Rethinking a Wheeler delayed-choice gedanken experiment

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Abstract: Based on an unconventional interpretation of quantum experiments, this article proposes that wave-particle duality is false. Instead, we are immersed in an ocean of zero-energy waves, which particles follow. Our theory is supported by our interpretation of a Wheeler delayed-choice gedanken experiment, experiments involving excited Rydberg atoms in a resonant cavity, and a neutron interferometer experiment. © *2012 Physics Essays Publication*. [DOI: 10.4006/0836-1398-25.3.390]

Résumé: Sur la base d'une interprétation peu conventionnelle des expériences quantiques, cet article explique que la dualité onde-particule est fausse. En fait, nous sommes plongés dans un océan d'ondes d'énergie zéro que les particules suivent. Notre théorie est soutenue par notre interprétation d'une expérience "gedanken" de Wheeler de choix retardé, ainsi que par les expériences impliquant des atomes excités de Rydberg dans une cavité résonnante et l'expérience de interférométrie de neutrons.

Key words: Jacques; Wheeler; Wave-Particle Duality; Theory of Elementary Waves; TEW; Lewis E. Little; Interferometer; Complementarity.

I. INTRODUCTION

This essay makes some ontological claims that wave-particle duality is untrue and that we are immersed in an ocean of zero-energy waves, which particles follow. The particles carry all the energy and momentum. Every particle has an associated wave, as Louis de Broglie said, but there are also waves that are independent of all particles. Usually particles and waves travel in opposite directions. These claims are presented as an alternative to wave-particle duality. To make such assertions, we need to demonstrate how we would interpret at least one of the delayed-choice experiments of quantum mechanics (QM).

The experiment we will select is Jacques *et al.* "Experimental Realization of Wheeler's Delayed-Choice Gedanken Experiment," published in *Science* in 2007.[1] When we have discussed this experiment at meetings of the American Physical Society, most of the audience tells us that they do not remember what the experiment was. Therefore, we need to describe the experiment, before we reinterpret it.

Briefly, the experiment consists of an interferometer of 48 m width, which it takes a photon quantum 160 ns to traverse (see Fig. 1). After the photon quantum has entered the interferometer, the experimenters assume it has committed itself to being either a wave *or* a particle, but not both. The experimenters then throw a switch called an electro-optical modulator (EOM), which determines whether the quantum is going to be observed as a photon or as a wave. If the EOM is turned off, it is the "open" configuration of the interferometer, which allows a photon particle to be detected. If the EOM is turned on, it is the "closed" configuration used for detecting a wave. This switch takes 40 ns to change and is controlled by random numbers, while the photon is inside the interferometer. This is said to be a "delayed choice" experiment because the EOM is switched on or off after the quantum has entered the interferometer and presumably committed itself to traveling as a wave or a particle.

The final data are those predicted by Wheeler and indicate that the choice of observables determines whether the photon quantum had previously committed itself to acting like a particle or a wave.[2] Such conclusions also support Bohr's proposal that the final position of detectors will determine what previously happened inside a QM experiment. We are speaking here from the viewpoint of the experimenters, a viewpoint that we will later argue is wrong.

There are various ways to interpret these peculiar results from the experiment of Jacques *et al.* One could claim that there is backward-in-time cause and effect. In other words, the random choice of EOM position causes the photon quantum to choose to act like a wave or a particle, at an earlier point in time. One could claim that it supports complementarity, according to which nothing can be known about what happens inside an experiment; all we can know is the data gathered from the detectors, because interference occurs at the level of the entire experiment. One could also claim that quantum mathematics lies outside space and time, and it is the mathematics that is in control.

Our position is different than any of those just stated. We assert that the experimenters misinterpreted and misunderstood their own experiment. We claim that there was no delayed choice. Much of what appears to have happened in this experiment was an illusion.

