Proposal for an interference experiment to test the applicability of quantum theory to event-based processes

M. Richter\textsuperscript{1}, K. Michielsen\textsuperscript{1}, Th. Lippert\textsuperscript{1}, B. Barbara\textsuperscript{2}, S. Miyashita\textsuperscript{3} and H. De Raedt\textsuperscript{4}

\textsuperscript{1} Institute for Advanced Simulation, J"ulich Supercomputing Centre, Research Centre J"ulich, D-52425 J"ulich, Germany, EU
\textsuperscript{2} Institut N"eel, CNRS, 25 Ave. des Martyrs, BP 166, 38 042 Grenoble Cedex 09, France, EU
\textsuperscript{3} Department of Physics, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-Ku, Tokyo 113-8656, Japan and CREST, JST, 4-1-8 Honcho Kawaguchi, Saitama 332-0012, Japan
\textsuperscript{4} Department of Applied Physics, Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, NL-9747 AG Groningen, The Netherlands, EU

E-mail: k.michielsen@fz-juelich.de and h.a.de.raedt@rug.nl

\textbf{Abstract.} We propose a single-particle Mach-Zehnder interferometer experiment in which the path length of one arm can change before each passage of a particle through the interferometer. We demonstrate that this experiment can be used to determine to which extent quantum theory provides a description of the observed detection events that goes beyond statistical averages or to refute a corpuscular model (De Raedt H., De Raedt K. and Michielsen K., Europhys. Lett., 69 (2005) 861) for this experiment. The proposed experiment also serves as a new type of test for the concept of particle-wave duality.
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1. Introduction

Consider the schematic diagram (Fig. 1) of the Mach-Zehnder interferometer (MZI) experiment in which the length of one of the arms can be varied by a control parameter $x$. According to Maxwell’s theory, carrying out the experiment with a fixed value of $x$ and with a coherent monochromatic light source $S$ with frequency $\omega$ gives for the normalized intensities $I_0$ and $I_1$, recorded by the detectors $D_0$ and $D_1$, [1]

$$I_0 = \sin^2 \frac{\omega(T_0 - T_1(x))}{2} = \sin^2 \frac{\phi_0 - \phi_1(x)}{2},$$

$$I_1 = \cos^2 \frac{\omega(T_0 - T_1(x))}{2} = \cos^2 \frac{\phi_0 - \phi_1(x)}{2},$$

where $\phi_0 = \omega T_0$ and $\phi_1(x) = \omega T_1(x)$. Equations (1) and (2) show that the signal on the detectors is modulated by the difference between the time-of-flights $T_0$ and $T_1(x)$ in the lower and upper arm of the interferometer, respectively, or in other words by the phase difference $\phi_0 - \phi_1(x)$.

Replacing the light source by a single-photon source yields the same interference patterns Eqs. (1) and (2). As a single photon can only be detected once, each photon emitted by the source is detected by either detector $D_0$ or detector $D_1$ but never by both [2]. In the single-photon case, each detection event adds to the total count of either $D_0$ or (exclusive) $D_1$. Experiments [2] show that after many single-photons have been detected, the normalized frequency distributions of detection events recorded by the

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**Figure 1.** Schematic diagram of the proposed Mach-Zehnder interferometer (MZI) experiment. S: Light source; BS: 50-50 beam splitter; $T_0$: Fixed time-of-flight; $T_1(x)$: Variable time-of-flight controlled by the external variable $x$; $D_0$, $D_1$: Ideal detectors. In single photon experiments $x$ may change before each passage of a photon through the MZI but not faster. For simplicity we consider experiments in which $x$ takes the values $-1$ and $+1$ only. The recorded dataset for $N$ detection events is given by \{ $x_i, d_{0,i}, d_{1,i}$ | $i = 1, \ldots, N$ \} where $d_{k,i} = 1$ if detector $D_k$, $k = 0, 1$ fired and $d_{k,i} = 0$ otherwise. Note that the value of the experimental setting parameter $x$ is not measured but is known and certain at each moment in time.
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detectors $D_0$ and $D_1$ fit well to the interference patterns Eqs. (1) and (2), respectively, and hence depend on the difference between the time-of-flights of the photons passing through the MZI. Moreover, the experiment in which the second beam splitter has been removed shows that detectors $D_0$ and $D_1$ never register a detection event simultaneously and therefore demonstrate the particle character of the single photons [2]. If we want to use classical concepts to interpret the results of these single-photon experiments, we must use a particle picture for the experiment in which the second beam splitter has been removed and a wave picture to explain the observation of interference when the second beam splitter is left in place. A question that is then often posed is whether photons are particles or waves, because classically they cannot be both.

