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# Experimental investigation of Popper's proposed ghost-diffraction experiment

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## Abstract

In an effort to challenge the Copenhagen interpretation of quantum mechanics, Karl Popper proposed an experiment involving spatially separated entangled particles. In this experiment, one of the particles passes through a very narrow slit, and thereby its position becomes well-defined. This particle therefore diffracts into a large divergence angle; this effect can be understood as a consequence of the Heisenberg uncertainty principle. Popper further argued that its entangled partner would become comparably localized in position, and that, according to his understanding of the Copenhagen interpretation of quantum mechanics, the 'mere knowledge' of the position of this particle would cause it also to diffract into a large divergence angle. Popper recognized that such behavior could violate the principle of causality in that the slit could be removed and the partner particle would be expected to respond instantaneously. Popper thus concluded that it was most likely the case that, in an actual experiment, the partner photon would not undergo increased diffractive spreading and thus that the Copenhagen interpretation is incorrect. Here, we report and analyze the results of an implementation of Popper's proposal. We find that the partner beam does not undergo increased diffractive spreading. Our work helps to clarify the issues raised in Popper's proposal, and it provides further insight into the nature of entanglement and its relation to the uncertainty principle as applied to correlated particles.

Keywords: Popper experiment, Copenhagen interpretation, ghost diffraction

(Some figures may appear in colour only in the online journal)

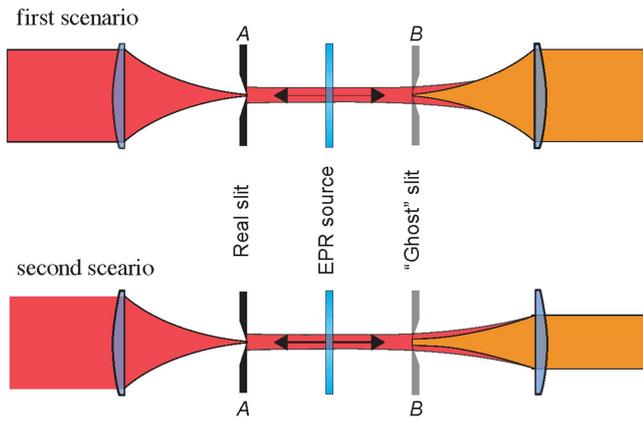
## 1. Introduction

Among different theories of physics, quantum mechanics plays an essential role in describing atomic and subatomic phenomena. Despite the fact that its formalism passes every rigorous experimental test, quantum mechanics has led to many controversies since its inception. In a seminal paper, Einstein, Podolsky and Rosen (EPR) conceived a *gedankenexperiment* using entangled particles to argue against the completeness of quantum mechanics [1]. They made

use of a pair of particles that are assumed perfectly correlated in both position and momentum—the EPR state. Their concern was that their thought experiment appeared to allow for the simultaneous reality of conjugate quantities, in apparent conflict with the Heisenberg uncertainty principle (HUP). The modern answer to the EPR argument is that quantum mechanics is a *truly* nonlocal theory [2], although it is nonetheless consistent with causality in that information cannot be transmitted faster than the speed of light, i.e. it obeys a no-signaling principle [3–6].

In addition to the EPR work, Karl Popper outlined an experiment that challenged the predictions of quantum mechanics

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**Figure 1.** Two possible outcomes of Popper’s thought experiment. Popper assumes a source (labeled EPR) of two particles that are entangled in both position and transverse momentum. If the particle on the left passes through a narrow slit at position A (as could be verified by placing a large area or ‘bucket’ detector after the slit), the position of the particle (in the vertical dimension) becomes known to high accuracy, and, by the HUP, its momentum becomes highly uncertain. The particle thus diffracts into a large divergence angle. The question asked by Popper was whether this particle’s entangled partner moving to the right would also undergo increased diffractive spreading, because its position is also very well defined at the position of the ‘ghost’ slit. Popper perceives two possible outcomes. In the first scenario (shown at the top), the width of the diffraction arising from the ghost slit, as measured in coincidence, is assumed to be comparable to the width of the diffraction that would arise from a real slit, that is, it would be as wide as the region with red shading on side A. This region on side B is shaded orange. This prediction is incompatible with causality in that, by suddenly introducing a real slit on side A, one could instantaneously influence the diffraction spread on side B. In the second scenario (shown at the bottom), the beam on the right as measured in coincidence becomes localized in the plane of the ghost slit (as this is a normal feature of entanglement) but does not undergo increased spreading in the far-field of the slit. The region on the right where the photon would be detected in coincidence is again shaded orange. According to Popper’s understanding, the Copenhagen interpretation of quantum mechanics predicts the first scenario, and therefore this theory is incompatible with relativistic causality. Our experimental results confirm the second of Popper’s scenarios.

