The Fallacy of the Attenuating Quantum Eraser

I present an analysis of the quantum erasing effect which categorizes the effect into attenuating and non-attenuating phenomena. It is shown that the attenuating quantum eraser is typically explained in a spurious fashion, and insight is given concerning the real phenomenon of interference between distinguishable states that would properly explain the attenuating eraser.

Interference Between Distinguishable Sources

In an earlier paper[1] I discussed the effect of interference between distinguishable states, and the current document is a clarification of the ideas presented there. The simplest explanation of interference in quantum mechanics without reference to a specific species of system or a specific arrangement involves the "bra-ket" formalism. The *detection probability* or *intensity* measurement in quantum mechanics is always calculated with an expectation value of an operator, a bra-ket. The bra-ket for a detection always has a final state of the absorbing system in the measurement, F, and an initial state of the absorbed system, G (for simplicity we have assumed that the measurement is an absorption). Both of F and G are total states of the system, so they may both actually be expressed as superpositions of simpler eigenstates of operators of the system in the chosen representations. In quantum mechanics, we assume that the transformation of the state is a unitary one-to-one mapping of all eigenstates of the initial system to the eigenstates of the final system. The bra-ket between these states, <F|G>, (without any operator in between) represents the probability of the system starting and ending in these states and because G and F are total states, this bracket must be unity. But this is only the probability of the state being the correct state, not the detection probability. The detection probability would evaluate the bra-ket with an operator in the expectation value, but this is specific to the case that one is analysing. Because we wish to generalize, we will keep our discussion to the probability bra-ket alone.

In interference we would prepare the two sources of an individual system coherently (but not necessarily in the same state). Let's call the states of the two possible sources of the system $|G^1>$ and $|G^2>$ where the superscripted 1 & 2 indicate the different source paths (different coordinate representation vectors). The main point is that *if we wish to get interference we must have a final state of the measuring system, F, which is one-to-one with the superposition of the two possible initial states of the measured system,*

$$2^{-\frac{1}{2}}\{|G^1> + |G^2>\} \;\; \rightarrow \;\;\;\; |F>$$

If this is fulfilled, then the measurement (absorption) of the interfering system is a projection onto the coherent superposition state at the time of measurement. This is absolutely necessary because the final state of the measuring system selects out this initial state of the measured system.

The problem with the conventional interpretation of interference in quantum mechanics is that it is always assumed that the set of possible final states of the measuring/absorbing system is a complete set of eigenstates of the measuring system's operators. If this is the case then the final states of the measuring system will be one-to-one with the complete set of eigenstates of the measured system's operators. This means that we could not have two possible sources of the interfering system that were in any way distinguishable, because this distingushability of the two sources would have to be a difference in the eigenstates of the two possible sources (a difference other than the fact that they have different paths). This distinguishability would show up in the final states of the measuring system, as it would be *in principle possible* to then measure the absorbing system to determine its eigenstate which

would then indicate which eigenstate the absorbed system was in and this would then indicate which of the two sources the system came from. This possibility of path information is not allowed in interference. It is fundamental to all interference effects that *the source path of the interfering system not be knowable in principle by virtue of any measurement at or after the time of measurement of the interfering system*.

The way around this problem, the way to allowing interference between two distinguishable states, is to use a measuring system which only allows a final state of the absorbing system which is one-to-one with a superposition state of the two distinguishable eigenstates of the interfering system. This way the interfering system is coherently projected onto a superposition of its distinguishable eigenstates at the time of measurement. The obvious example of this effect in optics is the effect of interference between two sources that have distinguishable polarization eigenstates, which can only be measured with a polarizing measurement device. When coherent overlapping beams with orthogonal polarizations are absorbed by a polarizing material, with its axis directed half way between the polarization directions of the two overlapping beams, then the absorption by the polarizer (which is a measurement similar to a detector) is actually displaying interference between the two beams. The two coherent beams are projected onto the state of polarization that is a superposition of the two orthogonal polarizations at the time of absorption. This is because the polarizer only absorbs this state.

