Reply to Comment [arXiv:1610.07734] by L. Vaidman on “Particle path through a nested Mach-Zehnder interferometer” [R. B. Griffiths, Phys. Rev. A 94 (2016) 032115]

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Abstract

The correctness of the consistent histories analysis of weakly interacting probes, related to the path of a particle, is maintained against the criticisms in the Comment, and against the alternative approach described there, which receives no support from standard (textbook) quantum mechanics.

The Comment [1] deals with an analysis [2] of the path followed by a photon (hereafter a “particle”) while inside the nested Mach-Zehnder interferometer shown in the figure. The photon enters through channel $S$ on the left, encounters various beam splitters leading to channels labeled $A$, $D$, etc., and is then detected by one of three detectors. A key feature is that the beamsplitters in the inner Mach-Zehnder containing channels $B$ and $C$ are such that a photon which enters through $D$ will always emerge in $F$, never in $E$.

Figure 1: Nested Mach-Zehnder interferometer. The tilted solid lines are beam splitters; the double tilted lines are mirrors; the semicircles are detectors. The horizontal and vertical lines indicate different channels which are possible particle (photon) paths.

Of particular interest is the case in which the particle is detected in $D_1$. In [3] it was claimed that this particle was earlier in all three channels $A$, $B$, and $C$ but, somewhat mysteriously, not in $D$ or $E$. That differs from the conclusion in [2], in agreement with [4], that such a photon was earlier in $A$ and not elsewhere. These contrary claims reflect different ways of analyzing the situation. In [2] the analysis was based on the consistent histories (CH) interpretation of quantum mechanics, for which the standard reference is [5], while [3] contains a short introduction. By contrast, [3] employs a phenomenological principle which says that a

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particle can be said to have been in any location where it left a “weak trace.” One way to model a weak trace is by means of a probe which is weakly perturbed by the presence of a particle in a channel. This approach was employed in Sec. V.B of [2] using two-state or qubit probes $a$, $b$, etc. coupled to channels $A$, $B$, etc., along with a special probe $w$ coupled to the combination $B + C$; and it was claimed that the statistics of measurement outcomes on these probes supported the analysis based on a situation with no probes present, that the particle detected in $D_1$ was earlier in $A$ and not elsewhere. It is this claim that is contested in [1].

It should be noted that in the CH approach, unlike standard quantum mechanics (SQM) understood as what one finds in typical textbooks, measurement plays no fundamental role. Measurements are simply physical processes which can be interpreted by means of quantum concepts that apply to all microscopic or macroscopic quantum processes. Thus the infamous measurement problem of quantum foundations is completely missing from (or fully resolved by) CH, which also has no need of wavefunction collapse, though that can sometimes be used as a mathematical tool to obtain results accessible by other less confusing methods whose physical content is much clearer. In addition, CH provides the tools needed for using measurement outcomes (“pointer positions”) to infer something about the state of the microscopic measured system prior to when the measurement took place, thus resolving what can be called the “second measurement problem” [7]. This is done by introducing a consistent family of quantum histories, a framework, in which prior microscopic properties are represented by subspaces of the quantum Hilbert space or, equivalently, projectors onto these subspaces. The numerous paradoxes which beset SQM are avoided by use of the single framework rule, which allows the use of different frameworks, but prohibits combining results from different incompatible frameworks. As applied to the situation shown in the figure, there is framework in which a particle detected by $D_1$ was earlier in $A$ and not in $B + C$, where $A$, $B$, and $C$ are projectors on particle states in the corresponding channels. Note that the quantum projector $B + C$ does not mean quite the same things as “$B$ OR $C$"”, since a coherent superposition of two wave packets, one in $B$ and one in $C$, will lie in the subspace $B + C$, but not in $B$ or $C$ separately. No phenomenological principles are required for this analysis, since the CH formalism itself provides all the tools needed to give precise answers to questions about earlier particle locations.

For a special choice of parameters in [2] there is both a framework which allows the inference from detection in $D_1$ to the particle having been earlier in $A$, and a second framework, incompatible with the first, which can be used to infer, again from detection in $D_1$, that the particle was earlier in $C$. This is mentioned in [1], but without noting the important fact that these incompatible frameworks cannot be combined. In discussing a particular run, one or the other framework provides a possible description, but not both together, and this excludes reaching the conclusion that the particle was both in $A$ and in $C$. (For a detailed analysis of this “three-box paradox” see Sec. 22.5 of [5].) Thus when properly analyzed this example provides no support for the claim in [3] that in a single experimental run the particle can have been in several locations.

A major difference between [1] and [2] is the interpretation of the probes. In [2], after the probes interact with the particle they are measured later, after the run is over (and the particle has been detected in one of the detectors), in an appropriate basis to determine whether or not they have been triggered. If the measurement indicates the probe has been triggered, this can be used to infer using CH (but not SQM) that the particle was earlier present in the corresponding channel; e.g., it was in $B$ if probe $b$ has been triggered. However, if the probe has not been triggered this tells one very little: the particle may have been absent, or it may have present but because the interaction was so weak it failed to trigger the probe. (Think of the weak light source in Feynman’s discussion in Ch. 1 of [8] of the two hole (double slit) experiment.) As noted previously, CH makes no use of wavefunction collapse, and nothing in [1] should be understood as indicating otherwise.