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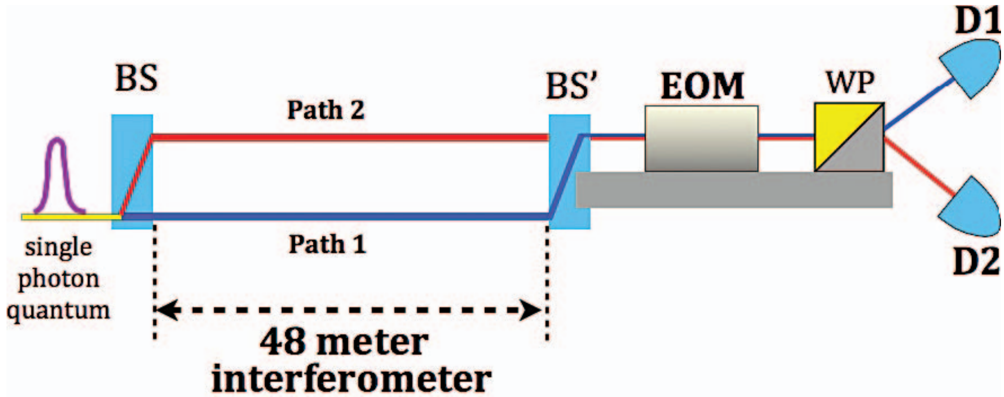

FIG. 1. (Color online) A rough approximation of equipment used by Jacques *et al.* A single-photon quantum enters the interferometer on the left and moves to the right, ending at either detector D1 or D2. BS refers to a beam splitter, and BS′ refers to reverse beam splitter. EOM is the electro-optical modulator. WP is a Wollaston prism. Path 1 (the upper red path) has a vertical polarization; Path 2 (the lower blue path) has a horizontal polarization. Waves are detected when the EOM is turned on so that wave interference is evident in the final data. Photons are detected when the EOM is turned off so that there is no wave interference. The final data show that if you look for waves, you will find waves, and if you look for photons, you will find photons. We interpret that last sentence to mean, therefore, that both waves and photons are always present.

To support our proposal, we must also discuss other things. We need to show how there could be such a thing as a zero-energy wave that has any impact on any particle or detector. We need also to show that the direction of waves is not necessarily the same as the direction of particles.

II. DESCRIPTION OF THE EXPERIMENT OF JACQUES *ET AL.*

Wave-particle duality is the starting point for the cascade of ideas that led to the experiment of Jacques *et al.* If wave-particle duality were true, then a photon quantum is a wave particle. If an interferometer is set up with an open configuration, then the quantum will behave like a particle. If the interferometer is set up with a closed configuration, then the quantum will behave like a wave. Wheeler's idea was that after the quantum has entered the interferometer, then (in a delayed manner) we would make the interferometer open or closed.

The peculiar thing is that when the detectors are arranged to detect a particle (open configuration), the photon quantum behaves as a particle, and when the detectors are arranged to see a wave (closed configuration), the photon quantum behaves as a wave. So how does the photon quantum, when entering the interferometer, know whether to commit itself to being observed later as a photon or a wave? To avoid the possibility that the detectors somehow communicate with the photon quantum as it enters the front door of the interferometer, Wheeler suggested "delayed choice." This means that the detector arrangement would be selected only after the photon was already inside the interferometer.

Jacques *et al.* built exactly the experiment that Wheeler envisioned and arrived at the conclusions that Wheeler had predicted. Figure 1 shows a simplified rendering of the experimental apparatus of Jacques *et al.* We have slightly simplified polarization (for example, we omitted a half-wave plate). Most of our information about polarization comes from Fig. 5 on page 8 of the online material supporting the Jacques 2007 publication and Fig. 2 on page 967 of the *Science* article.[3]

In the experiment a single-photon quantum is put into the interferometer on the lower left. Allegedly the quantum makes a decision whether to travel as a photon on path 1 (lower blue path), which is horizontally polarized, or a photon on path 2 (upper red path), which is vertically polarized, or as a wave on both paths. It takes 160 ns to traverse the interferometer, which is one half a football field long. After the quantum is inside the interferometer, the EOM, controlled by random numbers, will turn on or off in a matter of 40 ns. If it is on when the quantum arrives, it rotates the angle of polarization of the waves (assuming there are waves) by $\pi/4$. If it is off, it has no effect at all. The key is that there is no possible way for information about the EOM switch to be known at the front door of the interferometer when the photon quantum had entered the interferometer and made a commitment to one path, the other, or both.

