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Event-by-event simulation of a quantum delayed-choice experiment

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ABSTRACT

The quantum delayed-choice experiment of Tang et al. (2012) is simulated on the level of individual events without making reference to concepts of quantum theory or without solving a wave equation. The simulation results are in excellent agreement with the quantum theoretical predictions of this experiment. The implication of the work presented in the present paper is that the experiment of Tang et al. can be explained in terms of cause-and-effect processes in an event-by-event manner.

1. Introduction

In a Mach–Zehnder interferometer (MZI) experiment one can choose between measuring the wave-like and the particle-like properties of photons [1,2]. The wave-like behavior (interference) is observed using the MZI set-up depicted in Fig. 1. The particle-like behavior (no interference) is observed by removing the second beam splitter BS_2. The first and second set-ups are henceforth referred to as a closed and an open MZI, respectively. Hence, the observation of wave-like or particle-like behavior depends on the choice of considering a closed or open MZI, respectively, in accordance with the idea of wave–particle duality. One might therefore ask whether a *normal-choice* and a *delayed-choice* experiment would yield different observations. That is, is there a difference in the experimental results if the set-up is already predetermined to test either the particle or wave nature of a photon (normal-choice) versus a set-up that makes this choice while the photon has already passed BS_1 but not yet BS_2 (delayed-choice)? Experiments have been carried out to measure this difference and there appears to be no difference between these two situations [3–5].

Recently, a new type of delayed-choice experiment has been suggested in which BS_2 is a quantum beam splitter assumed to be in a superposition of being present and absent [6]. This so-called *quantum delayed-choice* experiment has been realized experimentally using NMR interferometry on ensembles of molecules [7,8] and using single-photon quantum optics techniques [9–11]. These experiments demonstrate that in one single experiment, particle- or wave-like behavior can be tuned continuously, which is interpreted as an indication that the complementarity principle needs refinement [9–11].

From the viewpoint of quantum theory, the central issue is how it can be that experiments such as these delayed-choice experiments yield definite answers [12]. As the concept of an event is not a part of quantum theory proper, quantum theory simply cannot address the question "why there are events?" [13]. One can get around this conundrum by constructing a description entirely in terms of events, ultimately related to human experience, and the cause-and-effect relations among them. Such an event-based description obviously yields definite answers and if it reproduces the statistical results of experiments, it also provides a description of the experiments on a level of detail that is not covered by quantum theory.

Essentially, the event-based approach is based on the fact that all that can be said about nature is constrained by the data a measurement apparatus can, at least in principle, produce. As Wheeler put it: "[…] every particle, every field of force, even the space-time continuum itself—derives its function, its meaning, its very existence entirely […] from the apparatus-elicited answers to yes-or-no questions […]" [14]. The event-based approach is to be viewed in this light; an event-based simulation does not necessarily mimic what actually

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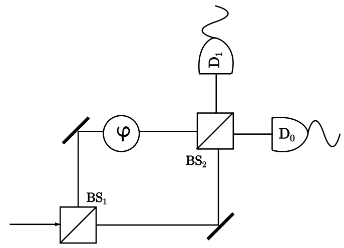

Fig. 1. Schematic of a Mach–Zehnder interferometer. BS_1 and BS_2: beam splitters; φ: phase shifter; D_0 and D_1: detectors.

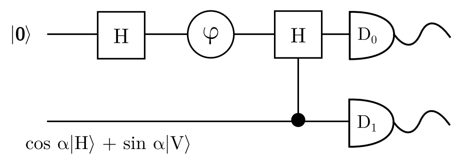

Fig. 2. Quantum network of a quantum delayed-choice experiment. The first Hadamard (H) gate, corresponding to BS_1 in Fig. 1, is followed by a phase shifter φ and a second Hadamard gate, corresponding to BS_2 in Fig. 1. BS_2 can be set in a superposition of being present and absent by controlling the state of an ancilla. The photon and ancilla are detected by detectors D_0 and D_1, respectively, after the control operation on the second Hadamard gate. The photon and the ancilla are prepared in the state $|0\rangle$ and $\cos\alpha|H\rangle + \sin\alpha|V\rangle$, respectively.

happens in nature: it only produces sets of data (e.g. detector clicks) that can be compared to experiments in the laboratory through a chronological, causally-connected sequence of events. From this it directly follows that such an event-based approach has no bearing on the interpretation, applicability, validity or possible extensions of quantum theory.