Quantum theory (QT) resolves this dissension by introducing the notion of particle-wave duality and complementarity, in the sense that different experiments are required to observe the particle or wave property of photons but that they possess both. However, interference experiments with single electrons [3] convincingly show that the interference pattern is built up, one-by-one, by the arrival of individual electrons, disposing of the idea that complementarity is relevant to the description of this single particle interference experiment. The quantum theoretical concepts of particle-wave duality and complementarity are therefore not only counterintuitive, they might be simply superfluous. Somehow we lack knowledge of the underlying physical processes that give rise to an interference pattern built up by single particles arriving one-by-one at a detector.

In this Letter we present a description of a single-photon interference experiment that can be intuitively understood in terms of particles only, that can be experimentally tested and that for some experimental conditions gives results that differ from those predicted by QT. We consider the MZI experiment (see Fig. 1) in which we allow the variable $x$ to change for each particle that travels through the MZI (not faster). Note that the value of $x$ is not measured but is always known and certain. We demonstrate that this experiment may be used to determine the conditions under which QT fails to describe single particle detection events or to refute the event-based corpuscular model (EBCM) proposed in Ref. [4] which has shown to reproduce the statistical predictions of QT for the MZI experiment.

For simplicity, but not out of necessity, we only consider experiments in which $x$ takes the values +1 and -1 and for which $\phi_1(x = +1) \text{mod} 2\pi = 0$ and $\phi_1(x = -1) \text{mod} 2\pi = -\pi/2$. We consider a systematic and a random procedure to change $x$ such that $x = +1$ and $x = -1$ occur with the same frequency. In the systematic procedure we replace $x$ by $-x$ after the single photon source has emitted $K$ photons. For $K = 1$ this procedure leads to an alternating sequence of $x$-values. In the random procedure we use a random number to decide whether or not we replace $x$ by $-x$ after the single photon source has emitted $K$ photons. In both procedures we repeat this sequence so that the total number of photons emitted by the source equals $N$. Each click of the detector $D_0$ or $D_1$ is labeled by the current known and certain value of $x$. After the $N$ photons have been sent and all clicks have been registered, we count
the number of detection events on \( D_0 \) and \( D_1 \) for each value of \( x \) separately, yielding the numbers \( N_0(x) \) and \( N_1(x) \). Finally, we define the normalized frequencies to detect photons by \( F_0(x) = N_0(x)/(N_0(x) + N_1(x)) \) and \( F_1(x) = N_1(x)/(N_0(x) + N_1(x)) \). Note that we made no assumption about the detection efficiency (see below).

2. Quantum theory

According to wave theory [1], the amplitudes \((b_0(x), b_1(x))\) of the photons in the output modes 0 and 1 of the MZI with a fixed value of \( x \) are given by

\[
\begin{pmatrix}
  b_0(x) \\
  b_1(x)
\end{pmatrix} = i e^{i \varphi'(x)} \begin{pmatrix}
  \sin \varphi(x) & \cos \varphi(x) \\
  \cos \varphi(x) & -\sin \varphi(x)
\end{pmatrix} \begin{pmatrix}
  a_0 \\
  a_1
\end{pmatrix},
\]

(3)

where the amplitudes of the photons in the input modes 0 or 1 are represented by \( a_0 \) and \( a_1 \), \( \varphi(x) = (\phi_0 - \phi_1(x))/2 \) and \( \varphi'(x) = (\phi_0 + \phi_1(x))/2 \). For the case at hand \( a_1 = 0 \) and without loss of generality, we may take \( a_0 = 1 \).

The Copenhagen interpretation (CI) maintains that the wave function provides a complete and exhaustive description of the experiment with an individual particle [5, 6]. Therefore, grouping all detection events of the individual photons according to the corresponding values of \( x \) at the time of their passage through the MZI, the CI predicts that the probability distributions to register detection events at \( D_0 \) are given by

\[
I_0(x = +1) = |b_0(x)|^2 = \frac{1}{2} \sin^2 \frac{\phi_0}{2},
\]

(4)

\[
I_0(x = -1) = |b_1(x)|^2 = \frac{1}{2} \sin^2 \frac{\phi_0 + \pi/2}{2},
\]

(5)

where the prefactor 1/2 comes from the fact that we have assumed that \( x = +1 \) and \( x = -1 \) occur with the same frequency. Note that Eqs. (4) and (5) are independent of the procedure that changes \( x \).