based on its Copenhagen interpretation [7, 8]<sup>6</sup>. He designed an experiment that he believed had two possible outcomes, as shown in figure 1. The first outcome would conflict with relativistic causality and the concept that information cannot travel faster than the speed of light, that is, with the no-signaling principle. The second outcome would be in conflict with Popper’s understanding of the predictions of the Copenhagen interpretation of quantum mechanics, and specifically with the concept that not all information about a single quantum system can be acquired simultaneously, that is, with the Heisenberg uncertainty relation between conjugate quantities. Popper favored causality over the Copenhagen interpretation and tended to favor the second outcome.

<sup>6</sup> It is worth mentioning that we tested the latest version of the Popper’s experiment, which was proposed in his 1982 book [8] and is known as Popper’s experiment nowadays. The first version appeared in his 1934 publication [7], but this version was later rejected by Popper as being incorrect.

In this article, we present experimental evidence that the second outcome is in fact what is observed, thus confirming that there is no violation of causality. We also stress that our confirmation of the second scenario does not challenge the standard interpretation of quantum mechanics. Previous workers have shown theoretically that the result we obtain is in fact consistent both with relativistic causality and with the standard formalism of quantum mechanics. We next review some of this work.

Since the time of Popper’s proposal, many scientists have looked into the questions he raised [9–17]. Notably, in 1987, Collett and Loudon proposed a more realistic model of Popper’s experiment where the source, instead of being a point source, is extended in the transverse direction of space [12]. They concluded that the transverse uncertainty of the source causes the diffraction spread on side B to decrease with the size of the slit on side A, hence reconciling quantum mechanics with causality. Ghirardi *et al* have presented [16] exhaustive arguments that show theoretically why one cannot obtain a larger scatter of one particle by narrowing the slit for the other particle, even though the two particles are described by a spatially correlated wave function. Ghirardi has also presented such arguments in book form [17]. In 1999, Kim and Shih [13] reported experimental results showing that the ‘ghost’ slit does not induce increased diffractive spreading. However, suspicion with regards to the explanation of their results was raised by Short [14], who formulated the results of the Popper experiment in terms of conditional uncertainties. Further theoretical work has questioned whether Popper’s thought experiment truly addresses either the Copenhagen interpretation or the HUP [15, 16]. Moreover, a detailed analysis of the experimental aspects of the Kim and Shih experiment has recently been published in [18].

## 2. Theory

The thought experiments of EPR and of Popper are closely related to the HUP, one of the fundamental concepts of quantum mechanics. The HUP states that there is a fundamental limit to the accuracy with which one can gain simultaneous knowledge of conjugate quantities, in our case the position and momentum of a single particle as described by  $\Delta x \Delta p \geq \hbar/2$ . Here  $\Delta x$  and  $\Delta p$  stand for uncertainty in position and momentum, respectively, and  $\hbar$  is the reduced Planck constant.

According to the arguments of EPR, either quantum mechanics is an incomplete theory or else it allows for simultaneous reality of the conjugate quantities position  $x$  and momentum  $p$  of a quantum system. However, Popper considered a somewhat different situation: he considered the implications of the HUP on the position and momentum of the second particle when in both cases the measurement on the first particle is made on the position degree of freedom. In this situation, one must consider both position–position and position–momentum correlations. Popper thought that this type of inferred measurement could lead to a violation of the uncertainty principle. Indeed, in the same manner in which

the standard uncertainty principle has a lower bound, the uncertainty principle relevant to Popper's thought experiment is [14]

$$\Delta(x_B|x_A)\Delta(p_B|x_A) \geq \hbar/2. \quad (1)$$

This equation should be interpreted as the uncertainty product for particle  $B$  given a measurement of the position of particle  $A$ . Below, we show that this inequality can be saturated for the case of a pure two-photon entangled state that exhibits strong EPR correlations. We note that the proper treatment of state reduction, which leads to these conditional probabilities, can be quite subtle. This issue has been analyzed in detail by Khrennikov [19], especially in connection with the EPR proposal.

