Another Counterexample to Markov Causation from Quantum Mechanics: Single Photon Experiments and the Mach-Zehnder Interferometer[*]

Nina Retzlaff

Abstract

The theory of causal Bayes nets [15, 19] is, from an empirical point of view, currently one of the most promising approaches to causation on the market. There are, however, counterexamples to its core axiom, the causal Markov condition. Probably the most serious of these counterexamples are EPR/B experiments in quantum mechanics (cf. [13, 23]). However, these are also the only counterexamples yet known from the quantum realm. One might therefore wonder whether they are the only phenomena in the quantum realm that create problems for causal Bayes nets. The aim of this paper is to demonstrate that not only the phenomenon of quantum correlations in EPR/B experiments create problems for causal Bayes nets, but also the temporal evolution of quantum systems, which is described as dualistic by quantum mechanics. For this purpose, it is shown that single photon experiments in a Mach-Zehnder interferometer (MZI) violate the causal Markov condition as well. It is then argued, however, that the Markov violation does not occur under the de Broglie-Bohm interpretation of Bohmian mechanics.

Keywords: *Mach-Zehnder interferometer, causality, causal Bayes nets, (global) causal Markov condition, screening off, quantum mechanics, Bohmian mechanics*

0 Introduction

The theory of causal Bayes nets [15, 19] seems, from an empirical point of view, to be the most promising approach to causation currently on the market. It is not only a powerful tool for formulating and testing causal hypotheses, but also for inferring causal structure from empirical

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data. Moreover, the theory of causal Bayes nets does not—contrary to classical philosophical theories such as Lewis [12], Reichenbach [16], Suppes [20], etc.—require an explicit definition of causation. Rather, like many successful empirical scientific theories, it connects theoretical causal notions to empirical data by means of several axioms. These axioms can be justified by an inference to the best explanation of certain statistical phenomena. In addition, the conjunction of these axioms does provably have empirical content [7, 18]. Thus, not only certain models of the theory, but the theory as a whole can be empirically tested.

However, there seem to be problems with the theory of causal Bayes nets as a general theory of causation. There are counterexamples to the theory's core axiom, the causal Markov condition, from the macro as well as from the micro realm. One of the most prominent counterexamples is Nancy Cartwright's chemical factory [4, 5]. This is a fictional example in which a chemical factory produces a target chemical substance with probability 0.8. This target substance can, however, only be produced together with a pollutant as a byproduct. Thus, by implying a dependence between the product and the byproduct, the chemical factory does not screen off the two effects (i.e., the target substance and the pollutant) from each other. It follows that the causal Markov condition, which has as a consequence that common causes screen off their effects (if no other causal connections among them are around), is violated. But a violation of the causal Markov condition would attack its basic metaphysical assumption, namely that stable dependencies do not occur randomly, but are produced by the system's underlying structure. It is shown in [18] that structure, as characterized by the causal Markov condition and another core condition of the theory (which is not part of this paper), can be justified as ontologically real by an inference to the best explanation. It is therefore not surprising that before questioning the causal Markov condition, one questions the causal models violating it. Thus, most of the proposals to solve the problems with counterexamples to Markov causation[1] assume that there are details missing in the causal models like causal connections, latent common causes, or that the variables themselves are not properly chosen (see, e.g. [9, p. 563]). Regarding the problem of common causes which do not screen off their effects, all of these solutions take for granted that the true causal structure, which has in one or another way been misrepresented in the models, is deterministic. If this were true, the violation of the causal Markov condition would vanish. However, exceptional cases are EPR/B counterexamples, which are typically assumed to be of an indeterministic nature. EPR/B experiments demonstrate the characteristic behavior of entanglement. An entangled system (e.g. entangled photons or electrons) is defined as a system whose entangled quantum state cannot be factored as a product of the quantum states of its local subsystems. This means that if a source emits an entangled pair of quantum objects toward two observers who can perform measurements on the physical property in which the quantum objects are entangled (e.g. polarization or spin), then not only the quantum state of that entangled system, but also a measurement on one of the entangled pair is associated with the outcome of the other one. A local measurement on a subsystem seems to affect the total quantum state of the whole system, doing so immediately and independent of the distance between the subsystems. For this reason, EPR/B experiments seem to pose the most serious threat to the causal Markov condition. However, no other clear counterexamples from the quantum realm are yet known. So, could EPR/B counterexamples be considered some kind of quantum mechanical curiosity? In this paper, I argue that the quantum realm (described by quantum mechanics) features at least one other counterexample to Markov causation: single photon experiments in a Mach-Zehnder interferometer (MZI). I also argue that this counterexample no longer occurs under Bohmian mechanics, whose ontological interpretation is a deterministic one.[2] Thus, the problem with MZI experiments shows that the causal Markov condition might be intertwined with ontological interpretations.

An MZI is an optical device to analyze interference phenomena. Such interference phenomena can be observed in experiments with light beams, which demonstrate the wave- like behavior of light[3]. Waves are expanded in space and can occupy many places at the same time. But it is also possible to construct a similar device which could be used on particles (point-like masses). Particles have the property of occupying only one single place at a time. Thus, they would not result in the occurrence of interference patterns. Because of these different properties of waves and particles, experiments with light beams lead to different results than experiments with particles. However, under certain circumstances, single photon experiments in an MZI show the same result as light beams and, under other circumstances, the same result as particles. Thus, it is generally concluded that single photons sometimes behave like waves and sometimes like particles. Because, as I will show, only single photon experiments in an MZI create problems for the causal Bayes nets theory and not the experiments with 'classical' systems, I conclude that the apparent dualistic behavior of single photons in an MZI is a real counterexample to Markov causation in the quantum realm.

