Particle or wave: there is no evidence of single photon delayed choice.

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Abstract Wheeler supposed that the way in which a single photon is measured in the present could determine how it had behaved in the past. He named such retrocausation delayed choice. Over the last forty years many experimentalists have claimed to have observed single-photon delayed choice. Recently, however, researchers have proven that the quantum wavefunction of a single photon assumes the identical mathematical form of the solution to Maxwell's equations for that photon. This efficacious understanding allows for a trenchant analysis of delayed-choice experiments and denies their retrocausation conclusions. It is now usual for physicists to employ Bohr's wave-particle complementarity theory to distinguish wave from particle aspects in delayed-choice observations. Nevertheless, single-photon, delayed-choice experiments, provide no evidence that the photon actually acts like a particle, or, instead, like a wave, as a function of a future measurement. And, a recent, careful, Stern-Gerlach analysis has shown that the supposition of concurrent wave and particle characteristics in the Bohm-DeBroglie theory is not tenable.

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1. Introduction.

Almost forty years ago Wheeler suggested that there exists a type of retrocausation, which he called delayed choice, in certain physical phenomena [1]. Specifically, he said that the *past* behavior of some quantum systems could be determined by how they are observed in the *present*. "The past", he wrote, "has no existence except as it is recorded in the present" [2].

As an example he described a single quantum of electromagnetic (E-M) energy, a photon, that encounters a two-slit screen. He told us that a system of lenses, a two-slit screen, and a rapidly-movable, venetian blind device, coated with a photographic

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emulsion, could demonstrate such retrocausation [3]. “Now we come to the new feature: delayed choice,” he wrote. “We do not have to decide in advance which feature of the photon to record, ‘through both slits’ that pierce the metal screen, or ‘through which slit’. Let us wait until the quantum has *already* gone through the screen before we - at our free choice - decide whether it *shall have* gone ‘through both slits’ or ‘through one’” [4].

Since that time many experimentalists have claimed to have actually observed single photon delayed choice. It is the aim of this article to deny those claims. Though the novel idea has yet to appear in quantum mechanics texts, and is not incorporated into all related, research publications, physicists have recently proven that the quantum wavefunction of a single photon is described by the identical mathematical form as the E-M wavepulse of that photon [5,6]. It is this potent understanding which has enabled a realistic analysis, and ultimately, rejection, of the assertions of single-photon delayed choice.

Before Wheeler, Neils Bohr had repeatedly argued for exclusive complementary properties of quantum systems, such as the wave versus the corpuscular nature of those objects, referred to as wave-particle duality [7]. Though Wheeler repeatedly described delayed choice as contrasting one way, versus simultaneous two way photon travel, he never mentioned wave-particle duality in those publications. But it is now usual to associate some aspects of the putative observation of single-photon delayed choice with wave-like, and other aspects, with particle-like behavior. Many of the experimentalists investigating delayed choice have done that. However, no single-photon observation has shown that a present measurement determines how the photon behaved in the past: as a wave, or as a particle.

One of the many currently-competing interpretations of quantum measurement was developed by David Bohm from deBroglie’s seminal idea that both wave and particle properties are exhibited by quantum systems. That theory, known as the Bohm-deBrogleie (B-deB)) interpretation, diverges strikingly from Bohr’s complementarity understanding, by insisting that wave and particle properties are not exclusive, but instead, exist concurrently. It has, however, been easy to demonstrate here, based on a very recent detailed analysis of the Stern-Gerlach experiment [8], that the B-deB theory fails to provide a realistic description of a Stern-Gerlach observation. By that very crucial standard, it lacks credibility.

Elsewhere I’ve critically examined Scully’s quantum-eraser theory, which is said to have a delayed-choice aspect [9]. Here, in section 2, I briefly consider the debate over whether light has wave or particle traits, and what the quantum measurement of a photon could mean. The Mach-Zehnder (M-Z) interferometer, often employed for delayed-choice experiments, is described in section 3. In section 4 I’ve used the Bohm-deBroglie theory to predict some relevant aspects of a delayed-choice, interferometer observation. I’ve also shown that failure of the B-deB interpretation to adequately depict a Stern-Gerlach experiment debilitates its credibility, suggesting an alternative understanding.