In our implementation of Popper's experiment, the entangled particles are generated through spontaneous parametric downconversion (SPDC), the theory of which is well-known [20–22]. Here, we consider only the horizontal distribution along  $x$ , which is perpendicular to the real slit, and sum our two-dimensional data over the  $y$  coordinate.

At the output of the crystal, the two-photon mode function takes the form [20, 21]

$$\Psi(x_B, x_A) = N \exp\left(-\frac{(x_A + x_B)^2}{4\sigma_p^2}\right) \exp\left(-\frac{(x_A - x_B)^2}{4\sigma_q^2}\right), \quad (2)$$

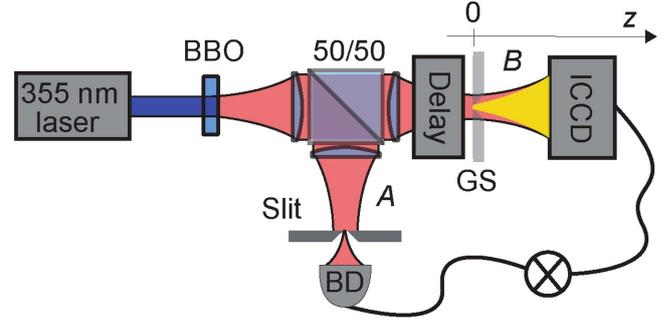
where  $N = (\pi \sigma_p \sigma_q)^{-1/2}$  is a normalization constant,  $\sigma_p$  is the  $1/e^2$  width of the intensity of the collimated Gaussian-distributed pump, and  $\sigma_q$  is the width of the position correlations, which is a function of the length of the crystal (see appendix A for more details). Upon detection of a photon in arm A at position  $x_A = 0$ , the conditional state of photon B takes the form of a Gaussian distribution:

$$|\Psi(x_B|x_A = 0)|^2 \approx N' \exp(-x_B^2/(2\sigma_q^2)), \quad (3)$$

where  $N'$  is a normalization constant. The standard deviation (SD) of the associated probability distribution is equal to  $\Delta(x_B|x_A = 0) = \sigma_q$ . We used the fact that the pump width  $\sigma_p$  ( $\approx 450 \mu\text{m}$ ) is much greater than that of the mode width of the SPDC position correlations  $\sigma_q$  ( $\approx 10 \mu\text{m}$ ), i.e.  $\sigma_p \gg \sigma_q$ . The conditioned mode function of photon B can be treated as a pure state (see equation (3)) and undergoes diffraction like a pure state. Using the Fourier transform of the position wave function of photon B, we find the conditional state of photon B in momentum space as

$$|\Psi(p_B|x_A = 0)|^2 \approx N'' \exp(-2p_B^2\sigma_q^2/\hbar^2), \quad (4)$$

where  $p_B$  is the momentum of photon B, and  $N''$  is a normalization constant, respectively. The SD of the probability distribution  $|\Psi(p_B|x_A = 0)|^2$  is equal to  $\Delta(p_B|x_A = 0) = \hbar/(2\sigma_q)$ . This distribution is identical to that of the unconditioned Gaussian distribution, and thus, for the case of the entangled state (2), the quantum formalism predicts that the second scenario of figure 1 will occur. Finally, taking the product of the conditioned SDs associated with equations (3)



**Figure 2.** Schematic of our implementations of Popper's experiment. Entangled photon pairs are generated through spontaneous parametric downconversion in a  $\beta$ -barium borate (BBO) crystal using type-I phase matching. The real slit on side A is placed in an image plane of the crystal, and a large-area (bucket) detector (BD) is placed after the slit; this detector registers those photons that pass through the slit and thereby determines their position with high accuracy. Photon B goes through an image-preserving delay line, and then is captured by an intensified charge coupled device (ICCD) camera that is triggered by the photons that pass through the real slit on side A (see appendix B for more details).