This paper is structured as follows: In section 1 (MZI experiments), I introduce the MZI and describe the results of the MZI experiments with light beams, particles, and single photons. In section 2 (Two different interpretations of the behavior of quantum systems), I discuss two possible interpretations of these experimental results. In section 3 (Causal Bayes nets), I first introduce the causal Bayes net framework. I then use this framework to model each of the three experiments (light beams, particles, and single photons). It will be demonstrated that the causal model representing the single photon experiment violates the causal Markov condition. In section 4 (Intertwining of the causal Markov condition and ontological interpretations), I argue that whether or not single photons violate the causal Markov condition in fact depends on the ontological interpretation of quantum phenomena. I then show how, depending on one's preferred interpretation, different strategies can be chosen to avoid Markov violations. I conclude in section 5.

1 MZI experiments: classical systems versus quantum systems

In classical physics, all properties of classical systems[4] are well defined and the related behaviors can be observed simultaneously. Classical systems can be disjunctively distinguished in systems that exhibit wave-like behavior and systems that exhibit particle-like behavior. While waves are expanded in space and can occupy many places at the same time, particles are more local. They can only occupy one single place at a time. In the case of quantum systems, depending on the circumstances, these systems behave analog to waves or to particles. As a result of the wave property of being expanded in space, experiments with waves show interference phenomena, while experiments with particles do not. Thus, experiments with quantum systems that show interference phenomena support the view that quantum systems exhibit wave-like properties. On the other side, experiments with quantum systems that show the same result as experiments with particles lead to the conclusion that quantum systems exhibit particle-like properties, which means, that they are point-like. However, it seems that quantum systems exhibit both, wave-like and particle-like behavior. This has already been demonstrated by a multitude of experiments. Depending on different setups in such experiments with quantum systems, one can observe either the experimental result of wave-like or particle-like behavior.

In this section I first describe the results of MZI experiments with light beams, particles, and single photons to be able to apply the framework of causal Bayes nets theory to each of the three experiments in the next sections. Secondly, I demonstrate what is meant by the (apparent) dualistic behavior of quantum systems in an MZI. For that purpose, I compare the results with those of MZI experiments with light beams (which demonstrate the properties of waves) and such experiments with particles.

An MZI consists of two 50/50 beam splitters (BS1, BS2), two mirrors (M1, M2), and two detectors (D1, D2) (see figure 1.1).

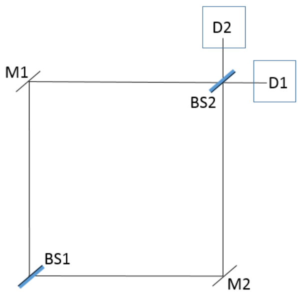

Figure 1.1: Mach-Zehnder interferometer (MZI).

Light beams in the MZI: In the experiment with light beams (see figure 1.2), a light beam coming from left first hits BS1 and is split into two subbeams, A and B. 50% of the original light beam is reflected towards mirror M1 (subbeam A), and 50% is transmitted to mirror M2 (subbeam B). The subbeams are then reflected by mirrors M1 and M2 in such a way that they both hit the second beam splitter BS2. There, both subbeams, A and B, are split again into two subbeams A1 and A2 and B1 and B2, respectively. The two resulting subbeams A2 and B1 hit detector D1, and the other two subbeams A1 and B2 cancel each other out on their way to detector D2. As a result only D1 responds, while D2 does not [14, pp. 73-74].

This result can be explained by the interference phenomena at BS2: The beam splitters used here are asymmetrically constructed. They consist of a piece of glass, where a metallic layer is applied to one side of the glass. On the side of the metallic layer, the reflected (but not the

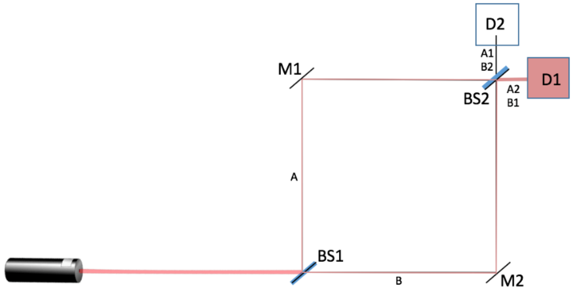

Figure 1.2: MZI with light beams.

transmitted) subbeam has a phase shift by π (for further explanation see, for example, [22, p. 125]). In such a phase shift, the wave is reversed. This means that, for example, a wave maximum would be transformed to a wave minimum during a phase shift. When a subbeam hits a mirror, then there is also a phase shift by π. So, the transmitted subbeam A2 and the reflected subbeam B1 both have a total phase shift of 2π. Because of this, the two subbeams A2 and B1 have the same phase and thus interfere constructively (see figure 1.3).

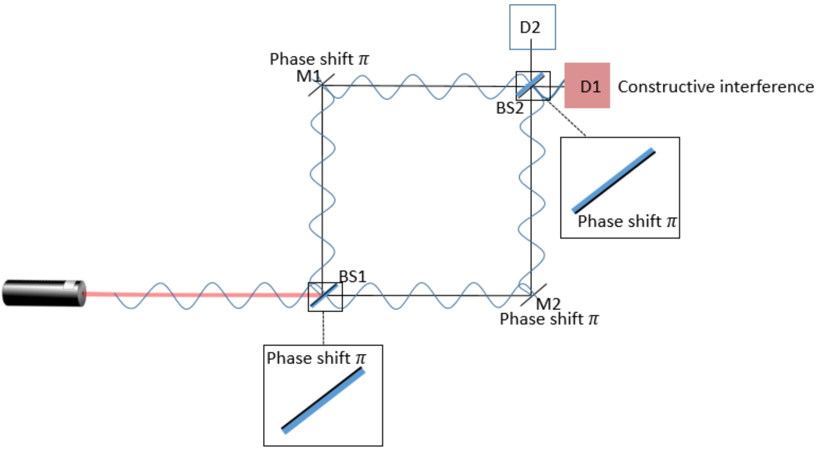

Figure 1.3: MZI with light beams. Constructive interference of subbeams A2 and B1 between BS2 and D1.

