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Analysis of counterfactuality of counterfactual communication protocols

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Counterfactual communication, i.e., a communication without particles traveling in the transmission channel, is a bizarre quantum effect. Starting from interaction-free measurements many protocols achieving various tasks from counterfactual cryptography to counterfactual transfer of quantum states were proposed and implemented in experiments. However, the meaning of conterfactuality in various protocols remains a controversial topic. A simple error-free counterfactual protocol is proposed. This protocol and its modification are used as a test bed for analysis of the meaning of counterfactuality to clarify the counterfactuality status of various counterfactual proposals.

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I. INTRODUCTION

The name "counterfactual" was coined by Penrose [1] for describing quantum interaction-free measurements (IFMs) [2]. It was applied for counterfactual cryptography [3] and counterfactual computation [4,5] but became more widely known after introducing the term counterfactual communication [6] where it was stated "We show how in the ideal limit, using a chained version of the Zeno effect [5], information can be directly exchanged between Alice and Bob with no physical particles traveling between them, thus achieving direct counterfactual communication."

In my understanding, "in the ideal limit" is about vanishing probability of the failure of the protocol in the limit of large number of ideal optical elements, the probability of events which are discarded by the rules of the protocol. If we are ready to consider only successful events, we need not to apply Zeno effect. The word "direct" means that we send a message directly and not by first establishing a secret key which can be achieved by using devices transmitting bit 1 only [3]. I will consider "counterfactual communication protocol" as a direct communication protocol, i.e., as a protocol capable of transmitting both bit 0 and bit 1. I will not require a small probability of failure in an attempt of communication. What I want to analyze in this paper is the meaning of the word "traveling."

In cases that the quantum state of a particle is not described by a localized wave packet, the standard quantum theory does not tell us where the particle is. What is more relevant for the case of a successful counterfactual protocol, when the photon was detected, is the question: Where *was* the photon responsible for the transfer of the information? Standard quantum theory has even less to say regarding this question. Apparently, Bohr would say that we should not ask the question: Was, or was not, the photon traveling between Alice and Bob? I find that we *can* make useful claims in discussing this question. The answer is not "yes" or "no." It is a consideration of possible meanings of "traveling" of a quantum particle and corresponding classification of counterfactuality of various protocols.

II. THE COUNTERFACTUAL COMMUNICATION PROTOCOL

The communication device is an interferometer, part of which is in Alice's site and part is in Bob's site; see Fig. 1. It is a particular combination of Mach-Zehnder interferometers (MZIs) tuned to complete destructive interference of some output ports. Detector D_1 is a dark port when the interferometer is free from disturbance. The interferometer which has a part on Bob's site is tuned to destructive interference toward Alice's site; see Fig. 1(a). The additional requirement is that when Bob blocks arm B of the interferometer, detector D_2 on Alice's site becomes a dark port (while detector D_1 cease to be a dark port). This can be achieved by properly tuned phases when beam splitter BS_1 is 3:8, beam splitter BS_2 is 1:2, and all other beam splitters are 1:1.

The communication protocol is as follows. At a particular agreed time, Bob transmits a value of a bit to Alice by blocking the arm B of the interferometer (value 1) or by leaving it open (value 0). Alice sends single photons into the interferometer from input port S until she gets a click in detector D_1 or D_2. The click at D_1 tells Alice that the bit value is 1 and the click at D_2 that the bit value is 0. If the interferometer made with ideal optical elements is perfectly tuned, then there will be no errors in the communication.

Eve, placed between Alice and Bob, has some efficient options for active attacks for which there are some ways of defense; see Sec. 10 of Ref. [7]. This protocol does not provide a better security against eavesdropping, but this is not the topic of this paper. Our question is: "Whether or not the photon "traveled" between Alice and Bob?" Clearly, some of the photons will travel between Alice and Bob. Those absorbed by the shutter (if present) and those lost after exiting the interferometer towards blocks at Alice's site, but these events are discarded. The protocol is defined for photons detected by Alice's detectors D_1 and D_2.

For counterfactuality analysis of this paper we limit ourselves to the "lucky" case of communication with a single sent photon which is detected by Alice on the first run. Probability for such an event is $2/11$, independent of the value of the bit.