and (4), we obtain

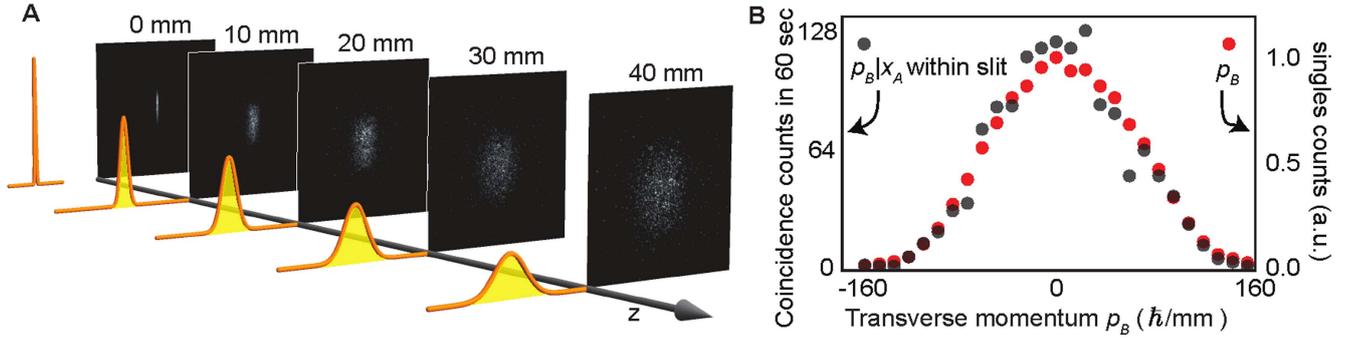
$$\Delta(x_B|x_A = 0)\Delta(p_B|x_A = 0) = \hbar/2, \quad (5)$$

a result that is consistent with the uncertainty principle in the form of equation (1). This result is to be expected because equations (3) and (4) are conjugate quantities related by Fourier transforms. It follows that for the initial state (2), the presence of a slit in A does not lead to increased diffractive spreading of photon B as the slit width is decreased. Therefore, quantum mechanics leads to the prediction of the second scenario shown in figure 1.

### 3. Experimental results

Figure 2 shows the schematic representation of our implemented Popper's thought experiment. Generated photon pairs are split out by means of a 50/50 non-polarizing beam splitter (PBS). They are sent into a  $10 \mu\text{m}$  wide slit that located at the image plane of the downconversion crystal in arm A and an image-preserving delay line in arm B, respectively. Photons that pass through the slit in arm A are registered by a bucket detector. This detector registers those photons that pass through the slit and thereby determines their position with high accuracy. We make measurements on a photon in arm B that are conditioned on the detection of a photon in arm A.

A triggered intensified charge coupled device (ICCD) camera placed in arm B in the image plane of the real slit and thus also in the image plane of the ghost slit is used to measure in coincidence the width of the ghost slit (see appendix B for more details). In figure 3, the frame at  $z = 0 \text{ mm}$  shows an image of the ghost slit. The width of this image, expressed in terms of its SD, is  $\Delta(x_B|x_A \text{ within slit}) = (19 \pm 1) \mu\text{m}$ . The predicted width of the image is given by the convolution of the transmission function of the real slit ( $10 \mu\text{m}$  wide) with the point-spread function of the imaging system, which is



**Figure 3.** Experimental observation of ghost diffraction from a slit. (A) Coincidence images from the ICCD showing ghost diffraction from a slit upon propagation. Images were recorded between the near-field of the BBO crystal  $z = 0$  mm and the far-field of the crystal  $z \rightarrow \infty$  (not shown). Here we show five images at 10 mm increments from the ghost slit. (B) Comparison between the ghost diffraction (conditioned  $p_B|x_A$  within slit) and singles (unconditioned  $p_B$ ) in the far-field ( $z \rightarrow \infty$ ). The black points show data for the conditional case, measured in coincidence; the red points show data for the unconditional case. Note that the conditional and unconditional distribution of photon  $B$  are essentially identical showing that placing a slit in arm  $A$  does not influence the momentum distribution of photon  $B$ .