The other two subbeams A1 and B2 have a phase difference of π. Hence, they interfere destructively at BS2 and thus no signal will be measured at D2 (see figure 1.4).

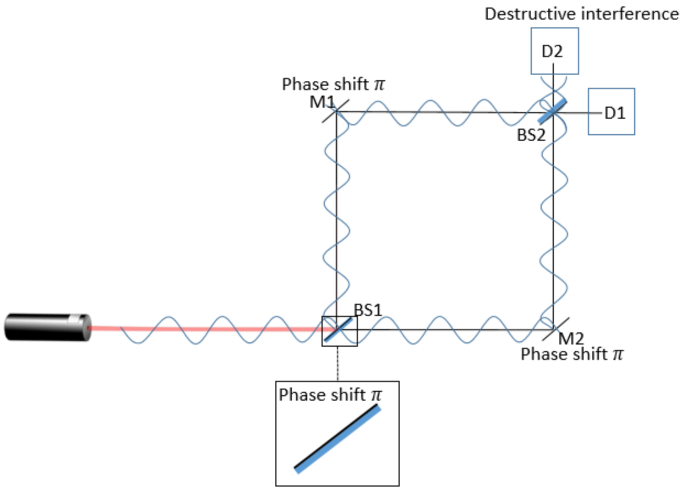

Figure 1.4: MZI with light beams. Destructive interference of subbeams A1 and B2 between BS2 and D2.

The wave nature of light also becomes obvious when we remove beam splitter BS2 from the experimental setup (see figure 1.5). In that case, subbeams A and B would not split further at BS2 and hence there would be no interference. Thus, subbeam A would hit D1 and subbeam B would hit D2. In that case, both detectors would respond.

Particles in the MZI: When using particles, the device has to be modified a bit. Both beam splitters are replaced by other components that formally have the same function as the original beam splitters (cf. [14, p. 75]). The difference is that they do not split beams of light, but either reflect (with probability 0.5) or transmit (with probability 0.5) particles. For reasons of simplicity, I will also refer to these devices by the term beam splitter in the remainder of this paper. In contrast to the experiment with light beams, here it is possible that not only D1, but also D2 responds as well. While light beams are split into two subbeams by the beam splitters, and thus, coexist at different spatial regions (i.e., they travel along the two pathways BS1—M1—BS2 and BS1—M2—BS2) at

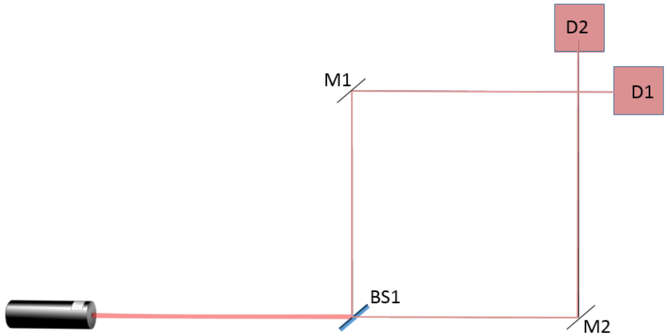

Figure 1.5: MZI without the second beam splitter BS2 and with light beams. Both detectors respond.

the same time, particles are either reflected or transmitted. They can only be at one place at a time, and hence, they can only be on one of the pathways, BS1—M1—BS2, or BS1—M2—BS2. Therefore, particles have exactly two possibilities to reach D2, either they are reflected or they are transmitted at both BS1 and BS2. Because both (reflection and transmission) have a probability of 0.5, a classical particle reaches D2 with the probability product which is 0.25 on the reflection pathway. Likewise for the transmission pathway. Thus, the particle ends up at D2 with probability 0.5. For the same reasons, the particle also ends up at D1 with probability 0.5. Thus, in the experiment with particles, both detectors D1 and D2 respond with the same probability 0.5. Due to the fact that particles cannot take more than one way at the same time, only one detector responds. Also in an experimental setup in which we remove beam splitter BS2, the particle nature is preserved: While in the experiment with light beams both detectors D1 and D2 respond, either D1 or D2 (but not both) would respond when using particles.

Single photons in the MZI: As we have seen above, the results of MZI experiments with light beams are different from those with particles. If only D1 responds, then we would explain the result by wave properties. If, on the other hand, either D1 or D2 (but not both) responds, then we would explain the result by particle properties. Interestingly, in case of a single quantum system like a photon, we can produce the differing results by modifying the experimental setup. When using single photons in the original setup, only D1 responds, which seems to show a wave nature of photons (cf. [14, p. 76]). If, however, we remove the beam splitter BS2, then either D1 or D2 (but not both) responds, i.e., we can observe the result of particle-like behavior (cf. [14, p. 330]).

In summary, depending on the setup, MZI experiments with quantum systems show the same results as MZI experiments with light beams or particles. So, it looks like quantum systems exhibit both behaviors: The wave-like behavior, which suggests the splitting at BS1 of a single quantum system, and thus, leads to the phenomenon of self-interference at BS2 and the particle-like behavior, which suggests that the photon has a point-like location and can only move along one of the pathways BS1—M1—BS2 or BS1—M2—BS2.

2 Two different interpretations of the behavior of quantum systems

So far, there is still no general agreement on how to interpret the different results of sometimes particle-like and sometimes wave-like nature. It is mathematically possible, however, to encompass this and other quite astonishing phenomena, in the context of experimentation on elementary systems like photons or electrons, into a general theoretical framework. The most prominent theory for that is quantum mechanics.