The Attenuating Quantum Eraser

With the above stated interpretation of interference we may now consider what is happening in the preparation of the quantum eraser effect[2]. Specifically we consider the case of a quantum eraser which is based upon a single photon interference effect[3] with a half wave plate and polarizer as the path marker and path eraser respectively. But first we wish to categorize the quantum eraser into two branches which requires a brief explanation of the erasing effect. In the quantum eraser there is a simple three stage protocol which most modern erasers follow; having an established interference effect, introducing a change to the preparation of the interfering system that marks one path and destroys interference (the path marker), and introducing another change to the preperation that allows interference again (the path eraser). When the path marker is introduced we will not collect interference and we will collect a measurement of *spontaneous emission* of the system. When the path eraser is introduced we will collect interference at the measurement site, but this interference will often be attenuated by that of the path eraser. This is where we categorize things, if the path eraser attenuates the intensity of the beam that we're measuring then we have an attenuating quantum eraser. If the path eraser does not attenuate the system then we have a normal quantum eraser.

Consider the simple form of quantum eraser in Figure 1, that of the Mach-Zehnder style attenuating quantum eraser with horizontally polarized (H) light. The Mach-Zehnder is an amplitude splitting interferometer where the pump light is split with a 50/50 beam splitter (BS), then recombined with a second 50/50 beam splitter at identical optical path lengths (to within a coherence length) and detected as an interferogram by varying the optical path difference. Basically, the intensities of the two detections always add to the total intensity emitted, but as the path difference is varied the relative intensities at the two detectors varies with it. However, in our example in Figure 1 we start with horizontally polarized pump light and there is a half wave plate (HWP) placed in one path that has the effect of rotating the polarization of the light to vertical polarization (V). This alone, adding the HWP as a path marker, results in destroying the interference pattern and the detectors would each display half of the spontaneous emission from the source regardless of the path difference. The interference with path difference is recovered by placing the ±45° polarizers in between the second beam splitter and the detectors. Both polarizers must have the same polarization, either of +45° or -45°. These polarizers are the "path erasers" in the experiment. The interference that results is dependent upon the choice of

angle; if the polarizers are at +45° polarization then we observe the fringe pattern of the original interferogram with a reduced intensity, and if the polarizers are at -45° polarization then we observe the anti-fringe pattern, where the constructive and destructive interference are interchanged, of a similarly reduced intensity. The intensities of the fringe and anti-fringe patterns are such that they add to produce the non-interference pattern of spontaneous emission (that which would be achieved with the HWP and no polarizers).
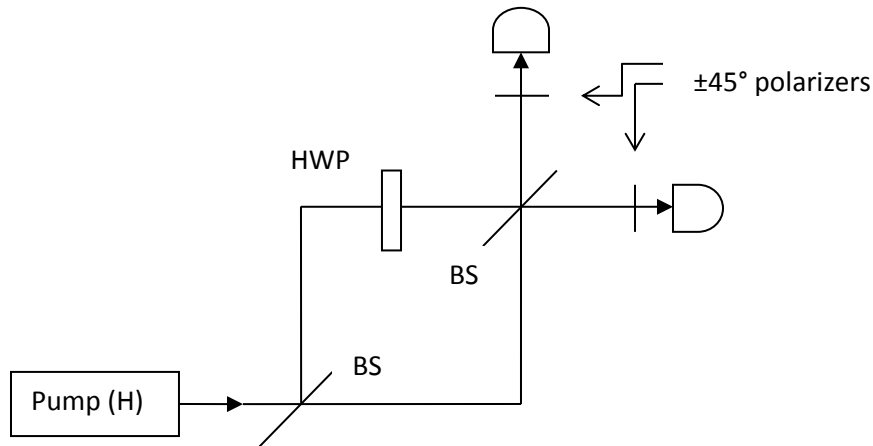

Figure 1 The Mach-Zehnder Style Attenuating Quantum Eraser : Horizontally polarized pump light is incident upon a beam splitter (BS). A half wave plate (HWP) is placed in one path which rotates the polarization to vertical. The two distinguishable beams are then combined at another beam splitter where the outputs are then made incident upon ±45° polarizers and detected. The HWP is the *path marker* and the polarizers are the *path erasers*. We ask, are the ±45° polarizers the *real* detectors?

For purposes of discussion, we assume that we have chosen the +45° polarizer angle for the path erasers. It is noted that the polarizers may be absorptive or reflective, and we assume for simplicity that the polarizers are absorptive. If the polarizers are absorptive then *in principle* the absorption is displaying a measurement. We would argue that this measurement is the *true* detection event which displays interference because it is absorbing the -45° polarized light in a manner that would display the anti-fringe pattern (if we were actually measuring the amount absorbed), and the polarizer allows the portion of +45° polarized light to pass where it is subsequently measured in the fringe pattern at the detector. The point is that the *real* measurement that produces the interference is occurring when the distinguishable polarization states of the two beams are coherently projected onto the state of superposition, and this is occurring at the polarizer. The exact time of "projection onto" is always the time of "update to the state description" which is always at the time of measurement. When we have a quantum eraser protocol where the path eraser is absorptive then the time of measurement is the time of absorption.