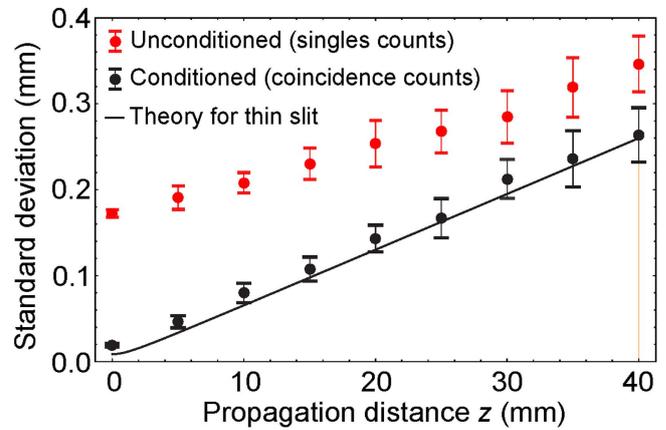
given by the mode function  $|\Psi(x_B, x_A)|^2$  taken to be a function of  $x_B$ . This calculated width is about  $12 \mu\text{m}$ . The measured  $19 \mu\text{m}$  width of the ghost slit is greater than the calculated width of  $12 \mu\text{m}$  because of non-ideal position correlations of the two photons, which we believe arise from misalignment or aberrations in our imaging system. Nonetheless, to within a factor of two, we confirm Popper’s expectation that the position of photon  $B$  is measured with ‘approximately the same precision’ as that of photon  $A$ . Of course, a complication arises from the fact that width of an image is often specified in terms of its SD. For a uniform transmission distribution, e.g. for a slit of width  $d$ , this SD is equal  $d/\sqrt{12}$ . However, in our analysis we take the physical width of the slit to be the measure of the position of photon  $A$ .

Using a lens with a focal length of 75 mm, we next place the ICCD camera in the far-field (Fourier transform plane) of the ghost slit and record the distributions of the singles and coincidence counts, as shown in figure 3(B). The SDs of these distributions are respectively  $\Delta(p_B)/\hbar = (0.048 \pm 0.001) \mu\text{m}^{-1}$  and  $\Delta(p_B|x_A \text{ within slit})/\hbar = (0.046 \pm 0.006) \mu\text{m}^{-1}$ . The widths of the two distributions are very similar. We conclude from these results that the detection of photon  $A$  after the real slit does not affect the far-field distribution of photon  $B$ . To express this thought more quantitatively, we note that for these data we find an uncertainty product of

$$\Delta(p_B|x_A \text{ within slit})\Delta(x_B|x_A \text{ within slit}) = (0.87 \pm 0.16)\hbar. \quad (6)$$

This product is greater than  $\hbar/2$  and is thus consistent with the uncertainty principle. The measured uncertainty product does not saturate the uncertainty principle of equation (5). As mentioned before, we attribute this increased uncertainty to aberrations and misalignment along the optical axis.

In figure 4, we compare the measured width of the conditional diffraction from the ghost slit (black points) to the theoretical width of a propagating Gaussian beam (black curve):  $a(z) = a(0)\sqrt{1 + (z/z_R)^2}$ , where  $z_R$  is the Rayleigh



**Figure 4.** Measured transverse width of particle  $B$ ’s field as a function of distance from a ghost slit. The black points show data for the conditional widths; the red points show data for the unconditional widths. The black line is a fit to the conditioned data using Gaussian beam propagation. The error bars correspond to a 95% confidence region of the width of a Gaussian distribution fitted to the recorded transverse distributions.

range associated with the conditioned mode-function of photon  $B$ . The theory fits very well for all points other than the point at  $z = 0$ , and we attribute this difference also to a slight misalignment along the optical axis. We also show the width of the singles counts on side  $B$  (red points) as a function of propagation distance. The width of the singles and the coincidence counts asymptotically approach one another upon propagation, and, as confirmed by figure 3(B), match perfectly at the far-field of the ghost slit.

#### 4. Discussion

The results from our experiment confirm that the second scenario outlined in figure 1 prevails. This outcome is precisely what Popper expected on the basis of the argument that

it conforms to the principle of causality. Popper was correct that the events in the near-field of the real slit on side *A* cannot influence the outcome of events in the far field of side *B* [23]. We find that the presence or absence of the real slit in arm *A* leads to no difference between the conditional and unconditional distributions on side *B* in the far field. We can express this thought somewhat differently as follows. The rate of singles counts measured at any position on side *B* is the same whether or not a position measurement is made on side *A*. In contrast, for coincidence measurements the distribution on side *B* is narrower than the singles distribution in the near-field of the ghost slit but has the same width in the far-field. Thus, the presence or absence of the slit on side *A* does not affect the photon distribution in singles or in coincidence in the far field for side *B*. We have noted that compelling theoretical treatments argue in favor of the second scenario, which is causal. This conclusion is in contrast to what Popper thought based on his understanding of the Copenhagen interpretation of quantum mechanics, which would preclude scenario 2. One possible flaw in Popper’s reasoning of the physical situation is that he assumed that the source of particle pairs was both perfectly correlated in transverse momentum and had a very small transverse extent [12]. Ghirardi *et al* argue that the laws of quantum mechanics prohibit the simultaneity of these two properties [16]. Thus, if the position of the source is known very well, then according to [16] no correlations in momentum are possible. We also conclude that Popper was simply mistaken in believing that the Copenhagen interpretation leads to the predictions of scenario 1.