This is essentially a Mach–Zehnder interferometer. A step motor slightly tilts the reverse beam splitter (BS′), thereby producing a phase shift in the waves from path 1 versus path 2 (assuming there are waves). That signal then passes through the EOM and through a Wollaston prism (WP), which has orthogonal eigenstates. Any wave particle horizontally polarized will go to detector D1 that clicks. Any wave particle vertically polarized goes to detector D2 that clicks. All data come from those two detectors.

There are two ways for the photon quantum to be processed. If the EOM is in an off position when the quantum arrives at the EOM, then any photon wave particle from path 1 (horizontally polarized) will strike detector D1, and any photon wave particle from path 2 (vertically polarized) will strike detector D2. On the other hand, if the EOM is on, any wave will undergo a phase shift of φ as it passes through BS′, where φ varies depending on the angle of tilt of BS′. This phase shift is

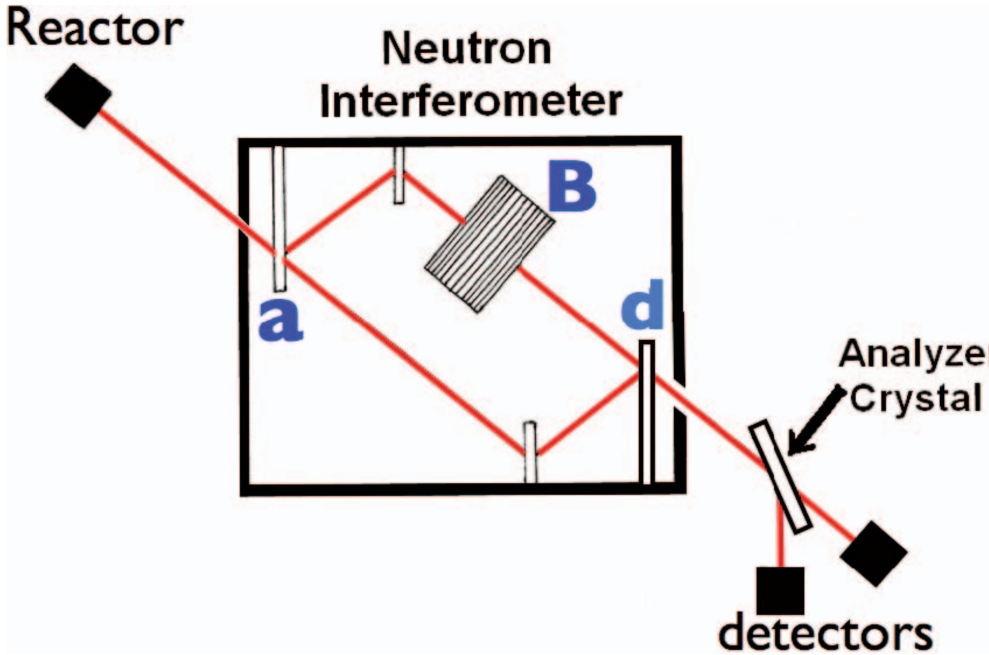

FIG. 2. (Color online) A neutron interferometer experiment (Ref. 11). According to QM neutron wave packets start in the upper left, following the red diagonal lines. Inside the interferometer they divide into an upper and lower path and then recombine inside silicon blade "d" where there is interference. "B" is a sample of bismuth, which slows neutron wave particles. The sample "B" is under control of the researchers. It varies from 0 to 20 mm in thickness. With a thick enough sample "B," the neutron wave packet taking the upper path is sufficiently delayed and all interference dies out, presumably because the lower neutron wave packet has already exited the interferometer before the upper wave packet reaches silicon blade "d." All of this occurred when the analyzer crystal in the lower right was absent. When the analyzer crystal is inserted, all the interference inside the interferometer is magically restored, as shown in Fig. 3. These data are more compatible with the idea of the waves traveling in the opposite direction as, and preceding, the neutron. The neutron then follows its particular wave backward.

then rotated by $\pi/2$ inside the EOM, which produces interference at the entrance to the WP. We know there is interference because in the final dataset, the rate of clicking of D1 versus D2 varies according to sinusoidal curves, as φ changes in value.