The experiment performed by Jacques and his collaborators serves as a prototype for other delayed-choice observations. I’ve analyzed it, and some simpler, previous experiments, in section 5. They do not establish the delayed-choice, retrocausation conjecture. Section 6 dissects the spurious redefinition, proffered by Ionicioiu and Terno, of particle-like, photon behavior. It would eviscerate the seminal characterization provided by Bohr. Subsequent delayed-choice experiments, incorporating that inapt misunderstanding, do not substantiate single-photon delayed choice. I’ve concluded, in Section 7, that single-photon delayed choice has not been demonstrated, and that there is a much more satisfactory understanding of photon behavior.

2. Some history, and quantum-measurement interpretations.

The question of whether light is a wave or a particle is almost as old as the science of physics. Newton believed it was a particle. Thomas Young was convinced that his observations of interference demonstrated that light must be a wave. In 1900 Planck discovered that the spectrum of light from a black body could only be properly explained if light energy were quantized as discrete photons [10]. The quantum theory which developed from that, and other observations of microscopic phenomena, led to a more penetrating understanding of the nature of light. Not, however, without continuing controversy.

Einstein noted that careful observation of the direction of momentum transfer by a single photon to a photoplate detector would determine through which of two slits it could have passed [11]. That's inconsistent with the production of an interference pattern at the detector, he said, indicating an inconsistency in quantum theory itself.

Bohr famously dissented [11]. If the plate detector is fastened to the slit screen so it doesn't move, then interference develops [12]. If, instead, the detector is allowed to slide with each photon capture, one can observe through which slit the photon passed, but no interference is seen. Bohr believed those two distinct observations, either through both slits, or through just one, are *complementary*, not contradictory experiments [11]. He said that the photon has many, exclusive, complementary properties, such as particle, or wave, depending on how it is measured.

Though he never mentioned wave-particle duality in describing delayed choice, Wheeler avidly endorsed Bohr's complementarity theory, indicating one slit, or simultaneous, two-slit photon passage, as an example. And he expanded Bohr's thesis with his consequential conjecture of delayed choice. He claimed retrocausation: the photon will have gone through both slits, or through just one, in the *past*, depending on how it is measured in the *present*.

Unfortunately, many contradictory interpretations of quantum mechanics currently compete to provide a consistent, reasonable explication of the quantum measurement process. A compilation of Bohr's ideas, called the Copenhagen interpretation, includes an understanding that many properties measured on a quantum system, wave or particle included, are complementary, depending on how the measurement is performed. This interpretation also supposes that quantum measurement always involves a non-negligible disturbance of the object measured.

The competing Bohm-deBroglie interpretation [13] has now been included in many textbooks. It claimed that a physical object exists at a single point in space time, and is guided on a continuous trajectory by the wavefunction. An object would have coexistent, not complementary, wave and particle characteristics. Initially, there is supposed to be a statistical ensemble of particles, rather than a superposition of possible locations for one. In this interpretation, obviously, no photon could pass simultaneously through two separated slits. Recent iterations of this theory focus on energy flow lines (and the Poynting vector for photons), allied with the quantum probability flux, to depict evolution of the quantum system. I'll consider this theory, and it's failure to adequately describe a Stern-Gerlach measurement, in more detail below.

Einstein, too [14], favored a type of ensemble interpretation now advocated by other physicists [15]. There is also a transactional interpretation, which claims a retarded as well as an advanced component for the wavefunction [16]. And, there is the many worlds interpretation [17], Mermin's Ithaca interpretation [18], spontaneous collapse [19], and, more recently, Zurek's quantum Darwinism [20], and others.

