Delayed Choice and Weak Measurement in the Nested Mach-Zehnder Interferometer

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Abstract: This note discusses interpretation of recent weak nested interferometer measurements in terms of state vectors traveling both forward and backward in time. A compatible quantum impedance interpretation is presented. Delayed choice variants are proposed.

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1. Introduction

Wheeler's delayed choice thought experiment [1] has three requirements; that it be performed with a single quantum particle initially in a pure state, that the particle enters an apparatus that creates an entangled superposition of eigenstates, and that the choice of detector used to project out one eigenstate be made after creation of the superposition.

In Wheeler's interpretation, there is in this experiment "...a strange inversion of the normal order of time." It suggests that the delayed choice retrodicts the wavefunction collapse backward in time to the entry of the particle into the apparatus that creates the superposition. That interpretation preceeded the ever more convincing demonstrations of the counter-intuitive reality of quantum non-locality [2]. These days it's more clear that there's no inversion of time, rather just standard quantum mechanical instantaneous nonlocal reduction of the unobserved entangled eigenstates.

The apparent time reversal observed in recent weak measurements [3] of the nested Mach-Zehnder interferometer is not so easily brought into perspective. Those measurements appear to provide experimental support for the time symmetric two state-vector formalism (TSVF) of quantum mechanics [4, 5], and in particular for weak (and only weak?) observation of the backward evolving state vector. In what follows one of the configurations employed in those measurements is presented, and reference is made to the results and their TSVF interpretation.

The possibility has been suggested [6] that the scale-invariant quantum Hall and far-field photon impedances are channels by which phase information is communicated in both local and non-local state reduction. An interpretation of the weak measurement results in terms of these impedances is presented.

2. The recent nested interferometer experiment

Figure 1 is a schematic of the apparatus used in the recent weak measurements [3], along with the observed spectrum for the configuration shown. The reader is encouraged to consult that paper and a similar one [7] for further details.

There are two confounding aspects to the appearance of f1 and f2 in the spectrum, while f4 and f5 are absent. First, the only routes out of the inner interferometer are via either or both of mirrors M4 and M5. How can photons modulated by M1 and M2 get to BS2 without having their trajectories similarly modulated by M5? And second, photons can't get from BS4 to M5 in the first place. The inner interferometer is phased such that there is destructive interference at the BS3 and BS4 ports facing M4 and M5. Photons can enter via the mirrors, but cannot exit via the mirrors. Intuitively, one would think that either aspect would be sufficient for absence of f1 and f2 from the spectrum.

The TSVF interpretation of the photon in this interferometer includes the conventional positive frequency forward wave departing BS1 at t=-3 and arriving at BS2 at t=+3, and the less familiar negative frequency backward wave simultaneously departing BS2 at t=+3 and arriving back at BS1 at t=-3. The backward wave could be considered a reflection of the forward wave from BS2, a reflection moving backward in time, perhaps in some 'many worlds' sense the entangled eigenstate that was not projected out at BS2 and measured at the detector.

The TSVF interpretation provides a partial explanation of the observed spectrum: The photon could be seen by weak measurement only where both forward and backward waves were present. There are at least two obvious questions.

First, why does weak detection appear to require the presence of both forward and backward waves?

A plausible simple answer is that weak measurement of quantum phase is possible as a result of interference in *either* space *or* time [8], that the requirement for a phase reference at mirrors M1, M2, and M3 can be satisfied by

