

Comment on “Past of a quantum particle revisited”

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The recent criticism of Vaidman’s proposal for the analysis of the past of a particle in the nested interferometer is refuted. It is shown that the definition of the past of the particle adopted by Englert *et al.* [B. G. Englert *et al.*, *Phys. Rev. A* **96**, 022126 (2017)] is applicable only to a tiny fraction of photons in the interferometer which indeed exhibit different behavior. Their proof that all pre- and postselected particles behave this way, i.e., follow a continuous trajectory, does not hold, because it relies on the assumption that it is intended to prove.

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A recent paper [1] by Englert *et al.* criticizes Vaidman’s description of the three-path interferometer with weak path marking [2] which is at odds with the single-path story told by common sense. In this Comment we defend Vaidman’s narrative by analyzing Ref. [1] and showing that the Englert *et al.* argument for a particular single-path story can be repeated equally well for another single path, contradicting (the Englert *et al.*) common-sense approach, according to which a particle must have a single continuous trajectory.

There is a large body of literature on this subject [3–35]. The novel aspect of Ref. [1] is “extracting unambiguous which-path information from the faint traces left by an individual particle on its way through the interferometer.” In the abstract of [1], the following is stated: “In our analysis, ‘the particle’s path’ has operational meaning as acquired by a path-discriminating measurement.”

This is not the meaning of the past of the particle according to Vaidman’s proposal. Vaidman argues that there is a consistent way to attribute location to a particle in the past without unambiguous path-discrimination measurements of the faint traces. He *defines* that the particle was where these faint traces are present. The information about the traces is obtained either by a calculation or by a measurement performed on the pre- and postselected ensemble, not by “unambiguous path-discrimination measurement” of traces of a single particle which would change the situation.

Note that in a hypothetical world with vanishing interaction of the photon with the environment, Vaidman’s definition is not applicable, but in the real world there is always some nonvanishing local interaction. Unquestionably, there is an unavoidable interaction of the photon with the mirrors and beam splitters of the interferometer.

It might seem that the disagreement is semantic: a difference in definitions. This can be so, if Englert *et al.* would declare, following Bohr’s approach, that the past is defined only in the (very rare) cases when the measurement unambiguously detects the trace of the particle. In fact, in these cases there is no disagreement between descriptions of the past of the photon by Vaidman and by Englert *et al.* However, Englert *et al.* argue that in Vaidman’s interferometer, even in the cases when the unambiguous path-discrimination measurement fails to detect the trace, the photons had the

common-sense single-path trajectory. These are the only cases of the disagreement, and it is not of a semantic nature.

The subject of our discussion, the nested interferometer, is a relatively simple setup and the reason why there are so many papers discussing the question, “Where was the particle?” is that standard quantum mechanics provides no answer. For a preselected only quantum particle, physicists are reluctant to consider this question, although a possible answer is present: Everywhere where the wave function is nonvanishing. In the case in which the particle is both pre- and postselected, the standard formalism has no any answer.

An approach that is sometimes considered as a common-sense interpretation is Wheeler’s proposal [36], according to which we associate a well defined path with a quantum particle when its wave function splits into wave packets with well defined trajectories and only one of them connects the source with the detector. A particular tuning of the nested interferometer is an example: A definite trajectory in Wheeler’s sense exists, the path C (see Fig. 1). Vaidman argued that the trajectory defined in this way is not helpful since it lacks operational meaning. He proposed an alternative definition based on an operational meaning: The particle was where it left a (weak) trace. In most cases, Vaidman’s and Wheeler’s definitions provide the same picture, but in the case of this interferometer, Vaidman’s definition yields a weak trace not only in path C, but also in the arms of the inner interferometer which are parts of paths A and B. Vaidman and co-workers also performed an experiment [3] demonstrating that there is a weak trace of the same strength in paths C, A, and B. Englert *et al.* criticized the experiment since it “does not make any information available about individual photons. . . [and] the data [are] perfectly consistent with an alternative story: Each photon of a small fraction leaves a discernible trace at checkpoint A or at B or at C, while most photons leave no trace at all.”

Vaidman intentionally avoids measurements providing unambiguous path information about individual photons. Without measurement interactions with macroscopic amplification, the Englert *et al.* alternative story is impossible in the framework of the standard quantum mechanics. We are in the regime of the Schrödinger equation which tells us that every

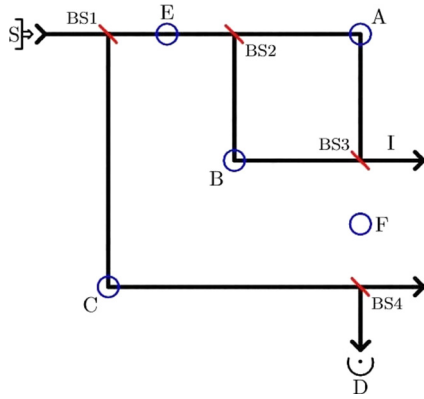


FIG. 1. Vaidman’s nested interferometer in the Englert *et al.* notation. The inner interferometer is tuned to destructive interference towards F.

photon alters the microscopic state of the environment. Every photon leaves some change (the trace). The Englert *et al.* verification measurement of the presence of this change, the unambiguous path discrimination measurement, can erase it, but without individual measurements, the trace must still be there.