We should note that the absorptive polarizing material that is being used as the path erasers could easily have been replaced by a combination of a polarizing beam splitter and two detectors at each output of the interferometer. The polarizing beam splitter could be set up to split the polarizations of +45° and -45°, so then any old detector would be sufficient to display the interference measurement. In this case the projection onto the ±45° polarization is occurring at the detector but it only occurs because of the evolution of the state through the polarizing beam splitter. This would not constitute an attenuating quantum eraser because none of the light is being lost via absorption.

This discussion is helped by reference to the *selection of subensembles* that occurs in all quantum eraser protocols. In the quantum eraser we have an interference effect that is hindered by the presence

of a path marker, and the sole effect of the path marker is to entangle the path with another degree of freedom of the system so that interference is not observed. Let's call this entangled degree of freedom the α degree of freedom, so that the entanglement associates path 1 and path 2 with eigenstates α_1 and α_2 respectively. The quantum eraser effect is then completed by adding a path eraser to the experiment, and the sole effect of the eraser is to evolve the state description of the system so that it is *ready for projection onto α substates of the system by virtue of any position measurement*. How is this achieved? The eraser must path split the system into two subensembles of α states, where the choice of α substates is specifically intended to be such that each substate may have resulted from the exact α_1 or α_2 states with equal likelihood. If the α degree of freedom is polarization (α_1 and α_2 become H and V) then the path marker must have entangled the two paths with the orthogonal H and V polarization states, and the appropriate path eraser is a 45° polarizer which will split the system into two subensembles of orthogonally polarized light (±45°) that could have resulted from the H-polarized or V-polarized state with equal likelihood.

To illustrate this protocol, we will correct the attenuating quantum eraser protocol of Figure 1 with a substitution of the appropriate apparatus as path eraser. This is shown in Figure 2 where we have an identical experimental setup to that of Figure 1 except with +45° polarized pump light and a different form of path eraser. In Figure 2 the +45° polarized pump light is directed to a normal 50/50 beam splitter and the outputs are recombined with another 50/50 beam splitter at identical optical path lengths (to within a coherence length). The half wave plate on the upper path has the effect of rotating the polarization of the light to that of -45° polarized. The path degree of freedom is then entangled with the polarization, as the upper path has -45° and the lower path has +45°. The recombined beam has two outputs that are both analysed with a polarizing beam splitter (PBS) and two detectors. The PBS has the effect of allowing H-polarized light to transmit and the V-polarized light will reflect, so all light will reach a detector. Because +45° and -45° polarization states can both be decomposed into equal portions of H and V polarization, and because each output of the second BS is an equal mixture of +45° and -45° light, we should expect that the four detectors all display similar intensities of light. However, because the PBSs act as path erasers we should expect interference to be recovered.
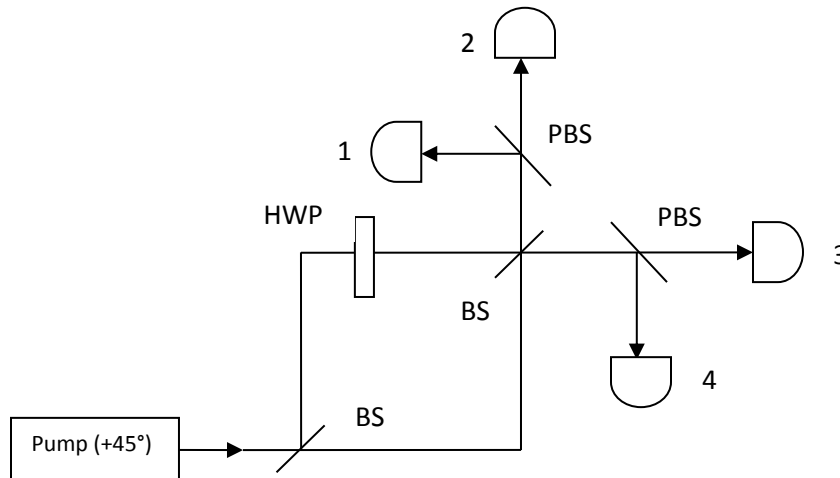

Figure 1 The Mach-Zehnder Style Non-Attenuating Quantum Eraser : +45° polarized pump light is incident upon a beam splitter (BS). A half wave plate (HWP) is placed in one path which rotates the polarization to -45°. The two distinguishable beams are then combined at another beam splitter where the outputs are then made incident upon polarizing beam splitters (PBS) and detected. The HWP is the *path marker* and the PBSs are the *path erasers*. No attenuation required, and all data preserved.