In the context of Popper’s experiment, the relevant uncertainty relation involves uncertainties in the position and the momentum of photon *B* conditioned on the position of photon of *A* [14]. Quantum theory predicts that this product is equal to  $\hbar/2$  and saturates the HUP. In our experiment, we obtained a value of  $0.87\hbar$  for this product because of imperfections in our laboratory setup.

## 5. Conclusions

In conclusion, we have implemented Popper’s proposed experiment with entangled photon pairs generated through SPDC. We find that our results conform with the predictions of scenario 2 of figure 1, the scenario that conforms with the predictions of standard quantum mechanics and that respects causality. Our measurements of the diffraction from the ghost image of a narrow slit closely matches the predictions of the corresponding model, derived from the theory of SPDC. Our results are consistent both with the quantum formalism, i.e. the HUP and with causality (the no-signaling principle) and confirm that there is no spread in the momentum distribution of one entangled photon due to presence of the slit for the other photon. We find that the conditional HUP,  $\Delta(x_B|x_A = 0)\Delta(p_B|x_A = 0) \geq \hbar/2$ , is validated theoretically and experimentally.

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## Appendix A. Theory

In our implementation of Popper’s experiment with entangled photons, we used SPDC to make a ghost image of a narrow slit and observe the subsequent correlated diffraction. In the degenerate SPDC process, one pump photon of energy  $\hbar\omega$  turns into two spatially entangled photons of energy  $\hbar\omega/2$ , where  $\omega$  is the angular frequency of the optical field. These correlations have been used to perform ghost imaging [24–26] and, more recently, entangled field imaging [27].

Under the assumption that walk-off inside the crystal is negligible, the two-photon SPDC mode function takes a simple form. As a function of the transverse wavevectors of photons *A* and *B*,  $\mathbf{k}_A$  and  $\mathbf{k}_B$  with  $\mathbf{k} = k_x\hat{x} + k_y\hat{y}$ , the two-photon mode function is given by

$$\Phi_Q(\mathbf{k}_A, \mathbf{k}_B) = N \tilde{E}(\mathbf{k}_A + \mathbf{k}_B) \tilde{F}\left(\frac{\mathbf{k}_A - \mathbf{k}_B}{2}\right), \quad (\text{A.1})$$

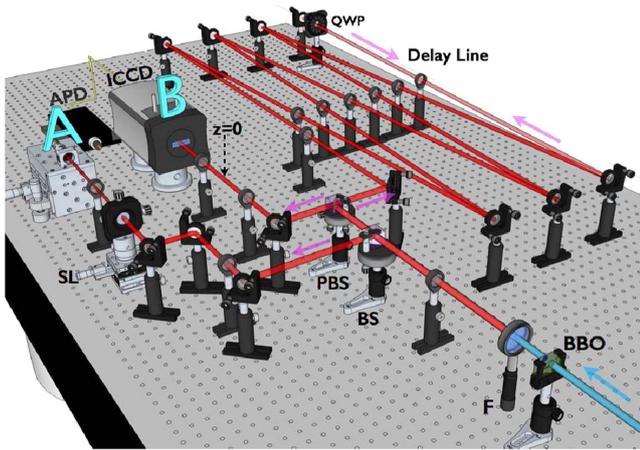
where  $N$  is a normalization constant,  $\tilde{E}(\mathbf{k})$  is the Gaussian-distributed angular spectrum of the pump laser, and  $\tilde{F}(\mathbf{k})$  is the phase-matching function [21]. In the paraxial wave approximation, the phase-matching function is of the form

$$\tilde{F}(\mathbf{k}) = \text{sinc}(\varphi + L|\mathbf{k}|^2/k_p), \quad (\text{A.2})$$

where  $\varphi$  is the phase mismatch parameter,  $L$  is the thickness of the crystal and  $k_p$  is the wavevector of the pump inside the crystal. Since  $|\varphi| \approx 0$  in our experiment, we work in the regime where the phase-matching function can be approximated by a Gaussian distribution [20, 28]. Further, we perform a Fourier transform to express the joint state in position space:

$$\Psi_Q(\mathbf{r}_B, \mathbf{r}_A) = N' \exp\left(-\frac{|\mathbf{r}_A + \mathbf{r}_B|^2}{4\sigma_p^2}\right) \exp\left(-\frac{|\mathbf{r}_A - \mathbf{r}_B|^2}{4\sigma_q^2}\right), \quad (\text{A.3})$$

where  $\mathbf{r} = x\hat{x} + y\hat{y}$ ,  $\sigma_p = 450 \mu\text{m}$  is the  $1/e^2$  width of the pump beam and  $\sigma_q = \sqrt{L/2k_p} = 9.2 \mu\text{m}$ . The two-photon mode function is now separable in its vertical and horizontal