Let us consider now the measurements of individual measuring devices which provide unambiguous path discrimination, as Englert *et al.* suggest. In the rare cases when an unambiguous mark is found, Englert *et al.* and Vaidman agree that there is a single continuous trajectory through the detected path. Englert *et al.* would use common sense, while Vaidman would calculate that, given the detection of the mark, there will be slight changes to the states of the systems of the environment only on one continuous path, creating a faint trace only on that path. The controversy arises when the mark is not detected. Englert *et al.* argue that the particle must take the common-sense path C, while Vaidman claims that the local environment will have a faint trace not only in the continuous path C, but also (and of the same strength) in parts of the paths A and B (inside the inner interferometer).

Now we present a simplified version of the Englert *et al.* argument. We neglect the terms proportional to ϵ , the parameter defined by Englert *et al.* to characterize the strength of the weak path marking, because the disagreement is not about differences of order ϵ . Indeed, in the caption to Fig. 5 in [1] Englert *et al.* claim that “[in] the limit $\epsilon \rightarrow 0$, all particles reach D via C.” Then the Englert *et al.* argument goes as follows. First is the (correct) observation that introducing an arbitrary phase in path C does not change detection probability in D, which is $1/9$. From this result, Englert *et al.* concluded that the photons which reach the detector passing through C are incoherent with those passing through all other paths and therefore, to find the probability in D, we have to sum the probability of photons from C with probability of photons from elsewhere. Second is the (correct) calculation of the fraction of photons from the source which pass through C and reach the detector D, which is also $1/9$. Then they have argued that the accounting exercise, presented in Sec. IV B in [1], shows that there is no room for any other photons and therefore no photons detected in D were in the inner interferometer.

If the photons passing through C are incoherent with all other photons reaching D, the Englert *et al.* argument holds. This incoherence can be arranged, for example, by adding to Vaidman’s setup an unambiguous 100% efficient marker on path C. We agree that in this case all photons detected at D pass through C. The calculation shows that a faint trace due to weak interaction of the photon will appear only on the continuous path passing through C. The only error of the simplified version of the Englert *et al.* argument is the claim that the photon wave packet in C is incoherent with other wave packets reaching D. The probability of detection in D is insensitive to the introduction of a phase in C not because of the lack of coherence, but because the other wave packets, passing through A and passing through B, interfere destructively.

Probably the most convincing way to show that our simplified version of the Englert *et al.* argument cannot be true is to apply it and reach a contradiction. Englert *et al.* claim that the photons go solely through C because detection in D is insensitive to the phase change in C and the intensity in D is equal exactly to the intensity in an alternative experiment when all paths except C are blocked. However, the same argument is true also for path B. The intensity in D is $1/9$ and it is insensitive to the phase change in B if it is introduced instead of the phase change in C; it remains $1/9$ if all but path B are blocked. It can be easily seen from the fact that there are essentially equal contributions to the amplitude reaching the detector from paths A, B, and C, except that the contributions from B and C are identical, while the contribution from A has an opposite sign. Thus, the Englert *et al.* simplified argument forces us to conclude that the particle took a continuous path solely through B and also that it took a continuous path solely through C. This contradicts the common sense.

Our simplified version of the Englert *et al.* argument was missing some details. We omitted all effects of order ϵ , but more importantly we did not follow the full history of the particle. We only considered the particle leaving the source, being in C and/or B and reaching the detector D. The Englert *et al.* approach added to the discussion the possibility of a passage through F (see their Fig. 5).

In the caption to their Fig. 5 it is stated that “[since] that fully accounts for the particles that took the path BS3 \rightarrow BS4 \rightarrow D, the inconclusive measurement outcomes (gray) surely identify particles that followed the path C \rightarrow BS4 \rightarrow D.” So, while we present the distinction between particles reaching D through C and not through C, Englert *et al.* consider the distinction between going through C and through F, which is the path BS3 \rightarrow BS4. They added a full section (VI) for the analysis of particles entering the inner interferometer and reaching point F. This section provided a correct conclusion: Every particle reaching point F left an unambiguous mark of its presence in one of the paths, A or B. Therefore, a particle passing through F cannot be one of the particles which left no trace in the markers.

