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REPLY

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Reply

Reply to the comment on 'Two-state vector formalism and quantum interference'

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Abstract

In the preceding comment it is claimed that we are mistaken in the analysis of the theory of the 'past of a quantum particle' proposed by the author of the comment. We show that the claim is unfounded. Moreover we show that the arguments presented in the comment are not consistent with the already proposed theory.

Keywords: two-state vector formalism, quantum interference, weak measurements, past of a quantum particle

The author of the comment [1] (a comment to our article [2]) has previously proposed a theory of the past of the particle [3–6] in which he has made a number of paradoxical claims for a quantum particle passing through a nested Mach–Zehnder interferometer, and has attracted considerable criticism from the community [2, 7–18]. In our article [2] we have shown that the theory presented by the author of the comment runs into problems when applied to systems with multiple weak measurements, and that the trick used in the theory can be used to refute it. This is challenged in the preceding comment [1] claiming that we are mistaken in the analysis of certain examples discussed in our article [2]. However, the arguments presented in the comment [1] either endorse our results, or are inconsistent with the previously proposed theory [4]. With such inconsistencies the claim that we are mistaken in [2] remains insubstantial. We present our arguments in the following.

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1. Inconsistencies in the comment

In this section we present our analysis of some ideas expressed in the comment.

1. In section 1 the author claims that since 'standard quantum mechanics does not make any statement about the past of the particle during the time it is inside the interferometer, so there cannot be any contradiction (of the theory of the past of the quantum particle) with quantum mechanics'. Here the author is stating a true fact and deriving a wrong conclusion. It is true that standard quantum mechanics does not talk about the past, but it does not mean that 'all predictions' of 'all theories of the past of quantum systems' are by default consistent with quantum theory. Moreover we have shown previously stark contradiction in the predictions of his theory and standard quantum mechanics [10] (setup 3 in [2]).
2. In section 2 a quantitative relation between the weak values and the weak trace is missing. So it is not obvious how in section 3 the weak values of order ϵ imply the weak trace of the order ϵ^2.
3. In section 3 the author of the comment proposes that we complete table 2 in [2] to include the backward propagating wavefunction. In the table he is referring to we give the standard quantum mechanical evolution of the system subjected to a weak measurement, and in standard quantum mechanics there is no backward propagating wavefunction.
4. Note also that in two-state vector formalism (TSVF) (that the author has used to propose his theory) the weak values do not depend on weak measurements. This is apparent from the weak value expression given in section 2 of the comment. However, the weak values given in section 3 do not follow this expression. We are afraid that the author in this part of the comment is making an argument inconsistent with his own theory.
5. Having mentioned the above inconsistencies, it is true that the trace in the path coming out of the inner interferometer is of second order. With the first weak measurement inside the inner interferometer with measurement strength parameter ϵ_1, and the second weak measurement on the path coming out of the inner interferometer with strength ϵ_2, the trace on the path coming out of the inner interferometer is $\propto \epsilon_1\epsilon_2$.
   For this second order trace, the author of the comment has modified his claim a number of times. He first proposed that 'The photon did not enter the interferometer, the photon never left the interferometer, but it was there' [3]. He later modified it to 'secondary presence' with the interpretation that the photon was present but did not leave a trace [6]. In this comment he is suggesting that this trace 'is postulated to be neglected'.
   Note however, that this second order trace ($\epsilon_1\epsilon_2$) is still at first order with respect to the second weak measurement, and in standard quantum mechanics it cannot be neglected. It has been shown that one can reveal the trace disturbed by ϵ_2 through Fourier spectrum techniques [9], where both the amplitudes of ϵ_1 and ϵ_2 are small.
   Note also that it is not justified to perform a weak measurement on a quantum system and then, to restrict the analysis to the *zeroth* order of the measurement perturbation. Doing so will likely give rise to paradoxes, as has been the case with the theory under discussion [4]. This was the point we raised in our article [2] that two-state vector formalism should not be applied to systems with multiple weak measurements unless the disturbances caused by the weak measurements are properly taken into account. We believe that the suggestion '(second order trace) is postulated to be neglected' endorses our point that the theory cannot be applied to systems with multiple weak measurements.
6. In section 4 the author wishes to imply that the measurements in our setup 2 in [2] are not weak enough. We deny it. However, we do admit that the trace revealed in the setup because of two weak measurements with measurement strength parameters ϵ_1 and ϵ_2,

respectively, is of the order $\epsilon_1\epsilon_2$. We have already discussed the second order trace in the previous point. Surprisingly the author, in this section, criticizes our comment that TSVF is a first order theory, despite having claimed in the previous section that second (and higher) order traces are postulated to be neglected.

