and vertical polarizations into +45 and −45° polarizations, creating the state $\hat{\rho}_{45}$.

The correlations between the beams expressed in Eqs. (3) and (4) are classical in nature. By this we mean that there is a local realistic description of these states, and hence they cannot violate a Bell inequality. By repeating the Bell inequality test we had performed using our entangled state, we find that the mixed state $\hat{\rho}_{HV}$ does not violate the Bell inequality.

In Fig. 6 we show interference patterns obtained when using the state $\hat{\rho}_{45}$. In Fig. 6(a) we show the interference pattern obtained when the half wave plate before the polarizer in the idler beam is oriented such that detector B measures idler photons polarized at +45°. As is seen in Eq. (4),

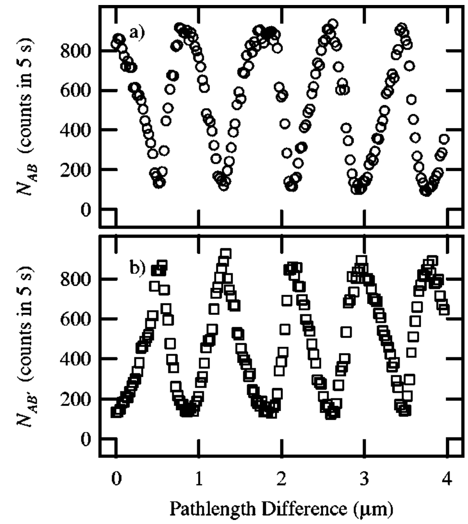

FIG. 6. The measured number of coincidence counts [N_{AB} in (a), and $N_{AB'}$ in (b)] as a function of the pathlength difference between the two arms of the interferometer. Here the source is in a mixed state, and detector B measures +45° polarized idler photons, while detector B' measures −45° polarized idler photons.

detection of this photon projects the signal photon into a state polarized at +45°. This signal photon takes both paths through the interferometer and displays interference. With this wave-plate orientation detector B' measures idler photons polarized at −45°. These detections project the signal photon into a −45° state which also exhibits an interference pattern, as shown in Fig. 6(b). As was the case for the entangled state $|\psi\rangle$ these two interference patterns represent fringes and antifringes. The mixed state $\hat{\rho}_{45}$ thus mimics the interference behavior of the entangled state shown in Fig. 4.

It is also possible to make the interference pattern disappear. We do this by orienting the half wave plate in front of the idler beam polarizer such that detector B measures horizontally polarized photons. Given a detection at B the signal photon is projected onto the state

$$\hat{\rho}_{s} = \frac{1}{2}(|+45\rangle\langle +45| + |-45\rangle\langle -45|). \quad (5)$$

A signal photon is thus equally likely to be polarized along +45° and −45°; in either case it will take both paths through the interferometer and interfere with itself. However, as is seen in Fig. 6, the +45° and −45° interference patterns are out a phase with respect to each other. Since we do not distinguish between the two possible polarizations, we are effectively sampling both patterns. The two out-of-phase patterns cancel each other out, and the net effect is that the interference effectively disappears, as seen in Fig. 7. Thus the mixed state $\hat{\rho}_{45}$ mimics the behavior of the entangled state $|\psi\rangle$ shown in Fig. 3.

By removing the half wave plates immediately following the downconversion crystals, we have also verified that the mixed state $\hat{\rho}_{HV}$ of Eq. (3) does not exhibit interference for any orientation of the analyzer wave plate in the idler beam.

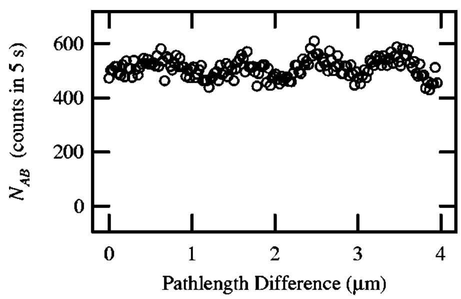

FIG. 7. The measured number of coincidence counts N_{AB} as a function of the pathlength difference between the two arms of the interferometer. Here the source is in a mixed state, and detector B measures horizontally polarized idler photons.

III. DISCUSSION

By comparing the interference patterns with different polarization analysis applied to the idler beam (Figs. 3, 4, 6, and 7), we see that the mixed state $\hat{\rho}_{45}$ can mimic the interference behavior of the entangled state $|\psi\rangle$. Thus the appearance or disappearance of an interference pattern is not necessarily due to polarization entanglement between the two beams, but due to polarization correlations between them.