This supports the accounting exercise of Englert *et al.* (Sec. IV B): All particles that left no mark had to pass only through path C. In this approach there is no contradiction: There is no equivalent proof that all particles detected at D passed through B. Indeed, the setup is not symmetric and there is no point to be the analog of F. Trajectories connecting A

with D and B with D pass through F, but trajectories going through C do not pass through F. There is no point in the intersection of the trajectories connecting C with D and A with D which is not on a trajectory connecting B with D.

In considering passing through F, Englert *et al.* made a tacit assumption: Every photon has a continuous trajectory. This assumption contradicts Vaidman's story: At intermediate times it is present simultaneously in three places A, B, and C, but before and after, it is only in C. Assuming that the photons always follow a continuous trajectory and adding an unambiguous path-discrimination measurement indeed explains the faint traces in A, B, and C and proves that all particles which left no trace passed through C. However, it is a circular argument: The Englert *et al.* approach "proves" that Vaidman's story is incorrect by assuming that it is incorrect.

Another justification for the accounting exercise of Sec. IV B is offered in Sec. IV C: "In view of the eventual conditioning on particles detected by detector D, we focus on the components that are processed by beam splitter BS4 and project out the then irrelevant path-I component,..." Englert *et al.* show that for the relevant inconclusive outcome, this projection leaves, at the moment before reaching BS4, only component C. This is a direct application of Wheeler's approach, the validity of which is at stake. By assuming that Vaidman is wrong, Englert *et al.* cannot prove that he is wrong.

Englert *et al.* also consider the experiment with unambiguous path-discriminating markers in Mach-Zehnder interferometer (see Sec. VII in [1] and [37]). However, the experiment

cannot provide a support for the criticism because there is no disagreement about the marked photons. In the Summary of [37] the following is written: "We confirm, in particular, that each photon that emerges from the dark output port of the balanced interferometer has a known path. This confirmation has an immediate bearing on the experiments by Danan *et al.* [3] and Zhou *et al.* [32], inasmuch as it implies that all photons will have a known path through Vaidman's three-path interferometer [2] if a suitable unambiguous path discrimination is performed." We agree that "if a suitable unambiguous path discrimination is performed" then "all photons will have a known path through Vaidman's three-path interferometer"; however, the question posed by Vaidman was about the past of the particle inside an interferometer in which we do not place unambiguous path-discriminating markers. In the experimental implementations of his proposal [3,32], for the vast majority of the photons the path was not unambiguously marked.

In summary, Englert *et al.* provided no sound arguments against Vaidman's proposal. The definition of the past of the particle as places where it left faint traces is consistent, even if it provides a picture which is at odds with the single-path story told by common sense.

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- [1] B. G. Englert, K. Horia, J. Dai, Y. L. Len, and H. K. Ng, Past of a quantum particle revisited, *Phys. Rev. A* **96**, 022126 (2017).
- [2] L. Vaidman, Past of a quantum particle, *Phys. Rev. A* **87**, 052104 (2013).
- [3] A. Danan, D. Farfurnik, S. Bar-Ad, and L. Vaidman, Asking Photons Where They Have Been, *Phys. Rev. Lett.* **111**, 240402 (2013).
- [4] Z. H. Li, M. Al-Amri, and M. S. Zubairy, Comment on "Past of a quantum particle", *Phys. Rev. A* **88**, 046102 (2013).
- [5] L. Vaidman, Reply to "Comment on 'Past of a quantum particle'", *Phys. Rev. A* **88**, 046103 (2013).
- [6] L. Vaidman, Tracing the past of a quantum particle, *Phys. Rev. A* **89**, 024102 (2014).
- [7] M. A. Alonso and A. N. Jordan, Can a Dove prism change the past of a single photon? *Quantum Stud.: Math. Found.* **2**, 255 (2015).
- [8] L. Vaidman and T. Izumi, When photons are lying about where they have been, *Entropy* **20**, 538 (2018).
- [9] H. Salih, Commentary: "Asking photons where they have been" - without telling them what to say, *Front. Phys.* **3**, 47 (2015).
- [10] A. Danan, D. Farfurnik, S. Bar-Ad, and L. Vaidman, Response: Commentary: "Asking photons where they have been" - without telling them what to say, *Front. Phys.* **3**, 48 (2015).
- [11] K. Bartkiewicz, A. Cernoch, D. Javurek, K. Lemr, J. Soubusta, and J. Svozilik, One-state vector formalism for the evolution of a quantum state through nested Mach-Zehnder interferometers, *Phys. Rev. A* **91**, 012103 (2015).
- [12] L. Vaidman, Comment on "One-state vector formalism for the evolution of a quantum state through nested Mach-Zehnder interferometers", *Phys. Rev. A* **93**, 036103 (2016).
- [13] V. Potoček and G. Ferenczi, Which-way information in a nested Mach-Zehnder interferometer, *Phys. Rev. A* **92**, 023829 (2015).
- [14] L. Vaidman, Comment on "Which-way information in a nested Mach-Zehnder interferometer", *Phys. Rev. A* **93**, 017801 (2016).
- [15] L. Fu, F. A. Hashmi, Z. Jun-Xiang, and Z. Shi-Yao, An ideal experiment to determine the 'past of a particle' in the nested Mach-Zehnder interferometer, *Chin. Phys. Lett.* **32**, 050303 (2015).
- [16] A. Ben-Israel, L. Knips, J. Dziewior, J. Meinecke, A. Danan, H. Weinfurter, and L. Vaidman, An improved experiment to determine the 'past of a particle' in the nested Mach-Zehnder interferometer, *Chin. Phys. Lett.* **34**, 020301 (2017).
- [17] D. Sokolovski, Asking photons where they have been in plain language, *Phys. Lett. A* **381**, 227 (2017).
- [18] L. Vaidman, Comment on "Asking photons where they have been in plain language", [arXiv:1703.03615](https://arxiv.org/abs/1703.03615).
- [19] D. Sokolovski, Reply to L. Vaidman's comment on "Asking photons where they have been in plain language", [arXiv:1704.02172](https://arxiv.org/abs/1704.02172).
- [20] R. Griffiths, Particle path through a nested Mach-Zehnder interferometer, *Phys. Rev. A* **94**, 032115 (2016).
- [21] L. Vaidman, Comment on "Particle path through a nested Mach-Zehnder interferometer", *Phys. Rev. A* **95**, 066101 (2017).