The statistical interpretation (SI) maintains to provide a description of the statistical properties of an ensemble of similarly prepared systems only [6]. For the case at hand, the output state of the MZI is represented by the density matrix \( \hat{\rho} = \sum_{y = \pm 1} \rho(y) \), where

\[
\rho(y) = \begin{pmatrix}
  b_0(y)b_0^*(y) & b_0^*(y)b_1(y) \\
  b_1^*(y)b_0(y) & b_1^*(y)b_1(y)
\end{pmatrix}.
\]

(6)

The probability to register detection events in output channel 0 of the MZI, is given by

\[
I_0(x) = \sum_{y = \pm 1} \text{Tr} \rho(y) \hat{I}_0(x, y)
\]

where

\[
\hat{I}_0(x, y) = \begin{pmatrix}
  1 & 0 \\
  0 & 0
\end{pmatrix} \delta_{x,y},
\]

(7)

also yielding Eqs. (4), (5). Note that the quantum theoretical description of the experiment would be different if \( x \) is not considered to be a parameter of the experimental setting which is known and certain at every moment in time, but is part of the measurement outcome and considered to be unknown until measured.
Both the CI and the SI predict the same outcome for the proposed experiment, as it should be because the mathematical formalism of QT itself is free of interpretation.

Taken literally, one may think that even for one particle the CI predicts an interference pattern but this contradicts the experiment in which only one click, either of $D_0$ or of $D_1$, is registered. This apparent contradiction is a manifestation of the quantum measurement paradox: Although QT provides a recipe to compute the frequencies for observing events, it does not describe individual events, such as the arrival of a single electron at a particular position on the screen or the detection of a single photon by a particular detector [5]. The SI tactically avoids the measurement paradox by being silent on the issue of individual events.

It is generally accepted that a description on the level of individual events necessarily entails a specification of the process of measurement itself [5, 6]. In view of the measurement paradox, extending the mathematical framework of QT to include the observation of individual events seems impossible [5]. To avoid, instead of solve, this fundamental problem it is convenient to postulate that in principle, it is impossible to give an explanation that goes beyond the description in terms of frequency distributions to observe events. Although in practice, it may be impossible to give such an explanation, the present state of knowledge does not support the premise that it is impossible in principle. Moreover, as there exist event-based, corpuscular, locally causal models [4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19] (to be discussed in the next section) that reproduce the statistical results of QT, this postulate is untenable.

If QT correctly describes the experiment with varying but always known $x$, we expect to find for the observed frequencies at detector $D_0$

$$F_0(x = +1) \approx I_0(x = +1) = \frac{1}{2} \sin^2 \frac{\phi_0}{2},$$

$$F_0(x = -1) \approx I_0(x = -1) = \frac{1}{2} \sin^2 \frac{\phi_0 + \pi/2}{2},$$

(see Eqs. (4) and (5)) independent of the procedure for changing $x$ being systematic or random and independent of the number of emitted photons $K$ per change of $x$. In fact, QT predicts that the result is completely independent of the sequence of $x$. Note that this cannot be true in general: One could consider $x = +1, \ldots, +1, -1$ so that there is only one event for $x = -1$. In this case the observed frequency does not correspond to an interference pattern although QT predicts that also for this case $I_0(x = -1) = \sin^2(\phi_0 + \pi/2)/2$.

It is precisely this feature, the fact that QT predicts results that are independent of the sequence of $x$-values, that we propose to test experimentally. Note that there is no indication, let alone a kind of proof that QT, being a theory that makes predictions about statistics only, correctly describes experiments in which the procedure for preparing the state of the photon (i.e. the state before the photon is being detected) can change with each photon.
3. Corpuscular model for interference

To dismiss the dogma that there is no explanation that goes beyond the quantum theoretical description in terms of averages over many events, one has to provide a rational, logically consistent explanation of the experimental facts in terms of causal, event-like processes. In general, such processes are formulated in terms of discrete events to which one can always associate “particles”.