7. In section 5 the author is suggesting that weak measurements inside the inner interferometer cannot restore the destructive interference on the output port. This is not correct. We can perform the weak measurement by coupling the photon inside the inner interferometer with another quantum system (e.g. an atom). Later the strong projective measurement of the meter projects the system to a pure state. Hence destructive interference can be restored.
8. In section 5 the author has proposed a new element in his theory. He suggests to put another detector after the last beam splitter and proposes to reveal the trace of the particle inside the inner interferometer through the change in the intensities detected at the two detectors (in the presence and absence of the weak measurement inside the inner interferometer). We would first like to point out that this suggestion is not consistent with his own theory. His theory considers well defined pre- and post-selection, and makes the predictions for a given post-selection, without considering the post-selection probability. Now he is suggesting to verify the prediction for a given post-selection by a different post-selection through the change in post-selection probability. This does not make any sense at all. The proposition is incorrect on another account as well. It has been previously established that the post-selection probability does not change as the result of weak measurement at the first order of measurement strength parameter [7].
9. The above faulty proposition has led the author to yet another incorrect conclusion that 'the change in the leakage and not the leakage itself is necessary for obtaining information about the presence of the particle in the paths of the interferometer'.
   The change in leakage can be from a small leakage to no leakage at all. In the 'no leakage' case the destructive interference on the output port of the inner interferometer is restored. With this destructive interference between the particle and the detector, the post-selection of the particle at the detector is not allowed in standard quantum mechanics.
   The connectivity of the wavefunction through the different regions that lead to post-selection is a basic requirement for the post-selection (in standard quantum mechanics). As a trivial example we can consider the tunnelling of a particle through the barrier, thanks to the evanescent wave in the barrier region that connects the wavefunctions on the two sides of the barrier. Letting go of this connectivity is equivalent to proposing that the particle can tunnel through the barriers having arbitrary widths. We are afraid that the author is making a similar claim by insisting that a particle from inside the inner interferometer can be post-selected at the detector in spite of having destructive interference on the way. He may argue that the connectivity is provided by the backward propagating wave, but the connectivity in standard quantum mechanics remains a very critical open question to the validity of his theory.
   It should also be noted that requiring the wavefunction to be connected through the different regions that lead to post-selection is not equivalent to asking for the trajectory of the quantum particle, as has been implied in the concluding remarks of the comment. The connectivity of the wavefunction just qualifies a class of trajectories that the particle can follow.
10. In section 5, the comment 'Introducing a transversal shifter in E causes a change in the position of the output beam at the detector. It cancels the shift introduced by the auxiliary shifter placed in C prior to the weak measurement.' needs to be clearly understood. Our claim is that according to standard quantum mechanics these are two different situations. In one case with both shifters E and C present and the destructive interference on the output port of inner interferometer, the beam is following the path A (The other arm of

the outer interferometer). In the other case with the shifter placed only along C and with tiny leakage on the output port of inner interferometer a part of the beam is coming from inside the inner interferometer leading to the shift observed at the detector.

11. Lastly, we wish to make a comment on an argument implied as ours in section 5 of the comment, 'since the leakage is crucial for reading the outcome of weak measurement, and the leakage is absent, the weak measurement will not show the presence of the particle inside the inner interferometer'. This statement is incomplete and may lead to misunderstanding. What we say in our paper is that the particle revealed by the weak measurement will not be post-selected at the detector. The correct argument will be 'The particle post-selected at the detector cannot be revealed inside the inner interferometer in the presence of the destructive interference on the way' [10].

2. Conclusion

In conclusion, we have shown that the analysis presented in the preceding comment is not sound. By suggesting that the second order trace is postulated to be neglected, the author is endorsing our point that his formalism cannot be applied to systems with multiple weak measurements. Moreover, the author has introduced new elements that are not consistent with his own theory like 'weak values that depend on weak measurement strength parameters', 'change in post-selection probability to reveal the past for a given post-selection', or which are inconsistent with standard quantum mechanics like 'change in leakage and not the leakage along the output port required to reconcile his theory with quantum mechanics'. With such inconsistent and flawed arguments the author is not able to substantiate his claim that we are mistaken in our criticism of his theory. We stand with our assertion that the paradoxical features his theory gives rise to are not present in standard quantum mechanics. Lastly we wish to emphasize that the repeated claims that such 'paradoxical features are consistent with quantum mechanics' need to be taken seriously and critically examined by the community.

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