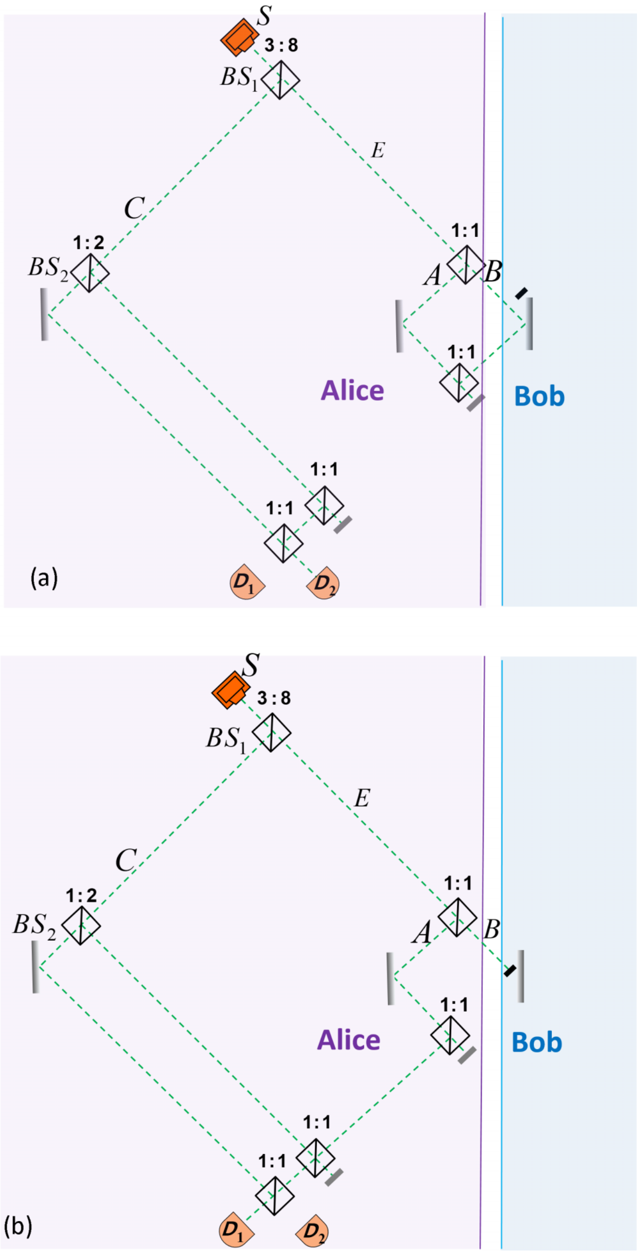

FIG. 1. The interferometer with a single-photon source S. (a) It is tuned such that internal MZIs have destructive interference in the left output ports, and, therefore, a destructive interference at detector D_1. (b) It is also tuned such that when arm B is blocked, there is a destructive interference at detector D_2.

Current counterfactual protocols, such as Ref. [6], use many more beam splitters (or recycle them) and apply a quantum Zeno effect to make the probability of the first run to be successful close to 1.

Our protocol is considered counterfactual because we can claim, arguing in a classical way, that the photon did not travel between Alice and Bob. Our classical physics assumption is that the photon must have a continuous trajectory between the source and the detector. We also make a natural assumption that the trajectory can pass only through regions where the photon wave does not vanish. We might not be able to know the trajectory, but we assume that it exists. This is an approach pioneered by Wheeler [8] and recently advocated by Englert *et al.* [9]; see the discussion in Ref. [10,11].

To show counterfactuality we need to consider two cases: bit value 0 when the interferometer is empty, and bit value 1 when the path B is closed. From Figs. 1(a) and 1(b) we see that in both cases there is no wave packet starting at the source and reaching Alice's detectors passing through Bob's site. Classically, for bit 1 we can say that the photon can reach Bob only through path B, but if it was there, it must have been absorbed by Bob's shutter. For bit 0 there is no shutter, and a photon placed at path B can reach Alice's detectors. However, the only way for a photon to reach path B is through path E. Every photon from path E interferes destructively toward Alice's site, so it also cannot reach Alice's detectors.

III. QUANTUM ANALYSIS

A photon is not a classical object. It is a quantum particle. If the photon wave is a localized wave packet, then it moves like a classical particle on a continuous trajectory, but if the wave packet splits, standard quantum theory does not tell us where the photon goes. A possible answer, that it was in all places where the wave function does not vanish, seems inappropriate since we want to ask where was a pre- and *post*selected photon, but this approach does not take into account the postselection.

Since standard quantum mechanics does not tell us where was a pre- and postselected photon, we have to consider possible definitions: What does it mean that the photon was present or not present in some place? An operational definition of the presence of a classical particle might be the following:

The particle is in a particular location when we know that the probability of finding it there is 1. The particle is not present in this location when the probability of finding it there is 0.

Classically, these are the only options: either the particle is present or not. For a quantum particle we might adopt these definitions with the understanding that they do not cover all cases. These leads to the following definitions.

The particle was in a particular location if the probability of the outcome 1 of the measurement of the projection operator on this location is 1. The particle is not in this location when the probability of the outcome 1 of the measurement of the projection operator on this location is 0.