Nevertheless, the interpretation of the lack of an interference pattern (Figs. 3 and 7) is different for the cases of mixed and pure states [11]. For the pure state we say that measuring a horizontally polarized idler photon projects the signal photon onto a horizontally polarized state. This signal photon takes only one path through the interferometer, and hence cannot possibly display interference. For the mixed state we say that the signal photon always takes both paths through the interferometer. However, signal photons of different polarizations produce out-of-phase fringe patterns, and detection of a horizontally polarized idler photon does not distinguish between these two patterns. The simple fact that we do not observe an interference pattern does not verify either of these interpretations. This raises the question, “Can we verify these interpretations?”

To answer this question we begin by reexamining the polarization interferometer of Fig. 2. The beam in the upper arm of the interferometer emerges from the first BDP vertically polarized; we refer to the beam in this arm as the v beam. We refer to the other beam, which emerges from the BDP horizontally polarized, as the h beam.

Consider first the case of the entangled state. What happens if we insert a beam block into the v beam? With this beam block in place the h beam is completely unaffected, meaning that count rates corresponding to horizontally polarized signal photons are unaffected. If the polarization analysis of the idler beam is arranged so that horizontally polarized idler photons are detected at B, a count at B means that the signal photon was also horizontally polarized and it is unaffected by the beam block. Thus whether we insert or remove the beam block in the v beam, the coincidence count rate N_{AB} will be completely unaffected. With this orientation for the polarization analysis in the idler beam, vertically polarized idler photons are detected at B'. A detection at B' indicates the presence of a vertically polarized signal photon, which will be blocked by the beam block. The insertion of the beam block will cause the coincidence count $N_{AB'}$ rate to drop to 0.

In our experiments with the entangled state, we have verified that the coincidence count rates N_{AB} and $N_{AB'}$ behave as described above upon the insertion or removal of the beam block in the v beam. This verifies the interpretation that the detection of a horizontally polarized idler photon forces to signal photon to take only one path when traversing the interferometer.

Now consider the case of the mixed state $\hat{\rho}_{45}$. For this state every signal photon splits equally into horizontal and vertical components at the first BDP. Inserting a beam block into the v beam will block half of the signal photons, independent of the detection events in the idler beam. We thus expect the coincidence count rates N_{AB} and $N_{AB'}$ to both drop by factors of $1/2$ upon insertion of the beam block. Our experiments indicate that this is exactly what happens, verifying the interpretation that signal photons in the mixed state always take both paths through the interferometer.

IV. CONCLUSIONS

We have demonstrated the operation of a quantum eraser using a polarization interferometer. Interference is made to appear and or disappear by modification of the measurement apparatus rather than a modification of the interferometer, indicating that this is an ideal quantum eraser.

The presence or absence of an interference pattern is independent of whether we use an entangled state or a mixed state source. However, in the presence of a beam block in one of the interferometer arms, the measured coincidence count rates do depend on whether the source state is entangled or mixed. In this sense we say that the mixed state can mimic most, but not all, of the entangled state behavior.

ACKNOWLEDGMENTS

We thank V. W. Donato and R. E. Davies for their work on some earlier interference experiments. We thank D. Branning, E. J. Galvez, and M. W. Mitchell for helpful discussions. This work was supported by the National Science Foundation and Whitman College.

[1] P. D. D. Schwindt, P. G. Kwiat, and B. G. Englert, Phys. Rev. A **60**, 4285 (1999).
[2] M. B. Schneider and I. A. LaPuma, Am. J. Phys. **70**, 266 (2002).
[3] E. J. Galvez *et al.*, Am. J. Phys. **73**, 127 (2004).
[4] P. G. Kwiat, A. M. Steinberg, and R. Y. Chiao, Phys. Rev. A **49**, 61 (1994).
[5] S. P. Walborn, M. O. T. Cunha, S. Padua, and C. H. Monken, Phys. Rev. A **65**, 033818 (2002).
[6] M. J. Pysher, E. J. Galvez, and K. Misra (private communication).
[7] C. H. Monken, D. Branning, and L. Mandel, in *Coherence and Quantum Optics VII*, edited by J. H. Eberly *et al.* (Plenum, New York, 1995), p. 701.
[8] C. K. Hong and T. G. Noh, J. Opt. Soc. Am. B **15**, 1192 (1998).
[9] A. Zeilinger, Rev. Mod. Phys. **71**, S288 (1999).
[10] Y. H. Kim *et al.*, Phys. Rev. Lett. **84**, 1 (2000).
[11] P. G. Kwiat and B. G. Englert, in *Science and Ultimate Reality: Quantum Theory, Cosmology, and Complexity*, edited by J. D. Barrow *et al.* (Cambridge University Press, Cambridge, U.K., 2004), p. 306.
[12] P. G. Kwiat *et al.*, Phys. Rev. A **60**, R773 (1999).
[13] D. Dehlinger and M. W. Mitchell, Am. J. Phys. **70**, 903 (2002).
[14] J. J. Thorn *et al.*, Am. J. Phys. **72**, 1210 (2004).
[15] We attribute low visibility interference patterns, when we expect to see no interference, to imperfections in the experimental alignment.