According to the postulates of quantum mechanics, the state of a quantum mechanical system like a photon is completely specified at a given time by its state vector $|\psi\rangle$ in Hilbert space. The linear combination of state vectors is again a state vector, this mathematical fact captures the principle of superposition. A total state can therefore be described by a superposition of its eigenvectors, which correspond to the states that are obtained during a measurement[5]. While an isolated system (i.e. without interaction with the environment) can be described by this superposition, a measurement of a system can be described by a single eigenvector only. This result captures the apparent dualistic behavior and offers scope for divergent interpretations. However, by the postulates of quantum mechanics there are two time evolutions of a quantum mechanical system: An isolated system is described by a deterministic and reversible dynamic, the so-called Schrödinger equation, while the indeterministic and irreversible dynamic of a measurement is given by the so-called projection postulate. The Schrödinger equation states that the temporal development d/dt of an isolated system is determined by its

Hamiltonian H, which is associated with the total energy of the system:[6]

$$i\hbar\frac{d|\psi(t)\rangle}{dt} = H|\psi(t)\rangle$$

The quantity to be measured (observable) is described by a Hermitian[7] operator O, which acts on the state vector $|\psi(t)\rangle$. The resulting measurement of a physical quantity described by O, can only be one of the eigenvalues λ_i corresponding to O. The eigenvalue equation is

$$O|\psi_{i,j}\rangle = \lambda|\psi_{i,j}\rangle, i = 1, 2, \ldots; j = 1, 2, \ldots, g_i.$$

Here, g_i is the degree of degeneracy of the eigenvalue λ_i [14, p. 175]. If a physical quantity (described by O) of a quantum system correlated with the state $|\psi\rangle = \sum_i \sum_{j=1}^{g_i} c_{i,j}|\psi_{i,j}\rangle$ is measured, then, according to von Neumann's projection postulate, the state is reduced to the projection of $|\psi\rangle$ onto the eigenspace belonging to the measured eigenvalue λ_i, which corresponds to O [14, pp. 182-193]:

$$|\psi\rangle \to \frac{1}{\sqrt{\sum_{j=1}^{g_i} |c_{i,j}|^2}} \sum_{j=1}^{g_i} c_{i,j}|\psi_{i,j}\rangle$$

According to the Born rule the eigenvalue λ_i will be measured with the probability $|c_{i,1}|^2$, when the degree of degeneracy $g_i = 1$ of eigenvalue λ_i (cf. [6, p. 47]). Thus, the state vector of a measured system is an eigenvector associated with the measured eigenvalue. The transition from a superposition state to a single state is called collapse of the wave function (or state reduction).

As we can see, the apparent dualistic behavior of quantum systems, derived from the different experimental results, seems to be produced by the measurement of a certain quantity. In accordance with the postulates of quantum mechanics, a quantum system mathematically exhibits wave-like properties (Schrödinger equation) if a quantum system is in isolation; if it is measured, it exhibits particle-like properties (state reduction). The state reduction can be seen in MZI experiments when only one signal per photon enters one of the detectors.

Now, one might wonder whether the measurement reveals the behavior of quantum systems or whether we actually produce this behavior by measuring. According to a standard interpretation of quantum mechanics like the Copenhagen interpretation[8], a measurement of a physical quantity is associated with the properties of a physical system in the sense that an observer-induced collapse of the wave function becomes factual: The wave function changes from the possibilities (given by the Schrödinger equation) to a factum (given by the projection postulate). But can we, as experimenters, really determine whether single photons are wave-like or particle-like? The de Broglie-Bohm interpretation of Bohmian mechanics provides a negative answer. In the de Broglie-Bohm theory, the system of interest is not only described by the wave function, but also by a well-defined configuration of it. The de Broglie-Bohm interpretation makes a clear distinction between the wave function on the one side and the described system on the other. Ontologically speaking, the underlying intuitions of (non-relativistic[9]) Bohmian mechanics and classical mechanics are similar, one can think of a point-like entity with fixed properties, but the difference is in the described dynamics. According to the de Broglie-Bohm theory, the wave function, and not the particle, determines the dynamic development of the system. The wave function describes the possible trajectories of the described system, while the system corresponds to only one of these trajectories (cf. [6, pp. 178-186]).

I have presented here two different possibilities to interpret the special behavior of quantum systems: A standard interpretation of quantum mechanics like the Copenhagen interpretation and the de Broglie Bohm interpretation of Bohmian mechanics. Even though the underlying ontology of both theories is different, their mathematical description of quantum mechanical phenomena yields, in general, the same results. One might wonder if the different ontologies play a role. In the next section I provide a positive answer to that question. However, in order to do so, I introduce the basics of the theory of causal Bayes nets first and then discuss reconstructions of the MZI experiments with light beams, particles, and single photons within that framework. It will turn out that the MZI with single photons violates the causal Markov condition. However, I will argue that such a causal Markov violation using single photons shows up only in quantum mechanics, but not in Bohmian mechanics.

3 Causal Bayes nets: classical systems versus quantum systems

In the last section we saw that depending on the experimental setup, MZI experiments with single photons show the same results as either MZI experiments with light beams or MZI experiments with particles: If the second beam splitter BS2 is included in the experiment, then only detector D1 responds (like in the experiment with light beams). If BS2 is removed from the experimental setup, then either detector D1 or detector D2 responds (like in the experiment with particles).

In this section, we will see that this special behavior of single photons in an MZI (derived from the experimental results) creates problems for the theory of causal Bayes nets, which seems to be the most promising approach to causation currently on the market. MZI experiments with single photons violate the core axiom of the theory of causal Bayes nets, the causal Markov condition [15, 19]. The basic idea underlying the causal Markov condition is that probabilistic dependencies do not occur randomly, but are always due to (causal) structure (cf. [18]). Before we go into more detail, let me briefly introduce the basics of the causal Bayes net formalism.