It has been demonstrated [4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19] that it is possible to construct event-by-event processes that reproduce the results of QT for single-photon beam-splitter and MZI experiments [2], Einstein-Podolsky-Rosen-Bohm experiments with photons [20, 21, 22], Wheeler’s delayed-choice experiment with single photons [23], quantum eraser experiments with photons [24], double-slit and two-beam single-photon interference, quantum cryptography protocols, universal quantum computation [9, 8], and the Hanbury Brown-Twiss experiments [25, 26]. This particle-like approach seems rather universal in that the same algorithms can be reused, without modification, to reproduce the statistical results of QT for many different quantum optics experiments. Interactive demonstration programs, including source codes, are available for download [27, 28, 29].

As it is an established fact that the frequency distributions produced by these event-based, corpuscular models cannot be distinguished from those predicted by QT [4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19], the key question is whether an experiment can be performed that can refute at least one of these event-based models.

The MZI experiment with the control variable $x$, depicted in Fig. 1 provides an instance of such an experiment. A detailed account of the EBCM that we will use is described in Ref. [4]. As we will adopt this model without any modification except for the trivial addition of the control variable $x$, there is no need to repeat its description here.

For fixed $x$, the results of the EBCM are in excellent agreement with Eqs. (4) and (5), that is with QT. Unlike QT, which predicts Eqs. (4) and (5) to be independent of details of the sequence of $x$-values, the EBCM of a MZI, described in Ref. [4], makes specific predictions for the frequencies observed at detector $D_0$ that depend on the procedure to change $x$ and on the number of particles $K$ that pass through the MZI while $x$ is constant. By construction [4], the EBCM produces detection events with frequency $I_0(x)$ if the particle travels along the upper arm of the MZI. However, if the particle takes the lower arm and $x$ changes before the particle is detected, the detection event will be associated with the “wrong” value of $x$. From the description of the EBCM, it follows directly that the observed frequencies at detector $D_0$ are given by [4]

$$\bar{I}_0(x = +1) = 1 - \frac{E}{2} \sin^2 \frac{\phi_0 + \pi/2}{2} + \frac{E}{2} \sin^2 \frac{\phi_0}{2},$$

$$\bar{I}_0(x = -1) = 1 - \frac{E}{2} \sin^2 \frac{\phi_0 + \pi/2}{2} + \frac{E}{2} \sin^2 \frac{\phi_0}{2},$$

where $0 \leq E \leq 1$ is the rate of making wrong associations. Numerical experiments show
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Figure 2. Results for the normalized frequency $F_0(x = +1)$ as obtained from simulations employing fully classical, locally causal, corpuscular models \[4\] for all the components of the MZI experiment shown in Fig. 1. For each value of $\phi_0$, $N = 10^6$ input events were generated and the model parameter $\alpha = 0.99$ (see Ref. \[4\]) for all simulation data shown in this paper. Dotted line: Prediction of QT, see Eq. (4); Bullets: Simulation data for $x = +1, \ldots, +1$, corresponding to $K = N$; Solid triangles: Simulation data for the case that $x$ changes sign ($x = +1, -1, +1, \ldots$) with each photon emitted, corresponding to the systematic procedure for changing $x$ with $K = 1$. The solid line through the data points is given by Eq. (10) with $E = 0.333$. Open triangles: Simulation data for the case that $x$ changes sign with every ten photons emitted, corresponding to the systematic procedure for changing $x$ with $K = 10$. The solid line through the data points is given by Eq. (10) with $E = 0.100$.

Figure 3. Same as Fig. 2 except that $x$ is changed according to the random procedure with $K = 1$ and that the solid line through the triangles is given by Eq. (10) with $E = 1/(2 + 2K) = 1/4$.

that $E \approx 1/(2 + 2K)$ provides a simple, fairly accurate approximation of the rate if the random procedure to change $x$ is used.

In Fig. 2 we present results for the normalized frequency $F_0(x = +1)$ as a function
of $\phi \in [0, 2\pi]$ for the experiment in which $x$ is changed according to the systematic procedure with $K = 1, 10, N$, where the number of particles $N = 10^6$. From these data, we conclude that

(i) For $K = 1$ (solid triangles), that is when $x$ alternates for each photon entering the MZI, the EBCM predicts significant deviations from the results of QT (solid line, Eq. (1)). There is excellent agreement between the simulation data and Eq. (10) (solid line through the solid triangles) with $E = 0.333$.