These definitions have a counterfactual meaning. We make statements about the probability of the results of measurements, if performed, when it is assumed that they were not performed. Quantum measurements change the state of a quantum particle, and we are interested in describing situations when this change was not done. My preferred definition of the presence of a particle is not counterfactual [12]:

The particle was in a particular location if and only if it left a trace there.

The trace is a change of the quantum state of the environment in this location. It must be of the order of the trace the localized wave packet of the particle would leave there, the case in which the question of presence of the particle is not controversial. In the interferometer this trace is weak, the quantum state of the environment does not become orthogonal to its state without the presence of the photon, but it never vanishes because there are always some local interactions.

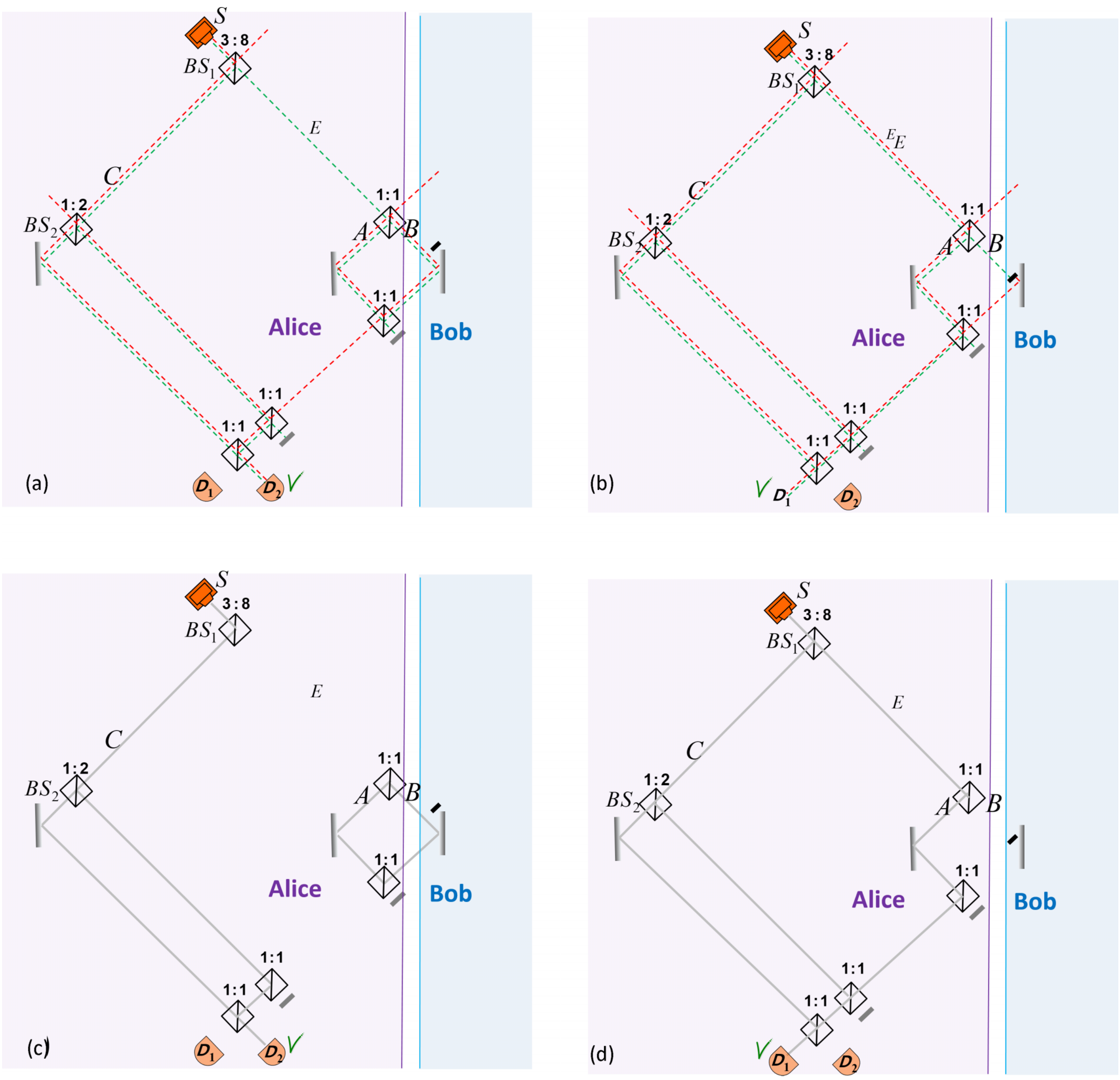

FIG. 2. Derivation of the trace left by the photon using two-state vector formalism. (a) Forward (dashed green line) and backward (dashed red line) evolving waves of the photon for transfer of bit 0. (b) Forward and backward evolving waves of the photon for transfer of bit 1. (c) Trace of the photon for transfer of bit 0. (d) Trace of the photon for transfer of bit 1.