The theory of causal Bayes nets [15, 19] connects causal structure to probabilistic (in)dependencies. A causal structure is represented by a causal graph G. A causal graph G is a pair $\langle V, E \rangle$, where V is a set of random variables and E is a set of directed edges $X_i \longrightarrow X_j$ (arrows) between variables in V. A random variable is a function $X : D \rightarrow \mathit{Val}(X)$ from a domain D of individuals to its value space $\mathit{Val}(X)$ and describes events or properties, while the arrows $X_i \longrightarrow X_j$ in E represent direct causal connections between two variables $X_i, X_j \in V$. If $X_i \longrightarrow X_j$, then X_i is a direct cause of X_j, while X_j is a direct effect of X_i. A chain of arrows of the form $X_i \longrightarrow \ldots \longrightarrow Z \longrightarrow \ldots \longrightarrow X_j$ connecting two variables $X_i, X_j \in V$ is called a directed path from X_i to X_j. In that case X_i is an indirect cause of X_j and X_j is an indirect effect of X_i. A variable Z (different from X_i and X_j) lying on a directed path from X_i to X_j is called an intermediate cause of X_i and X_j. A path of the form $X_i \longleftarrow \ldots \longleftarrow Z \longrightarrow \ldots \longrightarrow X_j$ is called a common cause path with Z as a common cause of X_i and X_j. A variable Z lying on a path connecting X_i and X_j that contains a subpath $Z_i \longrightarrow Z \longleftarrow Z_j$ is called a collider. Every chain of arrows connection two variables X_i and X_j in V is called a causal path between X_i and X_j. The strengths of the causal influences propagated over these causal connections are given by an associated probability distribution P. The probability distribution P over V maps all possible events described by variables in V to its probabilities in the interval $[0, 1]$. Two variables X_i and X_j are said to be conditionally independent given X_k if and only if $P(X_i|X_k) = P(X_i|X_j, X_k)$ holds for all X_i, X_j, and X_k values x_i, x_j, and x_k, respectively [15, p.11]. Dependence is defined as the negation of independence. We will represent the independency of two variables, X_i

and X_j, given X_k by $Indep(X_i, X_j|X_k)$; for dependency given X_k of the variables X_i and X_j we will write $Dep(X_i, X_j|X_k)$. A triple (V, E, P) is called a causal model. A causal model which satisfies the following condition, the causal Markov condition, is called a causal Bayes net. The causal Markov condition connects causal graphs (structures) to probability distributions and comes in two, for acyclic causal graphs[10] equivalent, versions: a local and a global one. In the following, I will always use the global version, which is also called the d-connection condition (cf. [18, p. 1084]):[11]

> **Definition 3.1 (global causal Markov condition):** A causal model (V, E, P) satisfies the global causal Markov condition (d-connection condition) if and only if it holds for all $X_i, X_j \in V$ and $U \subseteq V \setminus \{X_i, X_j\}$ that X_i and X_j are d-connected given U in G if they are probabilistically dependent conditional on U in P. $X_i, X_j \in V$ are d-connected given $U \subseteq V \setminus \{X_i, X_j\}$ if and only if there is a path π connecting X_i and X_j with no intermediate or common cause in U, while every collider on π is in U or has an effect in U.

The global causal Markov condition states that every (conditional) probabilistic dependence between two different variables implies a causal connection via a path connection them, i.e. as already mentioned, (conditional) probabilistic dependency is the result of the underlying causal structure. The causal Markov condition is basically a generalization of Reichenbach's common cause principle [16, p. 163]: If two events, A and B, are statistically dependent, but neither A causes B, nor B causes A, then there exists an event C, which is a common cause of A and B. Given the cause C, the events A and B are mutually independent.

Let us now build causal models for the three MZI experiments discussed in section 2. In particular, we will represent the MZI with light beams, particles, and single photons. As we saw in the last section, the special behavior of single photons in an MZI (derived from the experimental results) becomes obvious when we compare the results of the original experimental setup with the results of the setup after removing beam splitter BS2. Hence, beam splitter BS2 plays an essential role in making different behaviors visible. We represent the second beam splitter BS2 with a binary variable *BS2*. The two values of this variable are 'on' and 'off', where *BS2*=*on* means that the beam splitter is part of the experimental setup, while *BS2*=*off* means that the beam splitter BS2 has been removed. The dependence between the two detectors D1 and

D2 will turn out to be problematic for the (global) causal Markov condition. We represent the two detectors D1 and D2 with binary variables *D1* and *D2* with values 'yes' and 'no'. The values represent whether the detectors respond ('yes') or do not respond ('no'). To produce the phenomena of interest, we do not have to modify the other components, BS1, M1, and M2 of the MZI. We can assume these components to be fixed. In summary, our causal model of the MZI consists of the three variables

$$\begin{aligned} \mathit{BS2} &\text{ with value space } \mathit{Val}(\mathit{BS2})=\{\mathit{on},\ \mathit{off}\},\\ \mathit{D1} &\text{ with value space } \mathit{Val}(\mathit{D1})=\{\mathit{yes},\ \mathit{no}\},\\ \mathit{D2} &\text{ with value space } \mathit{Val}(\mathit{D2})=\{\mathit{yes},\ \mathit{no}\}. \end{aligned}$$

Light beams in the MZI: In the previous section we have seen that in the original experimental setup (with beam splitter BS2), detector D1 responds with probability 1, while detector D2 never does. We also have seen that both detectors respond with probability 1 if we remove the beam splitter BS2. Thus, the only probability that changes when going from context $BS2{=}on$ to $BS2{=}off$ is the conditional probability $P(D2|BS2)$: If $BS2{=}on$, then $D1{=}yes$ with probability 1 and $D2{=}yes$ with probability 0. If $BS2{=}off$, then $D1{=}yes$ and $D2{=}yes$, both with probability 1. This dependency between BS2 and D2 does not vanish by conditionalizing on D1: $Dep(BS2, D2|D1)$. Note that $Dep(BS2, D2)$ and $Dep(BS2, D2|D1)$ are the only dependencies among variables in $V = \{BS2, D1, D2\}$. Because causation is typically assumed to be forward directed in time (cf. [3, 16, 20]), with help of the (global) causal Markov condition we get the causal graph depicted in figure 3.1.

