Wheeler's Delayed Choice Experiment

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1 Introduction

Wave-particle duality of light has dumbfounded physical scientists for centuries. Sir Isaac Newton contended that light was made up of individual particles while Hooke (who was utterly despised by Newton) wrote on the wave-like properties of light.[6] In 1801, Thomas Young's double slit experiment demonstrated wave-like properties of light. In 1905, Einstein revisited the theory of light acting as a particle to resolve conflicts between the wave theory of light and certain experimental results such as the photoelectric effect.[11] Experiments confirming particle-like properties of light were not realized until later in the 20th century. In 1981, Grangier, Roger and Aspect published a paper titled *Experimental Evidence for a Photon Anticorrelation Effect on a Beam Splitter: A New Light on Single-Photon Interferences.* This paper reported on one of the first successful anticoincidence experiments which measured the particle-like behavior of light. The paper also reported on an experiment that used the same source and detection scheme as the anticoincidence experiment, which measured interference. Grangier, Roger and Aspect eloquently depicted the conundrum of the wave-particle duality of light. To what extent does this this complementary nature of light exist? How does light know when to display wave-like or particle-like properties? One popular answer to this was that light can 'sense' what the experiment is attempting to measure. Based on the initial 'feel,' light would decide whether or not it will display wave-like or particle-like behavior before entering the experiment. This hypothesis is aptly named the conspiracy theory.[2]

2 Wheeler's Experiment

Wheeler came up with a theoretical experiment that would test the conspiracy theory in 1978. The Delayed Choice experiment changes the boundary conditions of the Schrödinger equation after the particle enters the first beamsplitter. If the conspiracy theory were to hold true, the *initial* conditions of the experiment would be all that mattered to the photon and it could be 'fooled' into acting like a particle in a wave experiment or vice versa. Einstein believed this

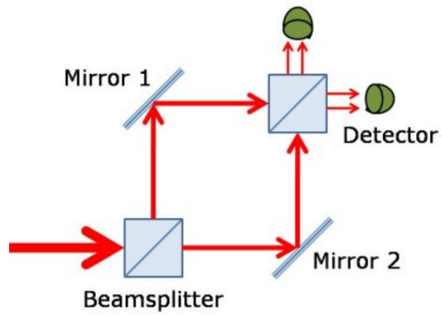

Figure 1: A Mach-Zehnder Interferometer

to be the case. Bohr, on the other hand, believed that the photon would behave like a particle or a wave based on the *final* boundary conditions. Wheeler described his delayed choice experiment with a Mach-Zehnder interferometer (superimposed on a baseball field, but I will leave the clever analogies alone for now) depicted in figure one.[3]. In his experiment, photons would enter a half-silvered beam splitter that reflects half the light towards path R and lets the other half goes through to path T. Two regular mirrors then reflect the light towards a second beam splitter. The experiment would be set up to show constructive interference occurring in the D2 detector, thus proving that all photons took *both* paths.[8] If the beam splitter is removed, the experiment becomes a 'particle' measuring experiment and the photons either take path T *or* path R. We can therefore choose whether or not the photons will travel through both paths or just one. In Wheeler's words:

> We can therefore choose whether the individual photons should act schizophrenically or not.[8]

The decision of whether the second beam splitter is to be inserted must occur *after* the photon enters the first beam splitter, thus putting the difference between the classical and quantum predictions to the test.

2.1 Experimental Realizations

In 1984, the first delayed-choice experiment was successfully carried out.[8] Since then there have been several more precise and technologically advanced delayed choice experiments. A German group led by Baldzuhn, Mohler and Martienssen published a delayed choice experiment using a Mach-Zehnder interferometer and photon pairs produced by paramagnetic fluorescence. Although the experiment was limited in its technology (the rate of coincidences were lower than expected and visibilities in the interference patterns were much less than 100 percent [1]), the experiment yielded similar results to the slightly earlier works of another German experimental group. Hellmuth, Walther, Zajonc and Schleich wrote on two experiments; one using a low-intensity Mach-Zehnder interferometer and the other using quantum beats in time-resolved atomic florescence. The experiment showed the same results for measuring spatial- and time-domain interference experiments.[4] A more recent experiment performed in 2007 attempted to replicate Wheeler's original thought experiment as closely as possible. Jacques et al. used a single-photon pulse that entered the first beam splitter and then traversed one of two 48 meter-long paths before either entering a second beam splitter or hitting the detectors. The choice of whether or not the second beam splitter is present is decided by a quantum random number generator.[5] This elegant experiment was the first to use a single photon.