The trace definition agrees with the definition of counterfactual measurements. The easiest way to see this is to use the two-state vector formalism [13]. There is a theorem [14] that for dichotomic variables such as a projection operator, the weak value equal to the eigenvalue if and only if the result of the (counterfactual) strong measurement is obtained with probability 1. A weak value describes all weak couplings and thus quantifies the trace the particle leaves. Therefore, if we know that the photon is to be found with probability 1, it will leave a trace equal to the trace of a localized photon placed there. On the other hand, if we know that the probability to find the photon is 0, then there will be no trace.

The trace definition also covers the case when the probability to find the photon is neither 0 nor 1. In this case the trace definition states that the particle is present. Indeed, in this case there will be a weak trace of the order of the trace of a single photon; otherwise, the weak value must be zero, and then the probability to find the photon must be zero, contrary to our assumption.

The two-state vector formalism also provides a very simple way to know where the photon leaves a trace. To have a weak trace in a particular location, the weak value of a local operator there must not vanish. Thus, the requirement is that at this location there is an overlap of the forward and backward

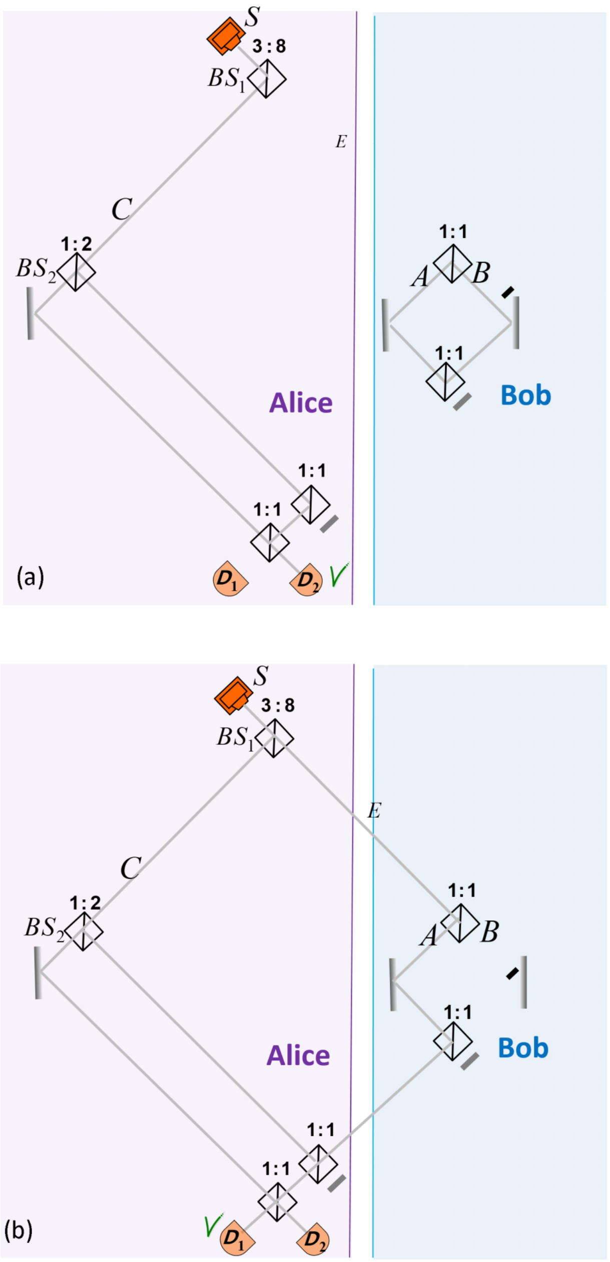

FIG. 3. Trace in the transmission channel for modified sites of Alice and Bob. (a) No trace in the transmission channel for transfer of bit 0. (b) The trace in the transmission channel is present for transfer of bit 1.

evolving states. In Fig. 2 the forward and backward evolving states and the traces are shown for the two cases, bit value 1 and bit value 0. We see that for value 1, the photon does not leave a trace outside Alice's site, but for value 0 there is a trace at the transmission channel between Alice and Bob. We can conclude then that the communication protocol for value 0 is not counterfactual, the photon "traveled" between Alice and Bob.

One can argue [15] that we can define sites of Alice and Bob differently, such that, for bit value 0, there will be no trace at the new "transmission channel" between Alice and Bob; see Fig. 3(a). But for this definition of the transmission channel, the photon will be there when the bit value is 1; see Fig. 3(b). Whatever definition of the separate sites of Alice and Bob are made, the photon will be in the transmission channel for (at least) one value of the bit. So, if "counterfactual" means no particles in the transmission channel, the protocol is not counterfactual.