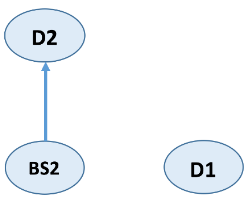

Figure 3.1: A causal graph representing the causal structure underlying the MZI with light beams.

Particles in the MZI: As we saw in the last section, both detectors D1 and D2 respond with probability 0.5 (but not together) in the original experimental setup (with BS2) as well as when we remove BS2. Thus, BS2 has no probabilistic influence on the detectors' responses: $Indep(BS2, D1)$, $Indep(BS2, D2)$. If (and only if) one detector responds, then the other does not. Thus, we have a probabilistic dependence between the two detectors: $Dep(D1, D2)$. This dependency between D1 and D2 does not vanish by conditionalizing on BS2: $Dep(D1, D2|BS2)$. Note that these are the only dependencies among variables in $V = \{BS2, D1, D2\}$. Because of this, and according to the (global) causal Markov condition, *D1* and *D2* have to be connected via a causal path. But this path cannot be a direct path connecting *D1* and *D2*, because both events are simultaneous: At the moment when one of the two detectors responds, one knows that the other does not. A direct causal influence between the two detectors would violate the principle of Einstein locality[12], because the influence would be spread faster than light. But how shall we represent this dependency?

One way to go is to look at whether some important information about the experiment is missing. Such missing information might be integrated as a hidden variable. Let us take a step back: What is the difference between the MZI experiment with light beams and the version that uses particles? In the experiment with particles, the beam splitters either reflect or transmit a particle with probability 0.5 respectively. Like in the case of a coin toss, if we had full knowledge of the system, then we could predict the outcome with certainty; we would know whether the coin lands heads or tails or whether the particle is reflected or transmitted. Thus, if we had full knowledge we could predict whether a particular particle would hit either D1 or D2: If both beam splitters reflect or transmit the particle, then D2 responds with probability 1. If one of both beam splitters reflects and the other transmits the particle, then D1 responds with probability 1. Thus, either D1 or D2 responds depending on the way that the particle takes. So, the way the particles take provides additional probabilistic information. One can represent the way of the particle by the binary variable *TP* with value space $Val(TP) = \{\textit{on the way to D1},\ \textit{on the way to D2}\}$. Thus, *TP* would be a common cause of D1 and *D2* that determines the values of both detectors $P(D1|TP), P(D2|TP) \in \{0, 1\}$. In addition, conditionalizing on *TP* would screen D1 and *D2* off each other: $Indep(D1, D2|TP)$. The causal graph by the (global) causal Markov condition is the one depicted in figure 3.2.

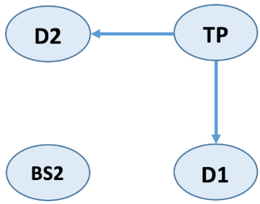

Figure 3.2: Causal graph representing the causal structure underlying the MZI with particles.

Single photons in the MZI: As we saw earlier, single photon experiments show, depending on whether the beam splitter BS2 is part of the experimental setup, the results of wave-like as well as particle-like behavior. If BS2 is part of the experiment, then we get the same result as with light beams: D1 responds (with probability 1), while D2 remains silent. If BS2 is not part of the experimental setup, then the result is the same as in the experiment with particles: each detector will respond with probability 0.5 and one of the two detectors respond if and only if the other does not. Thus, we get, like in the particle version of the experiment: $Dep(D1, D2)$. But since the probabilities of $D1$ and $D2$ change when conditionalizing on $BS2$, we also get the additional dependencies $Dep(BS2, D1)$ and $Dep(BS2, D2)$. Summarizing, we have the following dependencies: $Dep(D1, D2)$, $Dep(BS2, D1)$, and $Dep(BS2, D2)$. By the (global) causal Markov condition and the assumption that causation is always forward directed in time (cf. [3, 16, 20]), we get the causal graph depicted in figure 3.3.

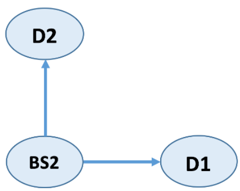

Figure 3.3: Causal graph representing the causal structure underlying the MZI with single photons.

The graph of the MZI experiment with single photons has the form of a common cause structure. One consequence of the (global) causal Markov condition is that common causes screen off their effects: $Indep(D1, D2|BS2)$. This implies that $P(D1 = yes|BS2 = no)$ has to be equal to $P(D1 = yes|BS2 = no, D2 = yes)$. But these conditional probabilities cannot be equal according to the description of the experiment above. According to this description, we get the conditional probabilities $P(D1 = yes|BS2 = no) = 0.5$ and $P(D1 = yes|BS2 = no, D2 = yes) = 0$. (The second conditional probability is derived from the fact that one of the detectors responds if and only if the other detector does not respond.) Thus, the screening off condition implied by the (global) causal Markov condition is violated.