- [22] G. N. Nikolaev, Paradox of photons disconnected trajectories being located by means of ‘weak measurements’ in the nested Mach-Zehnder interferometer, *JETP Lett.* **105**, 152 (2017).
- [23] L. Vaidman, Comment on “Paradox of photons disconnected trajectories being located by means of ‘weak measurements’ in the nested Mach-Zehnder interferometer”, *JETP Lett.* **105**, 473 (2017).
- [24] G. N. Nikolaev, Response to the Comment on “Paradox of photons disconnected trajectories being located by means of ‘weak measurements’ in the nested Mach-Zehnder interferometer”, *JETP Lett.* **105**, 475 (2017).
- [25] F. A. Hashmi, F. Li, S.-Y. Zhu, and M. S. Zubairy, Two-state vector formalism and quantum interference, *J. Phys. A: Math. Theor.* **49**, 345302 (2016).
- [26] L. Vaidman, Comment on “Two-state vector formalism and quantum interference”, *J. Phys. A: Math. Theor.* **51**, 068002 (2018).
- [27] F. A. Hashmi, F. Li, S.-Y. Zhu, and M. S. Zubairy, Reply to the Comment on “Two-state vector formalism and quantum interference”, *J. Phys. A: Math. Theor.* **51**, 068001 (2018).
- [28] Q. Duprey and A. Matzkin, Null weak values and the past of a quantum particle, *Phys. Rev. A* **95**, 032110 (2017).
- [29] D. Sokolovski, Comment on “Null weak values and the past of a quantum particle”, *Phys. Rev. A* **97**, 046102 (2018).
- [30] Q. Duprey and A. Matzkin, Reply to “Comment on ‘Null weak values and the past of a quantum particle’ ”, *Phys. Rev. A* **97**, 046103 (2018).
- [31] D. Paneru and E. Cohen, Past of a particle in an entangled state, *Int. J. Quantum Inf.* **15**, 1740019 (2017).
- [32] Z.-Q. Zhou, X. Liu, Y. Kedem, J. M. Cui, Z. F. Li, Y. L. Hua, C. F. Li, and G. C. Guo, Experimental observation of anomalous trajectories of single photons, *Phys. Rev. A* **95**, 042121 (2017).
- [33] Y. Aharonov, E. Cohen, A. Landau, and A. Elitzur, The case of the disappearing (and re-appearing) particle, *Sci. Rep.* **7**, 531 (2017).
- [34] H. Geppert-Kleinrath, T. Denkmayr, S. Sponar, H. Lemmel, T. Jenke, and Y. Hasegawa, Multifold paths of neutrons in the three-beam interferometer detected by a tiny energy kick, *Phys. Rev. A* **97**, 052111 (2018).
- [35] L. Vaidman, Comment on “Multifold paths of neutrons in the three-beam interferometer detected by a tiny energy kick”, [arXiv:1806.01774](https://arxiv.org/abs/1806.01774).
- [36] J. A. Wheeler, in *Mathematical Foundations of Quantum Theory*, edited by A. R. Marlow (Academic Press, New York, 1978), pp. 9–48.
- [37] Y. L. Len, J. Dai, B. G. Englert, and L. A. Krivitsky, Unambiguous path discrimination in a two-path interferometer, *Phys. Rev. A* **98**, 022110 (2018).