When the final data are analyzed, whenever the EOM is turned on (even if that is in the last few nanoseconds), a wave is detected. Whenever the EOM is turned OFF, a photon particle is detected. In other words, if you are looking for a wave, you will find a wave; if you are looking for a particle, you will find a particle. The experimenters consider this to be noteworthy because the photon quantum presumably made its commitment as it entered the interferometer, long before it was known what the final position of the EOM would be. Jacques *et al.* conclude, "Our realization of Wheeler's delayed-choice gedanken experiment demonstrates that the behavior of the photon in the interferometer depends on the choice of the observable that is measured, even when that choice is made . . ." later in time. The final data are in conformity with the predictions of QM. Because of the delayed choice, the implication is that there is no other possible explanation of the findings.

III. ALTERNATIVE EXPLANATION

This experiment hinges on the assumption that wave-particle duality is true. Instead, let us make the assumption that particles interact with waves, but the waves are independent of the particles, can travel in the opposite direction, and sometimes exist without any particle attached.

What does the experiment say? The answer is clear and simple: every time you look for a photon you will see a photon, and every time you look for a wave, you will see a wave. The conclusion is obvious: both photons and waves must be present at the same time! They cannot be two aspects of the same thing.

Because we are dealing with one quantum at a time, how can that quantum become both a photon and a wave? The logical explanation is that every quantum becomes a photon, and the waves are always present, with or without a photon! Because the energy of the quantum and the photon are about equal, there would be no surplus energy to power these hypothetical waves, so the waves in question would need to be zero-energy waves. Following the logic of this model, one would say that every time a detector clicks, it is because it is struck by a photon. Photons always follow waves, as evident from the presence of wave interference fringes (sinusoidal curves) in the final dataset. When the EOM is turned off, there will be no interference fringes, but that is because your equipment is incapable of seeing waves when the EOM is off.

With this explanation there is no "delayed choice." The choice whether the EOM is turned on (i.e., looking for a wave) or off (i.e., unable to detect wave interference) does not influence the previous behavior of the photon quantum inside the interferometer. Photons were photons (i.e., traveling on one path or the other but not both paths) and waves were waves (traveling on both paths), regardless how they will be observed at a later time.

IV. ZERO-ENERGY WAVES

Einstein worried that if photons carry all the momentum and energy, then they leave the associated wave to be a ghost, in the sense that it carried neither momentum nor energy. He spoke of these waves as "ghost fields" (Gespensterfelderi). He wondered how a wave with neither energy nor momentum could ever register its presence. A 1924 paper by Bohr *et al*. described "virtual waves,"[4] which were said to be the same thing as Einstein's empty waves.[5]

Franco Selleri developed the idea of "empty waves." He thought of a photon as a localized entity carrying energy momentum, accompanied by a very long wave that carried no energy and no momentum. He thought his theory was validated by the Pfleegor and Mandel experiments in the 1960s.[6] Two lasers were arranged such that their beams crossed. An interference fringe pattern appeared on a photographic plate at the intersection. The intensity of the lasers was turned down and down until only one photon (from one laser or the other) would be emitted at a time, and then there would be a pause before another photon was emitted. The interference fringe pattern at the intersection continued to be visible if you left the photographic film there long enough. The photons made the interference visible, but Selleri said waves were the only possible explanation of the interference fringes when no photon was present. To Selleri, this was evidence of his "empty waves." They were "empty" because the part of the wave in question did not contain the singularity (the photon).

Selleri pondered the question that Einstein had worried about: how could a zero-energy wave have any impact on anything? Selleri came up with two solutions. His main idea was that if an excited atom was about to decay and emit a photon, then the presence of an empty wave might trigger or facilitate that atomic decay, without contributing any energy to the process. That would imply that the wave was present prior to the existence of the photon. Also these waves would provide the path for the photon to follow.

V. EMPIRICAL DATA ABOUT ZERO-ENERGY WAVES

There have been many experiments concerning the rate of decay of excited Rydberg atoms in a resonant cavity,[7] compared with the rate of decay of such atoms in empty space (the Purcell effect).[8] If the diameter of the cavity is a multiple of $\lambda/2$ (where λ is the wavelength of a photon emitted when the outer electron transitions to a lower energy level), then the rate of decay of such an atom can be increased by 500 times compared to the rate of decay in free space (Γ_o).[9] If, on the other hand, the diameter of the cavity is not such a multiple, then the rate of decay of the excited atom can be reduced to 1/20 of what it would be in free space.[10]

This well-known phenomenon is sometimes called a "mode of the cavity" or an "available state." We could think of such a mode as a zero-energy standing wave inside the cavity, where the wavelength is a multiple of 2d and "d" is the diameter of the cavity. No matter what we call it, everyone agrees that such a mode of the cavity conveys zero energy.