Now one might assume that, like in the experiment with particles, relevant information about the way of the single photon is missing. But while a particle moves along one unique trajectory, i.e. it either passes a beam splitter or it does not, it is controversial what really happens in the quantum realm. Does a single photon itself have fixed, local properties, such as the local uniqueness of a particle (de Broglie-Bohm interpretation), or are the fixed, local properties generated by interactions with macroscopic systems (Copenhagen interpretation)? If single photons possess local uniqueness, then how can the dependence $Dep(BS2, D2)$ that reveals the system's wave-like behavior be explained? If single photons, on the other hand, do not have local uniqueness, then how can the property of being an elementary particle be integrated in the ontology of a single photon, which is described as being distributed through space until its local uniqueness is determined when reaching one of the two detectors? These are questions about how to interpret the wave function ψ (or state vector $|\psi\rangle$) of quantum systems. Unlike particles, quantum systems, as already mentioned in section 2, are described by a wave function ψ (or state vector $|\psi\rangle$). In the MZI, such a wave function ψ is split up by the first beam splitter BS1 (corresponding to an Operator T) in $T|\psi\rangle = (\sqrt{1/2}|\psi_{trans} - \sqrt{1/2}|\psi_{refl}\rangle)$,[13] where $|\psi_{trans}\rangle$ describes the transmitted part of the wave function and $|\psi_{refl}\rangle$ describes the reflected part (cf. [14, pp. 79-81]). Because both have the same probability of 1/2 of occurring, we take the pre-factor to be $\sqrt{1/2}$. In quantum mechanics, the superposition principle holds, because the state of a quantum system is described by a corresponding vector, which can be written as a linear combination of state vectors. While this is a valid mathematical description of what is going on, it does not answer the deeper ontological question of how to interpret it. In the next section we will see that different interpretations of the ontology of quantum systems, in particular the Copenhagen interpretation of quantum mechanics and the de Broglie-Bohm interpretation of Bohmian mechanics, provide different explanations of the dependency between the two detectors. In this section, we have reached our goal of showing that the problem of causal modeling the MZI is due to the contradictory apparent behavior of quantum systems.

4 Intertwining of the causal Markov condition and ontological interpretations

In this section, we will see that the dependency between the two detectors D1 and D2 only violates the (global) causal Markov condition if one endorses a collapse interpretation of quantum mechanics as is done within the Copenhagen interpretation. When subscribing to a particle-like ontology such as the (non-relativistic) de Broglie-Bohm interpretation, on the other hand, one can fully explain the dependency between the two detectors in accordance with the (global) Markov condition.

Collapse interpretations such as the Copenhagen interpretation describe the involved process of state reduction as indeterministic. Because of this, it is not possible to determine which way a single photon goes through the MZI. Thus, we cannot simply save the (global) causal Markov condition by adding another common cause variable (to the structure depicted in figure 3.3) that describes the way of the single photon as we have done in the MZI experiment with classical particles. However, as we have seen in section 2, we can use such a strategy within the de Broglie-Bohm interpretation of Bohmian mechanics (see figure 3.2).

Recall from section 2 that according to the (non-relativistic) de Broglie-Bohm interpretation, a single photon is not only described by a wave function ψ (like in quantum mechanics), but also by a configuration $Q(t)$, which defines the actual position of that photon at time t even without measurement. The de Broglie-Bohm interpretation clearly distinguishes between the wave function on the one side, and the described system on the other. While the wave function ψ describes the possible configurations of the system, (in non-relativistic Bohmian mechanic) one can ontologically conceive the system as a particle. Its difference to particles exists in the described dynamics. In the de Broglie-Bohm theory, the wave function, and not the particle, determines the dynamic development of the system. According to the (non-relativistic) de Broglie-Bohm interpretation, the motion of single photons is deterministically described by the so-called guidance equation, which relates the motion of single photons to the wave function. Thus, the particle trajectories are "guided" by the wave function (or rather by its phase). Both entities, wave function and photon, are determined. Hence, the de Broglie-Bohm theory is a deterministic theory. Since the actual position of the photon is determined, we can now introduce a hidden variable that models the unique initial values of the single photon. (cf. [6, pp. 178-186]) This variable would formally behave exactly like the variable *TP* in the MZI experiment with classical particles (see figure 3.2). Because the guidance equation determines the initial value for a single photon, this newly introduced variable would screen the two variables *D1* and *D2* off each other. As a result, the (global) causal Markov condition is not violated given the de Broglie-Bohm interpretation.

However, most scientists subscribe to the (indeterministically described) collapse interpretation of quantum mechanics. As we saw above, the strategy of adding an additional variable for the way of a single photon through the MZI is of no help in quantum mechanics. In the following, I will briefly discuss alternative strategies to avoid Markov violations. It will turn out that each of these strategies comes with its own problems.

1. Direct causal connection: One strategy to avoid the Markov violation would consist of assuming that there is a direct causal connection between the two variables *D1* and *D2* modeling the detectors D1 and D2. But, like in the experiment with particles, assuming a direct causal connection between *D1* and *D2* would violate locality: When *D1*=*yes*, then, at the same time, *D2* = *no*, and vice versa. But even if one allows for violations of locality in the quantum realm, there is still a problem with assuming a direct causal connection between *D1* and *D2*: If there were to be such a direct causal relation between *D1* and *D2*, then we would expect that intervening[14] on one of the two detector variables will lead to a change in the other variable's probability distribution (cf. [25, p. 98]). But if, for example, one intervenes on *D1* by shooting a single photon (from outside the MZI) at D1, then it is still possible that D2 also responds. The reason for this is simply that we still have the original photon coming from BS1 in the MZI that might hit D2. Another possibility to intervene on *D1* would consist of placing some kind of obstacle (e.g., an iron block) between BS2 and D1. In that case, D2 would not always respond when D1 does not respond. Summarizing, the response probability of *D2* would not change under interventions on *D1* (and vice versa). Thus, it seems that the dependence between D1 and D2 cannot be explained by a direct causal connection.

2. Latent common cause: Another strategy would be to assume that one or more common causes are missing in our model, such that conditionalizing on all of these common causes would screen off *D1* and *D2* representing the two detectors. But then the common causes together should produce every effect with certainty. Unfortunately, this strategy will not work for standard interpretations of quantum mechanics such as the Copenhagen interpretation that presuppose indeterminism w.r.t. the collapse of the wave function.