For many interference and entanglement phenomena observed in quantum-optics and single-neutron experiments, such an event-based description has already been constructed [15–19]. The event-based simulation approach reproduces the statistical distributions of quantum theory by modeling physical phenomena as a chronological sequence of events, by neither solving a wave equation nor by sampling a distribution as in a Monte-Carlo simulation. Hereby events can be actions of an experimenter, particle emissions by a source, signal generations by a detector, interactions of a particle with a material and so on [17–19].

In the context of the work presented in this paper we mention that the event-by-event simulations have successfully been used to reproduce the results of the single-photon MZI experiment of Grangier et al. [1] (see Refs. [15,17]), the single-photon Wheeler delayed choice experiment by Jacques et al. [5,20] (see Refs. [17,21]) and the proposal for a quantum delayed-choice experiment [6] in terms of quantum gates [22], thereby employing the event-based method to simulate a universal quantum computer [23].

In this paper we demonstrate that results of the single-photon quantum delayed-choice experiment [10], a so-called quantum-controlled experiment because conceptually it involves controlling the presence/absence of a beam splitter by a qubit, can be reproduced by an event-based model that is a one-to-one copy of the actual experiment. The event-based simulation is Einstein-local and causal and does not rely on concepts of quantum theory. Therefore, in contrast to the general belief [24], both the quantum delayed-choice experiment [6] and Wheeler's delayed choice experiment can be explained entirely in terms of particle-like objects traveling one-by-one through the experimental set-up and generating clicks of a detector, thereby providing a mystery-free explanation of the experimental results.

2. Quantum theoretical description

Conceptually, the quantum delayed-choice experiment [10] is conveniently represented by a quantum-gate network, see Fig. 2. The first Hadamard operation, equivalent to the operation of a beam splitter BS_1, transforms the initial state $|0\rangle$ into the superposition $(|0\rangle + |1\rangle)/\sqrt{2}$, where $|0\rangle$ and $|1\rangle$ represent the optical paths (spatial modes) of the photon in the MZI. The phase shifter φ changes the relative phase between the optical paths. This results in the spatial state $|\text{space}\rangle = (|0\rangle + e^{i\varphi}|1\rangle)/\sqrt{2}$ of the photon. In the quantum delayed-choice experiment beam splitter BS_2 is controlled by an ancilla and can be in a superposition of being present and absent. In the experimental realization [10] the polarization state $|\text{pol}\rangle$ of the photon is taken to be the ancilla. If the photon is horizontally polarized ($|\text{pol}\rangle = |H\rangle$), then the photon can pass BS_2 (closed MZI) and if it is vertically polarized ($|\text{pol}\rangle = |V\rangle$), then it cannot pass BS_2 (open MZI). Hence, BS_2 is a polarization controlled beam splitter.

If the ancilla is prepared in the state $|\text{pol}\rangle = \cos\alpha|H\rangle + \sin\alpha|V\rangle$, where α denotes the polarization angle of the photon, then the total state of the photon before arriving at BS_2 reads $|\psi\rangle = |\text{space}\rangle|\text{pol}\rangle = (|0\rangle + e^{i\varphi}|1\rangle)(\cos\alpha|H\rangle + \sin\alpha|V\rangle)/\sqrt{2}$. After the operation of the second Hadamard gate (BS_2) this state becomes $|\psi\rangle = \sin\alpha|\text{particle}\rangle|V\rangle + \cos\alpha|\text{wave}\rangle|H\rangle$, where $|\text{particle}\rangle = (|0\rangle + e^{i\varphi}|1\rangle)/\sqrt{2}$ and $|\text{wave}\rangle = e^{i\varphi/2}\left(e^{i\delta_0}\cos\frac{\varphi}{2}|0\rangle - ie^{i\delta_1}\sin\frac{\varphi}{2}|1\rangle\right)$ describes wave-like behavior. The extra phase shifts δ_0 and δ_1 originate from the specific experimental set-up [10].

There are now two ways to proceed. First, considering the polarization states $|H\rangle$ and $|V\rangle$ in $|\psi\rangle$ as a label for the particle and wave properties, a classical mixture of these properties is described by the mixed state $\rho = \sin^2\alpha|\text{particle}\rangle\langle\text{particle}| + \cos^2\alpha|\text{wave}\rangle\langle\text{wave}|$. This corresponds to Wheeler's delayed choice experiment [5,20]. In this case the normalized intensities at detectors D_0 and D_1 are given by

$$I_0 = (1 + \cos^2\alpha\cos\varphi)/2, \tag{1}$$

and

$$I_1 = (1 - \cos^2\alpha\cos\varphi)/2, \tag{2}$$