In this approach the definition of "traveling" between Alice and Bob is following a continuous trajectory between Alice and Bob. In this sense, the photon in the protocol does not travel between Alice and Bob because for any bit value there is a region between them in which the photon leaves no trace. Gisin [16] noted that if this is the only requirement of counterfactuality, then one can construct a classical "counterfactual" protocol which, however, requires a help of a "middle man" who sends a photon to Bob if he does not get a photon from Alice at a particular time.

Denying the idea of continuous trajectories for quantum particles [17] leads to defining "traveling" of a quantum particle between Alice and Bob as being in Alice's and Bob's sites. Here again "being" is defined as leaving a trace. In this sense, the protocol is not counterfactual for bit 0. The "direct counterfactual communication" [6] and all other published "counterfactual" protocols are also not counterfactual in this sense: at least for one bit value the photon leaves a trace both in Alice's and Bob's sites.

I adopt the definition of a counterfactual communication protocol as the one in which the particles left no trace outside Alice's site. In the next section we will show that such a protocol is possible.

IV. MODIFIED PROTOCOL

The noncounterfactuality of the "counterfactual" proposals is a common feature of numerous proposals [18–33]. We should exclude indirect counterfactual proposals, based on key distribution, which transmit only one bit value [3,34–36]. It led me to conjecture that noncounterfactuality of direct communication is an unavoidable property [7,37–41], but it turned out to be a mistake [42]. The modified counterfactual communication protocol, which is counterfactual also according to the trace criterion, is presented in Fig. 4. It is very similar to the original protocol except for replacing the MZI with a mirror at Bob's site by two consecutive MZIs both tuned to destructive interference toward the path continuing inside the large interferometer and readjusting the transmissivity of the beam splitter BS_1 to 3:32. According to the new protocol, to transmit the bit 0, Bob should not touch his part of the interferometer, while for bit 1 he has to block *two* interferometers, i.e., he has to block paths B and B'. If the interferometer is free, detector D_1 cannot click while detector D_2 has the probability to detect the photon $2/35$. If Bob blocks the two interferometers, detector D_2 cannot click while detector D_1 has the probability to detect the photon $2/35$. We, again, consider the "lucky" communication in which the first photon sent by Alice was detected by one of her detectors. (It is possible, with more mirrors and beam splitters, to devise a protocol with higher probability of success of the first run.)

The new protocol with ideal devices has a zero error rate as does the previous one, but now we can also claim that no trace is left outside Alice's site. In Figs. 5(a) and 5(b) we describe