3. Too coarse-grained variable: One can also assume that the common cause variable in our model is not fine-grained enough to adequately describe what is going on in nature. Hence, it should be replaced by a more fine-grained variable that would then screen *D1* and *D2* off each other. The problem with this strategy is that there seems to be no more detailed story to be told. One either decides to have the beam splitters as part of the experimental setup or not. There seems to be no additional relevant information available. Now, one might object that information about whether the beam splitters reflect or transmit could be relevant. But, as we saw above, it would be inconsistent for the supporter of (indeterministically described) collapse interpretations to assume that such information is available.

5 Conclusion

In this paper I have argued that the special behavior of quantum systems is not only hard to combine with our common sense view of the world, but also creates problems for more scientifically informed approaches to causation such as the theory of causal Bayes nets. I presented a new counterexample to the theory of causal Bayes nets' core axiom, the (global) causal Markov condition: single photon experiments in a Mach-Zehnder interferometer (MZI). Single photon experiments in an MZI involve a dependence between the two detectors D1 and D2 that cannot be fully explained by conditionalizing on *D1* and *D2*'s common cause in the experimental setup. I then argued that the problem can be solved within the de Broglie-Bohm theory by adding a hidden variable to our causal model which describes the way the single photon takes in the MZI. Such an additional variable would then screen *D1* and *D2* off each other. A similar strategy cannot, however, be applied in quantum mechanics, because—in contrast to the de Broglie-Bohm theory—in quantum mechanics the combination of the splitting process of the wave function at BS1 and the conservation of energy in one space point leads to the indeterministically described collapse of the wave function. I then briefly discussed standard strategies to avoid the Markov violation in quantum mechanics and highlighted their problems. I conclude with a kind of dilemma: The de Broglie-Bohm theory, which can, in principle, avoid the Markov violation, does not have many supporters. For quantum mechanics, to which almost every scientist subscribes, on the other hand, the Markov violation seems more serious. It seems to be unavoidable to conclude that our models in some sense misrepresent what is really going on in the quantum realm: The dilemma is that one can either maintain a/the standard approach to causality or a/the standard interpretation regarding the quantum realm, but one cannot maintain both of them. Now, there are at least three ways to proceed: First, one can take other interpretations than the usual collapse interpretation more seriously. Second, one can try to revise the (global) causal Markov condition, which amounts to a revision of the theory of causal Bayes nets. This strategy is put forward, e.g., by Schurz [17]. Third, one can argue for the existence of some kind of non-causal dependence between D1 and D2 and try to represent this kind of non-causal dependence in causal models. This possibility is further explored in [8].

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Notes

1 Markov causation is considered to be causation, which satisfies the causal Markov condition.

2 Indeed, as a non-local hidden variable theory Bohmian mechanics may explain EPR/B experiments as well (cf. [24, p. 356-396]).

3 Even if light beams propagate in straight lines, they can be split and superimposed, so that the wave properties become visible.

4 Classical systems are systems that can be described by classical mechanics.

5 E. g. Regarding the way of a single photon, a total state in the MZI without BS2 is the linear combination of the pathways BS1-M1-D1 and BS1-M2-D2. But by measuring the way of a single photon it can only be observed at one of the two pathways; either D1 or D2 responds.

6 The symbols i, $\hbar$ and H in the Schrödinger equation denote the imaginary unit of the complex numbers (i), the reduced Planck constant ($\hbar$) and the Hamiltonian (H).

7 The property of Hermiticity ensures that real-valued eigenvalues are always obtained.

8 The Copenhagen interpretation is one of the most famous interpretations of quantum mechanics and goes back to Niels Bohr and Werner Heisenberg. Both were not always in agreement and through further developments this interpretation is not reproduced uniformly in the literature. The main content of the Copenhagen interpretation is the interpretation of the interaction of a quantum object and its macroscopic measuring instrument during a measurement. While Bohr [2] states that the quantum objects' behavior cannot be separated from their interaction with the measuring instruments, establishing the conditions under which the phenomena appear, Heisenberg [10, 11] already assumed two dynamics, the dynamic of the possibilities and the dynamic of the factual. While the dynamic of the possibilities is given by the Schrödinger equation, the dynamic of the factual is given by a measurement according to von Neumann's projection postulate: "All perception is a selection of an abundance of possibilities and a limitation of the possibilities in future." [10, p. 197, my translation].

9 In relativistic space-time the ontology of Bohmian mechanics is no longer restricted to particles. The entities, which are assumed to exist in reality are represented by the so called beables. The beables of the theory could be particle positions, but fields are possible as well. (For more details, see [21])

10 An acyclic causal graph is a causal graph without a path of the form $X \longrightarrow ... \longrightarrow X$.

11 For the local version of the Markov condition, see [19, p. 29].

12 Einstein locality means that there are no causal processes faster than light [6, p. 128].

13 The minus before $|\psi_{refl}\rangle$ is due to the phase shift of the reflected part of the wave function (for more details,see for example [1, pp.64-65]).

14 The central idea of Woodward's interventionist theory is, that a variable X_i is a direct cause of another variable X_j iff there is a possible intervention on X_i that leads to a change in X_j or of its probability distribution [25, p. 59]. An intervention on X_i with respect to X_j is a change in X_i independently of X_i's other causes in such a way, that if any change in X_j appears, it only appears as a result of the intervention on X_i [25, p. 14].

Nina Retzlaff
University of Duesseldorf
Duesseldorf Center for Logic and
Philosophy of Science (DCLPS)
Universitaetsstr. 1
40225 Duesseldorf, Germany
<nina.retzlaff@uni-duesseldorf.de>

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