3. The Mach-Zehnder interferometer does not exhibit delayed-choice.

Many experiments purported to confirm Wheeler's delayed choice conjecture employ the Mach-Zehneder interferometer (Fig. 1). A single photon is generated by some technique and directed to the first beam splitter, BS_1. The photon's E-M wavepulse, and so, we now know, it's quantum wavefunction also, $|\psi_i\rangle$, is split in two there, $|\psi_i\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, traveling each route to a simple mirror, M_0 , or M_1. A phase shifter, PS, which can be a quartz plate, changes the phase of one wavepacket relative to the other, $|\psi_f\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\phi}|1\rangle)$. The two wavepackets recombine at the second beam splitter, BS_2, so that each detector, D_0 or D_1, records a photon-absorption probability which varies sinusoidally with the phase shift, either $\cos^2(\frac{\phi}{2})$ or $\sin^2(\frac{\phi}{2})$, demonstrating interference. Such interference has always been seen as evidence that the photon's wavefunction has behaved, quite obviously, as a wave, transiting both paths concurrently. Following Bohr, delayed-choice experimentalists, (but not advocates for the B-deB theory) say this displays the photon's exclusive, and complementary, wave-like behavior.

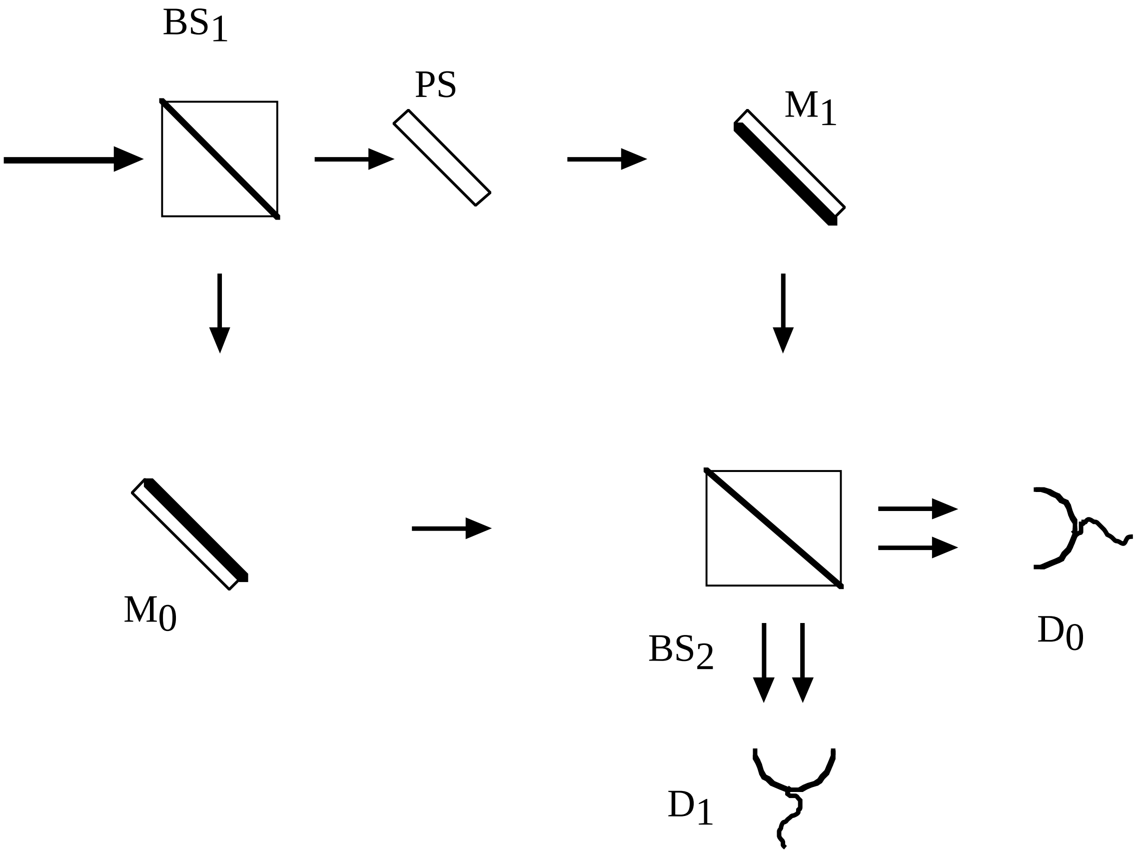

Fig. 1 A Mach-Zehnder interferometer splits the single-photon wavepacket into two packets traveling two paths at the first beam splitter, BS_1. The phase of one wavepacket may be shifted at PS. Those two wavepackets will be overlapped if the second beam splitter, BS_2, is present, before reaching one of the detectors.