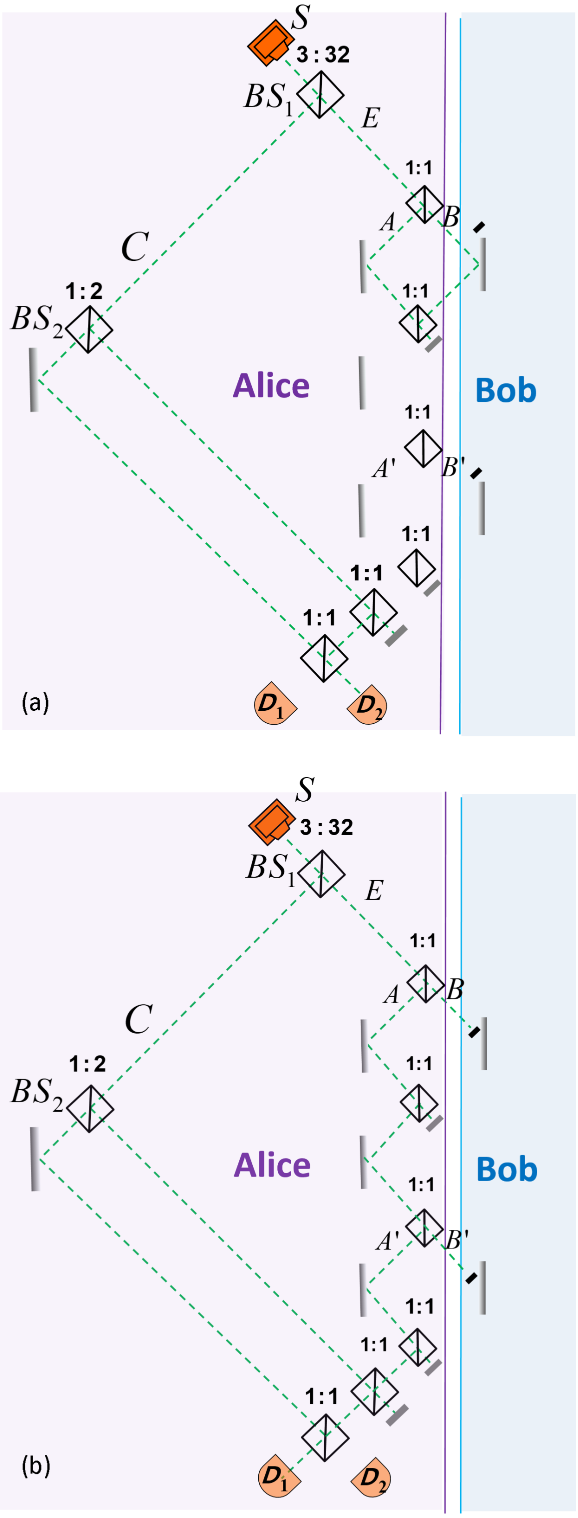

FIG. 4. Modified interferometer. (a) It is tuned to destructive interference in all internal MZIs toward left output ports and, therefore, to the destructive interference at detector D_1. (b) It is also tuned such that when arms B and B' are blocked, there is a destructive interference at detector D_2.

the forward and backward wave functions in this protocol. Their overlap provides the trace shown in Figs. 5(c) and 5(d). There is no trace outside Alice's site for both bit values of the communicated bit.

To make clear what I mean by the "trace" the photon leaves, let us consider a model [43] in which the state of the photon passing through a channel is not changed, but the quantum state of each channel, originally described by $|\chi\rangle$, is modified due to the passage of the photon:

$$|\chi\rangle \rightarrow |\chi'\rangle \equiv \eta|\chi\rangle + \epsilon|\chi^{\perp}\rangle, \qquad (1)$$

where $|\chi^{\perp}\rangle$ denotes the component of $|\chi'\rangle$ which is orthogonal to $|\chi\rangle$ and its phase is chosen such that $\epsilon > 0$. We assume that $\epsilon \ll 1$.

In the protocol of Sec. II for bit value 1 there is no trace outside Alice's site. The only place where the trace might be is arm B. The orthogonal component $|\chi^{\perp}\rangle_B$ does appear during the evolution, but it is created entangled with the spatial mode of the photon which is absorbed in the shutter. Thus, the component $|\chi^{\perp}\rangle_B$ is not present in the branch with detection of the photon by Alice.

In the modified protocol for bit value 1, the situation is similar. The orthogonal components $|\chi^{\perp}\rangle_B$ and $|\chi^{\perp}\rangle_{B'}$ appear entangled with the photon modes which do not reach Alice's detectors. After the click of Alice's detector, there is a trace in arm C, as if a single photon passed there, and the environment has the component $\epsilon|\chi^{\perp}\rangle_C \prod_{X\neq C}|\chi\rangle_X$. Some other arms in Alice's site also have orthogonal components with first order in ϵ amplitude, but outside Alice's site there are no arms with orthogonal components.

For bit value 0, however, in the protocol of Sec. II, the trace does appear in arm B outside Alice's site. The trace is the same as if we had a localized photon in arm B: $\epsilon|\chi^{\perp}\rangle_B \prod_{X\neq B}|\chi\rangle_X$. We also get the trace in arm C: $\epsilon|\chi^{\perp}\rangle_C \prod_{X\neq C}|\chi\rangle_X$. We cannot see simultaneously the traces in B and in C, the traces are there, but they are entangled in such a way that when we detect one, the other disappears.

In the modified protocol for bit value 0 the first-order trace appears only in arms of the interferometer in Alice's site [42]. To understand this we can note that the orthogonal components in arms B and B' appear only together with orthogonal component in an arm of another MZI, otherwise the photon mode on Bob's site cannot reach Alice's detector. The terms in the quantum state of the environment with two orthogonal components have factor ϵ^2. In the limit of better and better interferometer, when $\epsilon \rightarrow 0$, the traces outside Alice's site are infinitely smaller than the trace left by a localized photon, and thus it is natural to neglect them and take into account only the first-order traces. Note that making the modification with N consecutive MZIs, instead of the two, will lead to reducing the traces outside Alice's site to Nth order in ϵ.

The modification by replacement of Bob's MZI by two (or N) consecutive MZIs can be applied to the counterfactual communication protocol which has a high probability of success by applying the Zeno effect [6]. Even the counterfactual communication of a quantum state [24,28,40] can be made without a first-order trace outside Alice's site.