The claim in [1] that coincidences do not provide useful information seems odd. If in a particular run the presence of a particle at a succession of points is indicated by reliable measurements—they may be weak, but they do not yield false positives—most experimental physicists would consider this as evidence that the particle followed a particular path, especially with detectors triggered in the proper temporal sequence, a situation obviously not practical in the case of a photon, but easily arranged in a gedanken experiment like the one in the figure by adding more sophisticated probes connected to timers. Granted, in the absence of an appropriate theory of weak measurements one can infer nothing from coincidences, but CH provides a consistent theory whose results, reported in [2], deserve to be taken seriously.

By contrast, in [1] the probe system is analyzed using collapse of the total unitarily evolved wavefunction
for the particle and the probes at a time when the particle, no longer in the Mach-Zehnder, is detected by \( D_1 \). The result is a superposition state of the system of probes including cases in which zero, one, two, etc. probes have triggered, with different amplitudes. No interpretation of such a superposition is provided by SQM; instead, one assumes that some sort of measurement will take place later, and the state just mentioned can assign probabilities to the outcomes. These probabilities for the outcomes of measurements on the probes are exactly the same as those in Sec. 5.2 of \cite{2} for the case of a particle emerging in channel \( F \), so CH and SQM agree on this. But in addition CH allows one to draw the consequence that when, for example, probe \( b \) triggered, the particle actually was at the earlier time, when it interacted with the probe, in channel \( B \). For many physicists, especially those who carry out real experiments, this will seem intuitively obvious or at least plausible, despite the fact that SQM as found in the textbooks provides no justification for it. However, the statement in \cite{1} that measuring the probe can “collapse the state of the particle to the path of the probe,” which is probably intended to mean that the particle state is collapsed to the channel associated with the probe, is not supported by CH, which makes no use of collapse, or by SQM, where collapses do not somehow cause events in the past.

The concern expressed in \cite{1}, that what happens in a run when one or several probes are triggered need not represent the situation when no probes are triggered, must be taken seriously. Looking at a small sample and extrapolating the results to a much larger ensemble is common scientific practice; think of measuring the half-life of some nuclear species and then using the results for radioactive dating. Doing this requires making some assumptions and a modicum of theory. In the case of quantum measurements there is the difficulty that these can seriously disturb the measured system. Hence it is worth noting that the theoretical structure provided by CH can make quite definite statements about the position of a particle inside the interferometer, conditioned on where it was finally detected, without any reference to weak measurements; such an analysis constitutes the bulk of \cite{2}. Weak measurements with probes are analyzed in only one section of that paper, where they are shown to be perfectly consistent with the earlier results obtained when no probes are present.

By contrast, the weak trace approach in \cite{3}, defended in \cite{1}, is heavily dependent on a certain interpretation of weak measurements by probes which, as noted above, receives no support in SQM. So the issue of deciding what happens when a probe is not triggered, or when there are no probes to be triggered, is a serious problem. Indeed, the analysis in Lao and \cite{2} identifies a specific way in which the weak trace method of \cite{3} has led to an incorrect conclusion. When the \( b \) probe associated with \( B \) is triggered it has a drastic effect: the particle which would otherwise have emerged in \( H \) has a significant probability of exiting the inner Mach-Zehnder in channel \( E \) and continuing on through \( F \) to be detected by \( D_1 \). This effect is absent when the \( b \) probe (and also the \( c \) probe) does not trigger, indicating that the conclusion in \cite{3}, that any particle detected in \( D_1 \) was earlier in \( B \) (and in \( C \)), is based on a misunderstanding of the important difference between a situation in which a particular probe is triggered and when it is not triggered. By contrast, the CH approach provides reliable quantum descriptions both in the absence and in the presence of probes, whether or not they have been triggered.

The claim at the end of \cite{1}, that the weak probe \( w \) employed in \cite{2} gives unreliable results, is incorrect. To begin with, the analogy of two charged particles is misleading: a single quantum particle in a superposition of states at two locations is not at all the same thing as two particles, one at each location. That the \( w \) probe is “nonlocal” does not make it irrelevant; see Feynman’s use of a long wavelength (hence “nonlocal”) light source in his discussion of two-slit interference in Ch. 1 of \cite{8}. What the \( w \) probe measures is the property represented by the projector \( B + C \), which in quantum mechanics, as noted above, does not mean the same thing as “\( B \) or \( C \)”. Its reliability is confirmed by noting that for particles detected in \( D_3 \) rather than \( D_1 \) the rate at which it is triggered is exactly what one would expect. That it fails to indicate the presence of a particle later detected by \( D_1 \) is just what one would expect if that particle was never in \( B + C \), as maintained in \cite{4} and \cite{2}, contrary to \cite{3}. What the \( w \) probe does not do, unlike \( b \) or \( c \), is perturb the phase of a particle passing through the inner \( B + C \) Mach-Zehnder, and it is by ignoring this phase perturbation that \cite{3} has arrived at an incorrect result.

In conclusion, while the phenomenological principle embodied in the notion of a weak trace may sometimes be of value, its use in \cite{3} and \cite{1} has no support in standard quantum mechanics, and can give misleading results. By contrast, the consistent histories approach, which has no measurement problem and has resolved numerous quantum paradoxes, provides a consistent description of a particle passing through a nested Mach-Zehnder interferometer, including its weak interaction with probes should some be present.
References

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