(ii) For $K = 10$ (open triangles), that is when $x$ alternates for each ten photons entering the MZI, the difference between the data generated by the EBCM and the results of QT (dashed line, Eq. (1)) becomes rather small. There is excellent agreement between the simulation data and Eq. (10) with $E = 0.100$ (solid line through the open triangles).

(iii) For $K = N$ (bullets), that is for fixed $x$, the EBCM reproduces the statistical results of QT (solid line, Eq. (1)). Note that in this case, $E = 0$.

Simulations (data not shown) confirm the intuitively evident expectation that as the number of photons $K$ between changes of $x$ increases, the data produced by the EBCM converge to the prediction of QT Eq. (4). This also follows directly from the analytic expression Eq. (10) because $E \to 0$ if $K \to N$, as is clear from the excellent agreement between simulation data for $K = N$ (bullets) and QT (solid line).

In Fig. 3, we present simulation data for the case in which $x$ is changed according to the random procedure with $K = 1$. Qualitatively, the results are the same as when $x$ changes systematically (see Fig. 2). However, the rate $E$ is different. For $K = 1$, $E = 0.333$ for the systematic procedure and $E = 0.25$ for the random procedure In the case of the random procedure, simulation data for various $K$ (not shown) are rather accurately represented by Eq. (10) with $E = 1/(2 + 2K)$. Although the quantitative differences between the normalized frequencies $F_0(x = +1)$ computed for the EBCM and QT are larger if the systematic procedure for changing $x$ is used instead of the random procedure, the data obtained with the random procedure for changing $x$ might be more useful for comparing with the outcomes of laboratory experiments, as discussed in the next section.

4. Discussion

As already mentioned, QT gives an accurate description of the statistics of an experiment in which the procedure of preparing the particles before they are detected does not change during the experiment. As the experiment that we propose can be performed such that this condition is not satisfied, it is of interest to perform this experiment and verify that it agrees with the quantum theoretical prediction. To head of possible misunderstandings: If the proposed experiment shows deviations from the quantum theoretical prediction, this finding does not refute QT as such. It merely provides experimental evidence that QT cannot be applied to statistical experiments in which
the procedure of preparing the particles before they are detected changes in the course of the experiment.

The EBCM [4] operates on a level that QT has nothing to say about and it can easily cope with a preparation procedure that changes with each particle \((K = 1)\). As this model reproduces the results of QT under the condition that the preparation procedure is fixed \((K \text{ and } N \text{ large}) \) [4], conventional quantum optics experiments cannot refute the EBCM. However, as Figs. 2 and 3 show, the proposed MZI experiment with a phase difference alternating between \(\phi_0\) and \(\phi_0 + \pi/2\) (see Fig. 2) or with a phase difference randomly taking the values \(\phi_0\) and \(\phi_0 + \pi/2\) (see Fig. 3), can discriminate between QT and the EBCM [4], at least in principle.

To appreciate the subtleties that are involved, it is necessary to recognize that there are experiments in which the preparation procedure is not fixed in time and for which we do not expect the predictions of QT to deviate from the experimental results, independent of the pace at which the preparation procedure changes.

As a first example, consider Wheeler’s delayed choice experiment with single-photons [23]. In this experiment, the random choice between the open and closed configuration of the interferometer with each passage of a photon does not affect the agreement of the experimental observations with predictions of QT [23]. The reason is that a passage of a photon in the open configuration has no causal effect on the passage of a photon in the closed configuration. As the event-based corpuscular approach reproduces the results of QT for Wheeler’s delayed choice experiment [17] this experiment [23] cannot be used to refute this approach.

As a second example, consider again the MZI experiment of Fig. 1 but replace the time-of-flight control unit by a device that blocks the photon if \(x = -1\) and lets the photon pass if \(x = +1\). Performing the event-based corpuscular simulation for this experiment (data not shown) shows that the same EBCM as the one employed in this paper reproduces the results of QT, independent of the rate at which \(x\) changes signs. Thus, although the presence of the second beam splitter at all times is a necessary condition, it is not sufficient for the MZI experiment to discriminate between the predictions of the EBCM and those of QT.

The experiment that we propose in this paper is fundamentally different from e.g. Wheeler’s delayed choice experiment with photons in that the second beam splitter, being the physical cause for interference to occur at all, is present at all times and that, in a corpuscular picture, the physical state of a beam splitter may change with each photon passing through it.