V. HIGHER ORDER TRACES

For bit value 1 the original and modified protocols have no any trace outside Alice's site. Even if the interferometer is not ideal, in particular, when a localized photon leaves some

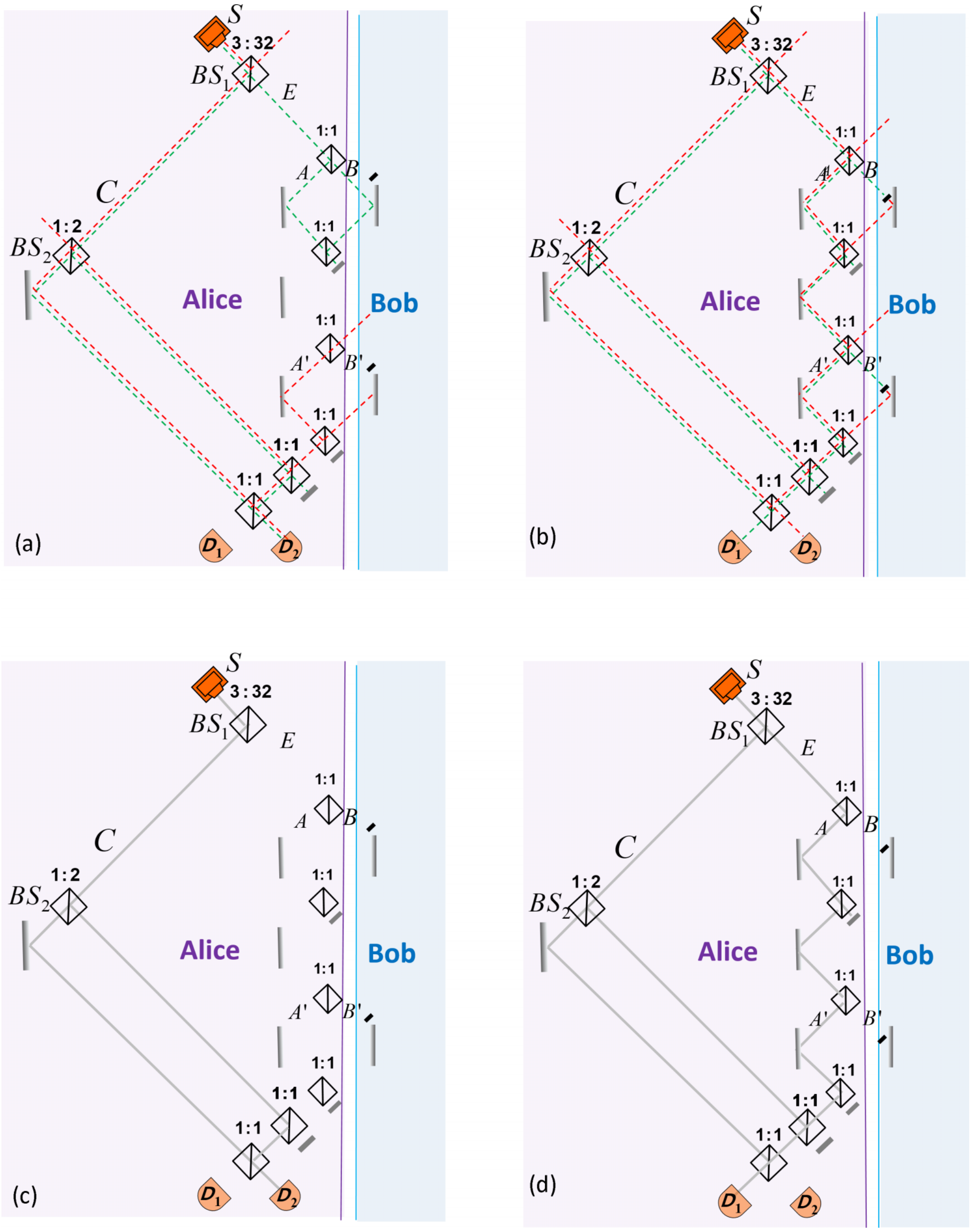

FIG. 5. Derivation of the trace left by the photon in the modified protocol using the two-state vector formalism. (a) Forward and backward evolving waves of the photon for transfer of bit 0. (b) Forward and backward evolving waves of the photon for transfer of bit 1. (c) Trace of the photon for transfer of bit 0. (d) Trace of the photon for transfer of bit 1.

trace passing through an arm of the interferometer, the photon in the protocol will not leave a trace outside Alice's site. The only requirements for full counterfactuality, i.e., no trace of any order, is that the source produces an exact single-photon state and that the shutter is 100% opaque. Other imperfections might lead to errors but cannot spoil counterfactuality.

The situation for bit value 0 is different. The original protocol leaves a trace in Bob's site as if a localized photon was there. Even in the modified protocol there is some trace in Bob's site. Maybe the strongest argument that even the modified protocol is not counterfactual is that at least one of the nondemolition measurements of presence of the photon, one in arm B and another in arm B' performed together, will find the photon with certainty.