**Figure A1.** Schematic of our implementation of Popper's experiment. Entangled photon pairs are generated through SPDC at a  $\beta$ -BBO crystal. The pump beam is filtered out by a high-pass filter (F). The two photons of a given pair are separated by a 50/50 non-polarizing beam-splitter (BS). The mode of photon A is imaged with unit magnification to a  $10\ \mu\text{m}$ -slit and then collected by a multimode optical fiber with a  $200\ \mu\text{m}$  core diameter that is connected to a single-photon detector that triggers the ICCD camera. Photon B, initially vertically polarized, is reflected by the polarizing beam-splitter (PBS) towards an image-preserving delay line. Photon B hits the final mirror of the delay line and makes its way back with a horizontal polarization because of its two passes in the quarter-wave plate (QWP). Photon B then traverses the PBS and reaches the ICCD camera, which records photon B in the far-field of the BBO crystal. The BBO crystal is imaged with a magnification of one to the plane indicated by  $z = 0\ \text{mm}$ .

components. We can thus integrate over the vertical degree of freedom and consider the joint mode from equation (2).

Since we have  $\sigma_p \gg \sigma_q$ , the term that governs the strength of the near-field correlations is  $\exp[-(x_A + x_B)^2 / (4\sigma_p^2)]$  while the term that mostly determines the mode of the singles is  $\exp[-(x_A - x_B)^2 / (4\sigma_p^2)]$ , where  $\sigma_p$  will be defined later (it is a function of  $\sigma_q$ ). Indeed, if we assume perfect position correlations,  $\delta(x_A - x_B)$ , the intensity profile of the singles is exactly given by the term  $\exp[-(x_A + x_B)^2 / (4\sigma_p^2)]$ .

## Appendix B. Experimental setup

In the experiment a frequency-tripled quasi CW mode-locked Nd-YAG laser (not shown) with a repetition rate of 100 MHz and average output power of  $P = 150\ \text{mW}$  at  $\lambda = 355\ \text{nm}$  is used to pump a 3 mm thick  $\beta$ -BBO crystal cut for type-I degenerate phase matching, see figure A1. The generated photon pairs (photon A and photon B) via SPDC are split out by means of a 50/50 non-PBS and sent into an actual slit (path A) and a delay line (path B), respectively. Photon A is imaged on a  $10\ \mu\text{m}$  slit (SL) via a 4f-system with a unit magnification, and then coupled into a  $200\ \mu\text{m}$  core diameter multimode optical fiber. The coupled photons are detected by a silicon avalanche photodiode (APD) and used to trigger an ICCD camera. On the other side, photon B is sent to a delay line, which is made of a PBS, three 4f-system and a QWP. Photon B, then, after a certain delay time, inquired by response time of

APD and ICCD camera, is imaged on the ICCD camera, which was positioned (i) near-field and (ii) far-field of the BBO crystal.

The spatial modes A and B are imaged to the plane of the real slit and the ghost slit, respectively, with a unit magnification, such that the exponential term on the right of equation (2) determines the width of the correlations. Indeed, when photon A is detected at position  $x_A = 0$ , the ghost slit takes the form of a Gaussian distribution.

We put a large aperture in the path of B (near the far-field of the crystal), such that the phase-matching function can be approximated closely by a simple gaussian beam. The phase-matching function then becomes  $\tilde{F}(\mathbf{k}) = \exp(-k_p^2 / (4\sigma_q^2))$  with  $\sigma_q^2 = \sigma_q^2 + r_a^2$ , where  $r_a$  is related to the phase mismatch parameter  $\varphi$  and, mostly, to the size of the aperture;  $r_a$  needs to be measured.

A ghost image necessarily has finite resolution either limited by the numerical aperture of the lenses used or by the strength of the correlations. Here, the bottleneck is the latter.

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