5. Realization

We now address some issues that become relevant when the proposed experiment is performed in practice. Essential for the proposed experiment to refute the EBCM or to show the aforementioned limitation of QT is that the rate at which photons are emitted is lower than the rate at which the time-of-flight in the upper arm of the interferometer
(see Fig. 1) is being switched between two different values. Assuming that there is some uncertainty about whether or not the source emits a photon with each applied pulse and assuming that the frequency of these pulses is incommensurate with the frequency with which $x$ changes, to describe the experiment we may, as first approximation, use the model in which $x$ is changed according to the random procedure with $K = 1$. We emphasize that for the proposed experiment to be successful, the time-of-flight of a photon from the source to detector should be much less than the time between changes of $x$ such that there is a one-to-one correspondence between the value of $x$ and the photon (independent of whether it is actually detected). Equally essential is that the procedure to change the time-of-flight of the particles traveling in the upper arm of the MZI does not alter the particle’s direction towards the second beam splitter.

Refuting the EBCM [4] by an experiment will be a real challenge. The central question is how to collect and analyze the experimental data. To see this, consider the expression for the normalized frequency of events on output channel 0. In general, that is for $\phi_1(x = +1) \mod 2\pi = 0$ and $\phi_1(x = -1) \mod 2\pi = \delta$, the EBCM predicts

$$I_0(x = +1) = \frac{1 - E}{2} \sin^2 \frac{\phi_0}{2} + \frac{E}{2} \sin^2 \frac{\phi_0 - \delta}{2} = \frac{1 - \Delta \cos(\phi_0 - \psi)}{4},$$

(12)

where $\psi = \arctan(E \sin \delta / (1 - E + E \cos \delta))$ and $\Delta = (2E^2 - 2E + 1 + 2E(1 - E') \cos \delta)^{1/2}$. From Eq. (12) it follows directly that a least-square fit of a sinusoidal function to the data produced by the EBCM must lead to the conclusion that, independent of the values of $E$ and $\delta$, this data is described by QT, albeit with a reduced visibility ($|\Delta| < 1$). Thus, employing this naive procedure to analyze data of single-photon interference experiments cannot lead to a refutation of the EBCM. However, the proposed experiment may be carried out such that there is a chance that the EBCM [4] can be refuted.

Specifically, for each pulse applied to the single photon source (labeled by the subscript $i$), the experiment should collect the triples $\{x_i, d_{0,i}, d_{1,i}\}$ for $i = 1, \ldots, N, N + 1, \ldots, 2N, 2N + 1, \ldots, 4N$ where $d_{k,i} = 1$ if detector $D_k, k = 0, 1$ fired (within a properly chosen time window) and $d_{k,i} = 0$ otherwise. Note that recording $d_{0,i}$ and $d_{1,i}$ is required for ensuring the single-particle character of the experiment [2]. For each value of $\phi_0$, in the first stage (the first $N$ pulses), $x = +1$ is kept fixed while in the second stage of $N$ pulses $x = -1$ kept fixed. Finally, in the third stage of $2N$ pulses $x$ should change much faster than the pulse rate at which single photons are emitted. Assuming that the MZI is stable enough to allow a sufficient amount of triples to be collected, by comparing the number of detection counts of the first and second stage with the one of the third stage, we should or should not (if QT applies) see a significant change in the detection counts (see Figs. 2 or 3) for some values of $\phi_0$. Changing the order of the stages and repeating the experiment should provide some information about the reproducibility of the experimental data.

It will not have escaped the reader that we have not made any assumption about the efficiency of detecting the photons. Although for photons this efficiency may be quite
low [30], this should not affect the conclusions that can be drawn from the experimental data as long as this data is not contaminated by a significant fraction of dark counts. The dark counts may be reduced by using a source emitting pairs of photons in opposite directions and by correlating the detection times of the photons detected in the MZI with those detected on the other side of the source.

Although our proposal has been formulated in terms of single-photon experiments, it should be evident that, at least in theory, one can replace “photon” by “neutron” without altering the conclusions.

We hope that our proposal will stimulate experimenters to take up the challenge to determine the extent to which QT provides a description of event-based processes that goes beyond statistical averages or to refute one of the EBCMs [4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19] that, without invoking any concept of QT, reproduce the statistical results of QT.

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