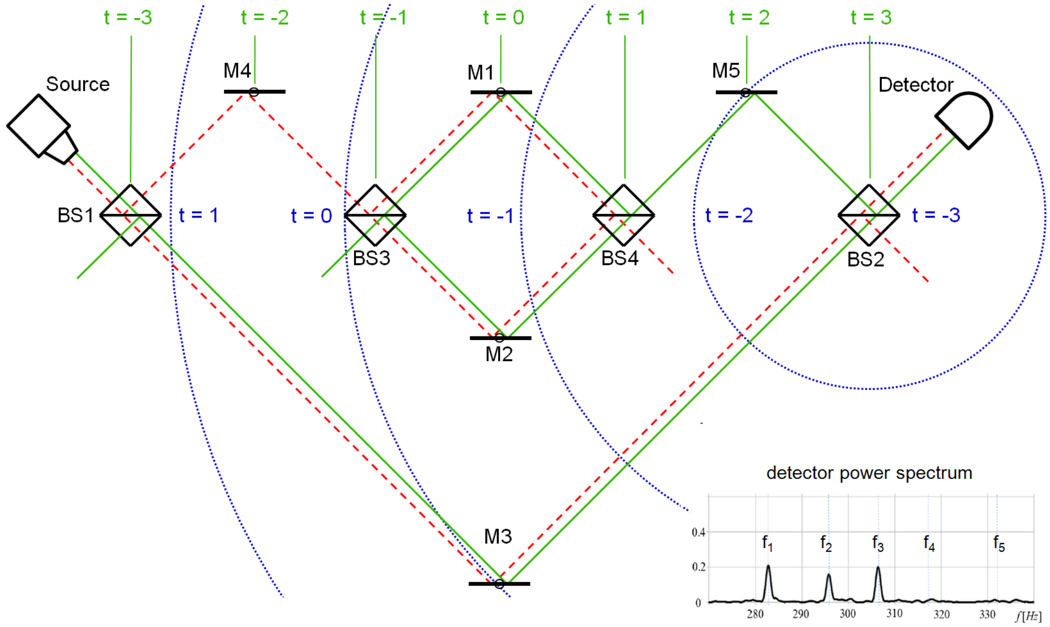

Fig. 1. Red broken lines are the forward waves, green solid the backward waves. Green timestamps are for the TSVF interpretation. Blue timestamps and circles are for the impedance model. Unit of time is that taken for instance by a photon to travel from BS1 to M4 or BS2 to M5. Time symmetry follows from exchanging the roles of source and detector. As shown, signals from micro-oscillations of mirrors can be measured in the position-sensitive detector power spectrum.

entangled eigenstates that are nonlocal in time as well as space, and that interference between forward and backward waves at the mirrors satisfies this phase reference requirement.

And second, how does the phase information get from the inner interferometer to the detector?

A partial answer [7] could be that "...weak coupling to the measuring device slightly spoils the destructive interference and a tiny wave goes toward the second beamsplitter of the large interferometer."

Weak amplification [9] also takes a role. An explanation [7] of the approximately equal levels of f1 and f2 relative to f3 in the power spectrum suggests that "...due to the amplification effect of post-selection, the shift ... is comparable with the shift caused by a particle which is fully present near the measuring device." The argument here seems to be that if enough weak measurement statistics could be gathered, f5 would emerge from the noise floor down from f1 and f2 by the magnitude of the weak amplification gain.

However, a first order effect of mirror M5 is to introduce a half-wave phase shift, required for appearance of the photon at the detector. How can the oscillating mirror provide the essential full strength longitudinal phase shift sans weak amplification without simultaneously and observably perturbing the transverse photon trajectory? Even with leakage and weak amplification the path between the inner interferometer and the detector remains cloudy.

3. Testing the TSVF Interpretation

A recent experimental realization [2] of Wheeler's thought experiment [1] utilized an electro-optic modulator (EOM) to accomplish the delayed choice, to insert or remove the final beamsplitter from the interferometer. The same technique can be employed here, sweeping the insertion time of BS2 relative to the entry of the photon at BS1. The weak measurement [3] found phase shift only where both forward and backward waves were present. Introducing the time degree of freedom via the EOM permits some control of when and where both are present.

The assumption here is that once BS2 is inserted by the EOM it remains inserted until the photon is detected. If we require that both waves be present at mirrors M1 and M2 for their signals to appear in the power spectrum, for insertions at or before t=3 the signals should be present. For later insertions there should be no signal.

Single versus multiple photon operation is also a consideration [10].

4. Testing the Impedance Interpretation

Scale invariant impedances cannot be shielded [6, 11]. Once an EPR photon pair is launched, the photons remain entangled by their scale invariant far field impedances irrespective of obstacles placed in the path joining them after their passing. Similarly, the scale invariant Lorentz and centrifugal impedances responsible for phase shifts (this is what complex impedances do - they shift wave phases) operative in the Aharonov-Bohm effect cannot be shielded.

How does one switch impedances that cannot be shielded?

In the AB effect one simply switches the current in the shielded loop. In principle, one would think that a delayed choice AB experiment would show that the onset of phase shift experienced by the entangled eigenstates of the electron that passes on both sides of the shielded flux quantum is not instantaneous. The conjecture here is that the onset sits on the light cone of switching of the shielded current loop, and that this is subject to experimental verification.

An analogous photon interferometer switch would permit to insert the unshieldable invariant impedance with a bandwidth comparable to that of the EOM used in the TSVF test. When BS2 is inserted, the 'impedance wave' propagates outward as shown by the blue light fronts. If inserted at t=-3, simultaneous with the entanglement of the input photon by BS1, then the impedance wave and the photon arrive at mirror M3 simultaneously, at t=0.

The point here is that this is not true for M1 and M2. As can be seen from the figure, the rising edge of the unshieldable t=0 impedance wave passes through the inner interferometer and beyond BS3 before the photon enters. Due to the geometry of the layout, in both time and space the photon travels a path that is $\sqrt{2}$ longer than the direct path taken by the rising edge of the unshieldable impedance wave. By virtue of the geometry, differential phase information is available in the interferometer experiment that is absent in the AB effect. For insertions before t=-3/$\sqrt{2}$ (as opposed to t=+3 for the TSVF interpretation) the signals from M1 and M2 should be present. For insertions later than that, there should be no signal.

The greatest obstacle to realization of this experiment appears to be the implementation of BS2. In the case of the photon, exactly how does one switch the unshieldable scale invariant impedance? This question and those that follow from its answer (including a more detailed exploration of the absence of f5 from the detector spectrum) will hopefully be addressed in more detail in following notes.

5. Conclusion

There appears to be a connection between the invariant impedances, weak measurement, and time symmetry. Invariant impedances transfer no energy, only phase. Weak measurement measures phase, which is acausal. Thus the impedance model is compatible with a time symmetric TSVF of state vectors coupled by invariant impedances only.

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