Here, then, is a remarkable thing! The presence or absence of something of zero energy determines whether or not an excited Rydberg atom decays! If decay does occur, all the energy comes from the atom (i.e., the transition of the outer electron to a lower energy state and emission of a photon carrying the missing energy). The ratio of the rate of decay of an excited atom in a microcavity is 10 000 to 1, depending on whether that cavity does or does not have a mode corresponding to the wavelength of that atomic decay. This shows that something of zero energy can have a large impact, as Selleri said!

We call such a mode of the cavity an "elementary wave."

VI. EMPIRICAL DATA ABOUT THE DIRECTION OF WAVES VIS-À-VIS PARTICLES

De Broglie, Einstein, and Bohr considered it so obvious that waves and particles travel in the same direction, that they never wrote anything about what was the empirical data supporting that assumption. The history of science has been the history of disproving that which was considered to be "obvious." We will discuss one experiment that makes most sense if particles and waves travel in opposite directions.

Kaiser *et al*. published a neutron interferometer experiment in *Physical Review A* in 1992.[11] The equipment is shown in Fig. 2. According to the experimenters, a neutron wave packet is said to enter a neutron interferometer from the upper left, following the red diagonal lines. Inside the interferometer it splits into upper and lower paths that rejoin and interfere inside silicon blade "d" in the interferometer. Detectors outside the interferometer then record interference fringes. Consider first the situation when there is no "Analyzer Crystal" in the lower right of Fig. 2.

Inside the interferometer the upper path (shown in red) passes through a sample of bismuth ("B") the thickness of which can be varied from 0–20 mm. Bismuth slows the neutron beam, depending on the thickness of the sample, between 0 and 185 wavelengths (435 Å). The upper neutron beam is delayed as it rejoins the lower neutron beam inside silicon blade "d." The more it is delayed, the less it overlaps the lower neutron wave packet. With enough delay, the lower wave packet passes through silicon blade "d" and leaves the interferometer before the upper wave packet arrives at "d". As a result, with enough bismuth (12 mm or more), the magnitude of

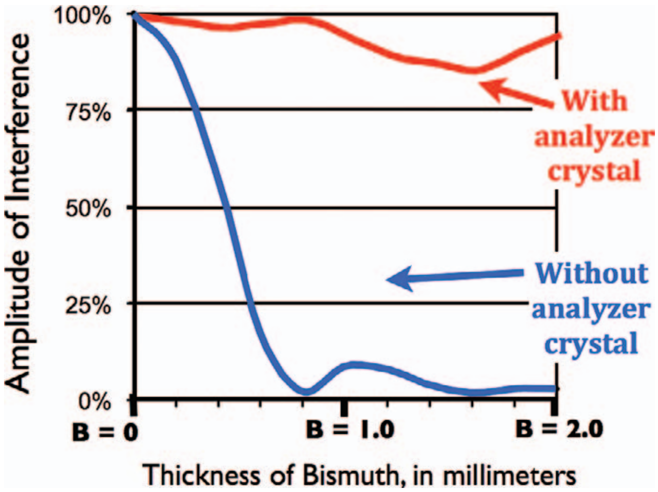

FIG. 3. (Color online) Impact of the analyzer crystal inserted downstream from the interferometer. As more and more bismuth is added inside the interferometer, the interference inside the interferometer drops to almost zero (blue curve at the bottom). However, when an analyzer crystal is inserted outside of and downstream from the interferometer, all the interference inside the interferometer is restored (red curve on the upper half). This suggests that the analyzer crystal must be upstream from the interference and that neutron waves travel in the opposite direction as neutrons.

the interference fringes dies down to zero amplitude, as shown in the blue curve at the bottom of Fig. 3. In other words, the upper wave packet is so delayed by the bismuth that it misses the target, the "target" being the lower wave packet. All of what we just said occurs when there is no analyzer crystal present.