I, however, view this correct statement as a strong argument against considering counterfactual strong measurements for discussing the presence of a pre- and postselected quantum particle. Strong measurements change the situation, and properties which are true for a system with measurements might not be true when the measurements are not preformed.

There is also a trace argument. The local trace in Bob's site, i.e., the appearance of the orthogonal component $|\chi^{\perp}\rangle_{B}$ at the limit of small coupling, is negligible. Not just because it is small, but because it is much smaller than the (small) trace a localized photon would leave there. A local trace is the appearance of an orthogonal component of a quantum state of the environment in one location. However, the nonlocal trace, appearing as orthogonal components in two locations, such as $|\chi^{\perp}\rangle_{B}|\chi^{\perp}\rangle_{B'}$, is the same as for the case of a localized wave packet of a single particle passing through the arms B and B'. In both cases the trace is of second order in ϵ. Still, it is natural to neglect this second-order trace since the particle leaves (in Alice's site) the first-order local trace.

Is there a protocol in which for both bit values there is no *any* trace, even of higher order, in Bob's site? It seems that in a recent preprint [44] there is a claim of the existence of such a protocol. An interferometric scheme employing manipulation of polarization of the photons allows us to transmit bit value 0 without any trace on Bob's site even if the localized photon does leave a trace in the arms of the interferometer. However, I do not consider it as a counterexample. It is true that given a click at the detector signifying bit 0, there is no trace on Bob's site. However, for bit 0, the imperfection of the interferometer leads to a nonvanishing probability of a click of the other Alice's detector, which is a legitimate event in the protocol announcing bit 1. Together with the error, we also spoil the counterfactuality: in such an event, there is a trace on Bob's site.

VI. DISCUSSION AND CONCLUSIONS

The main analysis of counterfactuality was based on the weak trace left in the transmission channel after completing the communication. Although an explanation of the trace was done in the framework of the two-state vector formulation of quantum mechanics, I want to stress that it was just a tool which simplified the analysis and hopefully provided deeper understanding, and that all calculations of the traces could be performed using a standard formalism.

Counterfactual communication protocols are very paradoxical phenomena, and the question What is "truly" counterfactual? remains controversial. Arvidsson-Shukur, Gottfries, and Barnes [45] applied sophisticated information tools (Fisher information, etc.) to evaluate the counterfactuality of various protocols showing an advantage of protocols such as counterfactual key distribution [3] in which there is no any trace on Bob's site since only communication of bit 1 is used. It will be of interest to see the evaluation of the modified counterfactual protocol without the first-order weak local trace presented here. Another important analysis which goes beyond the scope of this paper is a consideration of realistic devices, in particular nonideal sources of single photons. When there is a nonvanishing amplitude for two or more photons, even the protocols based only on communication of bit 1 leave some nonvanishing trace in the communication channel, so all questions about counterfactuality become quantitative.

There are also alternative definitions of counterfactuality. Arvidsson-Shukur and Barnes [46] proposed their own meaning of "counterfactual" communication: when particles go from Alice to Bob, while the information goes from Bob to Alice. Indeed, it is easy to achieve such a situation using the IFM scheme with the Zeno effect [47]. The scheme is counterfactual when Bob places the shutter: the particle detected by Alice never reaches Bob, and therefore, it does not go from Bob to Alice. On the other hand, when the shutter is not placed, the photon does not come back to Alice, it ends up at Bob's site, so again, the particle does not go from Bob to Alice. I, however, hardly see in this protocol a justification for the name "counterfactual." The photon was traveling between Alice and Bob. According to Arvidsson-Shukur and Barnes' definition of Alice's and Bob's sites, the photon goes to the transmission channel from Alice and comes back. If we enlarge Alice's site to include the beam splitters, then the photon does not go from the transmission channel to Alice, but then it goes from Bob to the transmission channel. We already discussed cases when the particle does not go the whole way between Alice and Bob.

The possibility of counterfactual communication without a first-order weak trace outside Alice's site and communication of bit 1 without any trace outside Alice's site is very paradoxical phenomena which go against the spirit of science, which searches for a local causal explanation of nature. It sounds like an action at a distance. My way to resolve the paradox [48] is to accept the many-worlds interpretation [49] which removes action at a distance on the level of all worlds together, explaining an illusion of action at a distance in our world.

To summarize, I proposed a counterfactual communication protocol which theoretically has no errors. The first version is counterfactual only if one considers traveling between Alice and Bob as following the whole continuous trajectory between them. The modified version is counterfactual based on a much stricter definition of having no first-order trace outside Alice's site. These protocols allowed us to analyze various aspects of counterfactuality of other proposals for counterfactual communication.

ACKNOWLEDGMENT

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