2.2 Weird Results: Common Sense Looses!

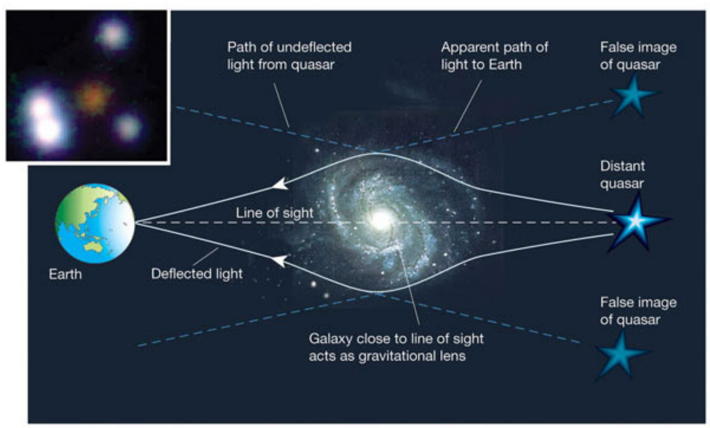

Figure 2: An Extreme Delayed Choice Experiment

All of the experiments mentioned above produced results in agreement with *quantum* theory. It does not seem to matter when the boundary conditions of the experiment are changed; only the *final* boundary conditions of the experiment will affect whether light takes on wave-like or particle-like properties. It was even proposed by Englert, Scully, and Walther that perhaps changing the boundary conditions after the experiment had taken place would change the path of the particle, though this was quickly disproved.[7] Since quantum theory does not measure single events, these results do not pose any conflicts in this area. This does, however, defy common sense. The results conclude that *after* a particle has traversed a certain path, the path it took can then change. A more severe example is depicted in *The Quantum Challenge* when Greenstein explains a hypothetical delayed-choice experiment using a quasar.

Light from the gravitationally lensed quasar (see figure 2)[9] is passed through a delayed-choice experiment on earth. If we then put in a second beam-splitter, according to our previous results, billions of years of history could be altered.[2] This forces three interesting questions:

1) What is the quantum explanation?
2) Do these results truly violate causality or can they be resolved classically?
3) Who counts as an observer?

3 Some Quantum Thoughts

In quantum mechanics, there has been a long-standing debate to the location of a particle just before it is measured. The most widely-accepted answer was previously the Copenhagen interpretation. This states that the time evolution of the wave function of a particle is unitary (preserves normalization) until the particle is measured. The very act of measuring the particle then collapses the wave, in a non-unitary way, into a single position. This once again forces the question, "Who counts as an observer?" In his Ph.D. thesis, Hugh Everett III asked what would happen if the time evolution of the whole universe was viewed as unitary? Though this idea would avoid the observer question, it would mean that instead of the wave function collapsing, the observer of a measurement would enter a superposition of possible outcomes. [8] Although it was not proven to be wrong, most physicists ignored Everett's claim on the basis that it was too weird. Einstein held that physical theories must be deterministic to be complete, and since these were non-deterministic ideas, there must be some other 'hidden variable' that has not been taken into account. As Einstein famously said, *"I can't believe that God plays dice."*[10] Bell's theorem showed that there is no way to reproduce quantum-mechanical predictions with any local hidden variable theory. The next step in quantum-mechanical understanding of the delayed-choice experiment was kicked off by Dieter Zeh of the University of Heidelberg. In his paper *On the Interpretation of Measurement in Quantum Theory*, Zeh showed how the Schrödinger equation had a type of censorship. [12] This effect is what came to be known as decoherence.

3.1 Along Came Decoherence

Decoherence provides an explanation for why Schrödinger's equation appears to collapse upon measurement. The short version is that entanglements are generated with almost all systems and their environment. Viewed together, the system plus environment evolve in a unitary fashion. Measure the system alone, and the system's dynamics are non-unitary. Decoherence is often studied using density matrices, which are statistical generalizations of wave functions. To illustrate, consider a simple experiment in which a coin is tossed. There are two possible outcomes, so the state of the system is represented by the two by two density matrix shown below.

$$\rho = \begin{pmatrix} a & b + \imath c \\ b - \imath c & 1 - a \end{pmatrix}$$

The diagonal elements are probabilities for the outcomes 'Heads' and 'Tails.' The off-diagonal elements are complex conjugates representing, loosely speaking, the amount of quantum superposition between the two states. For a classical coin toss, there is no such superposition and the density matrix is

$$\rho = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$$

Decoherence theory predicts that interactions with the coin's environment will tend to rapidly push any off-diagonal elements towards zero, replacing any quantum superposition with classical probabilistic ignorance.[8] Observing the outcome of a coin toss changes the diagonal elements in a non-unitary way.

$$\rho(Heads) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \qquad \rho(Tails) = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

The 'observer' responsible for decoherence can be anything that interacts with the coin: a dog, a cat, or even an electron. This explains why superpositions are not routinely seen macroscopically; it's extremely difficult to keep large systems (like Schrödinger's poor cat) isolated from the environment. It's much easier to keep microscopic objects - say, a photon in a delayed-choice experiment - isolated so that they may keep their secrets and quantum behavior [8].

4 Classical Sense

Whereas there is perhaps sense to be made in the quantum world, is it possible to relate these experimental findings to classical physics? I found one paper by S. Zhao et al. based on the 2007 experiment *Experimental Realizations of Wheeler's Gedanken Experiment* mentioned earlier. This paper provides an event-by-event computer simulation of the Wheeler experiment, with the authors concluding that it was possible to give a particle-only description of the experiment.[13] The authors contend that many particles hitting a detector can eventually show interference patterns. While this paper stays far away from quantum theory, it does propose a realistic, classical explanation for the delayed-choice findings.

5 Conclusion

Wheeler's delayed choice thought experiment put the wave-particle complementarity principle of quantum mechanics to the test. Several experiments conducted over several decades showed that the quantum prediction of the experiments' outcomes was more correct than the 'common sense' classical predictions. Interpretation of the findings is still a matter of debate. Some physicists are attempting to find a classical interpretation - in some cases, completely ignoring quantum mechanics altogether - while others consider the experiment relevant to explaining quantum decoherence. As with many classic thought problems, the realization of Wheeler's delayed choice experiment has answered one question and created several new ones.

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