Indeed, interference is recovered. The four detectors will display intensities in a manner that all the H-polarized light will be detected at detectors 2 & 3 and the V-polarized light will be detected at detectors 1 & 4. For each output of the second BS, the polarization (±45°) is entangled with the path. The PBS that follows will split the mixed ±45° polarized wave into H and V polarized light that is then detected. This is the exact protocol of guidance that we have suggested for the non-attenuating quantum eraser. The path eraser (the PBS) has path split the system into two subensembles of polarization states, where the choice of polarization subensembles (H & V) is such that either may have resulted from the entangled +45° and -45° states with equal likelihood. In order to collect interference we simply vary the optical path difference and collect an interferogram for each detector. Detectors 2 & 3 will display a fringe pattern with a central maxima and detectors 1 & 4 will display an anti-fringe pattern with a central minima. Naturally, the fringe and anti-fringe patterns will add to that of the total spontaneous emission that is emitted from the source.

Conclusions

  We note that the protocol of Figure 1, our example of an attenuating quantum eraser, is both inefficient and misleading. The attenuating quantum eraser always loses half of the data, because in any given trial we may only collect the fringe or the anti-fringe pattern. For this reason it is inefficient. The attenuating quantum eraser is also misleading, because it leads one to the conclusion that in fact interference is being collected at a detector that can't display interference between distinguishable sources where there is path entanglement. The *real* detector in this case is the polarizer which does display interference between distinguishable sources.

  I now mention a list of quantum eraser protocols which may or may not be attenuating, and for each I offer interpretational advice.

- In reference 3 we have an attenuating quantum eraser which does not explain the erasing preparation in terms of interference between distinguishable states. It does not recognize the polarizer as the true detector.
- In reference 4 the authors present a perfect non-attenuating quantum eraser.
- In reference 5 the authors present a perfect non-attenuating quantum eraser. However the authors describe the generalized quantum eraser protocol on page 3 with reference to an attenuating quantum eraser, and they do not explain this erasing preparation in terms of interference between distinguishable states.
- In reference 6 the authors present a quantum eraser which measures second order interference in the coincidence counts of downconverted photons. The downconverted photons are analysed with a HOM interferometer to measure an interference dip in the coincidence counts. To achieve quantum erasure they use a HWP to mark one path and then they use a pair of polarizers as the path erasers. This is a second order attenuating quantum eraser. The *true* detectors where the HOM dip should be measured are the polarizers. If the authors had measured the absorption rates of the polarizers they would have measured a similar dip in the coincidence counts.

References

1) Thomas Alexander Meyer, *Interference Between Distinguishable States*, (2013), available at http://www.vixra.org/abs/1305.0185

2) Marlan O. Scully and Kai Druhl, *Quantum Eraser : A proposed photon correlation experiment concerning observation and "delayed choice" in quantum mechanics*, *Phys. Rev. A*, **25**, 2208 (1982).

3) Rachel Hillmer and Paul Kwiat, *A Do-It-Yourself Quantum Eraser*, *Sci. Am*., 90 (May 2007).

4) Peter D. D. Schwindt, Paul G. Kwiat,1, and Berthold-Georg Englert, *Quantitative wave-particle duality and nonerasing quantum erasure*, *Phys. Rev. A*, **60**, 4285 (1999).

5) Paul G. Kwiat and Berthold-Georg Englert, *Quantum Erasing The Nature Of Reality Or, Perhaps, The Reality Of Nature?*, *Science and Ultimate Reality: Quantum Theory, Cosmology, and Complexity*, (Cambridge University Press), 306 (2004).

6) Paul G. Kwiat, Aephriam M. Steinberg, Raymond Y. Chiao, *Observation of a "quantum eraser": A revival of coherence in a two-photon interference experiment*, *Phys. Rev. A*, **45**, 7729 (1992).