However, when an analyzer crystal is inserted into the experiment, unexpected things happen. This analyzer crystal is inserted downstream from and outside the interferometer (see Fig. 2). Suddenly all of the interference that had been obliterated by a thick sample of bismuth is restored (see red curve on the upper half of Fig. 3). Why? What is the effect of such an analyzer crystal? It reduces the standard deviation of a neutron beam from $\sigma_\lambda =$ 0.0120 Å to $\sigma_\lambda = 0.0003$ Å but keeps the same wavelength $\lambda = 2.3456$ Å. The impact of such a crystal on a neutron wave packet of coherence length $\Delta x = 86.2$ Å would be to elongate it into a wave packet of coherence length $\Delta x =$ 3450 Å.

It is impossible to see how such an analyzer crystal outside of and downstream from the interferometer could restore the full amplitude of the interference that had previously occurred inside the interferometer (see Fig. 2). How could a downstream analyzer crystal impact interference that occurred upstream and previously?

Kaiser *et al.* admit they cannot explain the results shown in Fig. 3. They say that perhaps they do not need to explain it, because they have a Fourier transform equation that fits the data, and they imply that if the math works, then one does not need to understand it. Ultimately, they attribute these unexplainable results to Wheeler's smoky dragon.

An alternative model is this. Neutron waves start at the detectors, go backward through the interferometer, interfere inside silicon blade "a," and scatter. Some of the waves travel to the upper left and enter the reactor where they interact with nuclei about to decay. As decay occurs, a neutron follows its wave backward and strikes that detector from which its particular wave originated.

This alternative model could explain this experiment. In this case the analyzer crystal would be inserted upstream from the interference, because the waves would be traveling from right to left. The impact of the analyzer crystal would be to modify the wave in such a way that it could penetrate (backward) a full sample of 20 mm of bismuth without any trouble. The analyzer crystal would have increased the wave packet of coherence length from $\Delta x = 86.2$ Å to $\Delta x = 3450$ Å. Without the analyzer crystal, the 435 Å delay caused by a thick sample of bismuth would cause the upper wave packet to miss the lower wave packet inside blade "a," and therefore there would be no interference (each wave packet being 86.2 Å in length). When the analyzer crystal is inserted, each wave packet (on the upper and lower path inside the interferometer) would be 3450 Å in length, so the two wave packets would still overlap despite a full sample of bismuth, and there would still be interference, if an analyzer crystal were present in the lower right.

This experiment is more compatible with a model in which neutrons and neutron waves travel in opposite directions, than with a model in which they travel in the same direction. As the experimenters (Kaiser *et al.*) imply, QM cannot explain this experiment.

VII. COMPLEMENTARITY

Complementarity is often used to understand quantum experiments. Some of our readers criticized this article because we did not follow the rules of complementarity. We are deliberately avoiding complementarity. Why? Because our central thesis is that wave-particle duality is wrong. When Bohr introduced complementarity in 1927, it was for the specific purpose of "explaining" the apparent contradictions implicit in wave-particle duality.[12] It would be impossible to see the problems we are focusing on, if we used complementarity. Wave-particle duality and complementarity are so intertwined that it is impossible to reject the one without rejecting some aspect of complementarity also.

If you set aside assumptions about complementarity and wave-particle duality, then the experiment of Jacques *et al.* produces straightforward results. It is simple to understand. It says that whenever you look for waves, you will find them, and whenever you look for particles, you will find them. Therefore, both waves and particles must always be present. It tells us that wave-particle duality cannot be true.

If, on the other hand, you start with the conviction that wave-particle duality *is* true, then the experiment of Jacques *et al.* makes no sense at all. In that case you would need complementarity to justify your inability to comprehend what the data are telling you. Complementarity allows you to look at the data only on a global scale and avoid focusing on the details. Therefore, it would be a way of obscuring the fact that you do not understand the experiment, because the details of the experiment would be lost in a fog.

In the Kaiser *et al.* experiment, if you have no preconceptions about the direction of waves and no preconceptions about wave-particle duality, then the experiment is likewise simple and straightforward. It tells us that wave-particle duality cannot possibly be true, because the waves travel in the opposite direction as the neutrons.

If, on the other hand, you are committed to the assumption that wave-particle duality is true, then the experiment makes no sense at all. In that case you likewise need complementarity for damage control. It would allow you to say that because interference and measurement occur at the level of the entire experiment, it does not matter that you do not understand the details.

VIII. OTHER COMMENTS ON THIS ARTICLE

The ideas in this article have, of course, been subjected to blind peer review. The vast majority of the comments stimulated improvements in the evolving manuscript, but two comments could not be integrated elsewhere into this article and are stated here.

One critic said that he or she disliked our ideas because we allegedly propose "yet another filling of space with intangible unverifiables, like ether." We reply that the ideas in this article are refutable, and furthermore, ether was also refutable. We have designed several experiments in which our theory and QM predict different outcomes. These experiments have not yet been conducted, although a research team in Poland is working on one of them. As for ether, the Michelson–Morley experiment showed that ether could be refuted. That is why ether was rejected as a theory.

Another reviewer says that Kaiser *et al.* should have positioned their analyzer crystal upstream from the interferometer, in addition to downstream. If the outcome of the revised experiment (analyzer crystal both up- and downstream) was the same, then that would not refute our argument, but it would help to develop our theory to the next level. It is currently unknown whether elementary waves only travel in the opposite direction as the neutron. Another possibility is that there are two elementary rays that are coaxial, traveling in opposite directions at the speed of light, and that they somehow work as a pair. If the Kaiser *et al.* experimental results were the same with the analyzer crystal upstream, as they were with the analyzer crystal downstream, that would be evidence for that higher level of elementary wave theory.

IX. SUMMARY

In summary, our proposal is that wave-particle duality is incorrect. Instead, we claim there are waves, and there are particles and they interact, but are not identical. If waves sometimes travel in the opposite direction as particles, then they cannot be two aspects of the same thing.

According to our theory we are immersed in an ocean of zero-energy waves, which are subject to wave interference, whether particles are involved or not. Selleri said that the Pfleegor and Mandel experiments show wave interference when there is no photon involved.

Particles follow some of these waves. In one of the delayed-choice experiments, the "Wheeler delayed choice gedanken experiment," the experimental results are obvious. However, one might ask how can one quantum of energy become both a wave and a particle, if the quantum has only enough energy to make a photon. We reply that one quantum does not become two things. It always becomes a photon. Zero-energy waves are always present, long before the experiment started.

Some readers reject the idea of a zero-energy wave. After all, wave equations such as Schrödinger's are built around the energy of a wave. Consider an analogy. If you walk in the woods and come to a fork in the path, would you be more likely to take the wide path, the narrow path, or to bushwhack? No matter which way you go, the path contributes no energy to your hike. Yet, the path will have a probabilistic influence on your direction. Most likely you will take the wide path. It is unlikely that you will bushwhack. Perhaps our thesis would be easier to understand if we referred to "elementary paths" instead of "elementary waves." Feynman's "probability amplitude" conveys no energy but is like a path that a particle might follow.

The idea of zero-energy waves has been discussed in the history of QM, especially by Franco Selleri. Experimental support for zero-energy waves can be found in experiments concerning the decay of an excited atom in a resonant cavity. Other experiments suggest that waves may travel in the opposite direction as the particles, i.e., that waves and wave interference precede the emission of a particle, and the particle then follows the wave backward.

This article thinks outside the box, and wave-particle duality is the box outside of which we think. We are not adding additional waves to QM. We are not using QM concepts such as wave packet, superposition of particles, decoherence, wave function collapse, complementarity, nor entanglement. In this article we propose a new kind of wave that is physically real, not a mathematical construct. We also propose that there is a physical reality at the quantum level. This article is not a "hidden variable" theory and is not compatible with Einstein's writings.

The theory of elementary waves, discovered by Lewis E. Little, consists of the study these waves.[13] This theory was first published in *Physics Essays*. Little was the first to propose that waves travel in the opposite direction as particles (as in Kaiser's neutron interferometer). These "waves" are not in the form of plane waves. They are in the form of rays of zero energy. Precisely what such a ray looks like is unknown. How a particle interacts with, or follows such a ray, is unknown.

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