Now suppose the second beam splitter, BS_2, is removed from the M-Z interferometer. Experimentalists have now found remarkable ways to do that while the photon is still traveling through the interferometer. Then, each detector will record an equal probability for photon absorption, regardless of phase shift. Wheeler claimed this as evidence that the photon itself must have traveled just one way, along either one, or the other arm, of the interferometer. As in the two-slit apparatus, "…one of the two counters will go off and signal in which beam – and therefore from which slit – the photon has arrived" [21]. Clearly, that would be evidence of retrocausation, demonstrating that the photon had behaved differently in the past if, in the present, BS_2 were absent, or in place. Since then, many researchers have mistakenly accepted Wheeler's explanation.

But, the photon's wavefunction, just like it's electromagnetic pulse, is always divided in two at the first beam splitter, and always traverses *both* paths through the interferometer. There is nothing whatsoever about photon behavior, inside the interferometer, that changes if BS_2 is removed. It cannot be delayed-choice retrocausation that is being seen here. The mistake is conceptual: believing that equal probability at either detector, regardless of phase shift, implies a photon wavefunction that must have traveled just one way. It does not [22, 23].

Even without the second mirror, BS_2, a wavepacket travels each path, unimpeded, to a particular detector, with a fifty percent chance of photon absorption there. Or, if the second mirror is in place, the two wavepackets, with distinctive phases, are overlaid, resulting in an oscillating detection probability, and interference.

Given that the single photon's wavefunction is divided equally at BS_1, all the above quantum measurement interpretations, including Copenhagen, would agree that retrocausation is not real. What distinguishes the Bohm-deBroglie theory is not an acceptance of retrocausation, but its determined rejection of wave-particle duality. B-deB adherents do not believe that an equally divided wavefunction at BS_1 implies a wave-like photon that traveled both paths in the interferometer. They say the photon always exhibits single-path, particle characteristics, guided by whatever form the wavefunction may take. An interference pattern observed at the M-Z detectors, they claim, is not evidence of exclusive, wave-like, photon activity.

4. The Bohm-deBroglie theory, and a more satisfactory understanding.

The Bohm-deBroglie theory developed from a simple, alternative expression for the quantum wavefunction. Bohm wrote it in polar form [13], $\Psi(\mathbf{r},t) = R(\mathbf{r},t)e^{\frac{iS(\mathbf{r},t)}{\hbar}}$, with R^2

being the probability density, $P = R^2 = \Psi^*\Psi$. If that form is inserted in Schrödinger’s equation for a system of mass, m, and real and imaginary parts equated, then,

$$\frac{\partial P}{\partial t} + \nabla \bullet (P \frac{\nabla S}{m}) = 0, \qquad \text{(Eq. 1)}$$

and,

$$\frac{\partial S}{\partial t} + \frac{(\nabla S)^2}{2m} + V + Q = 0. \qquad \text{(Eq. 2)}$$

V is the usual, classical potential experienced by the system, and Q is then what Bohm called the quantum information potential,

$$Q = \frac{-\hbar^2}{2m} \frac{\nabla^2 R}{R}. \qquad \text{(Eq. 3)}$$

Q can be determined by solving the Schrödinger equation for $\Psi(\mathbf{r}, t)$.

Quantum probability flux expresses lines of likely energy flow, and is a discerning way to describe the evolution of an initial ensemble of quantum objects. It is often employed in contemporary B-deB analyses [24, 25]. For a quantum system,

$$\mathbf{J}(\mathbf{r}, t) = \frac{-i\hbar}{2m}(\Psi^* \nabla \Psi - \Psi \nabla \Psi^*) = \frac{\hbar}{m} \mathrm{Im}(\Psi^* \nabla \Psi). \qquad \text{(Eq. 4)}$$

With the wavefunction in polar form,

$$\mathbf{J}(\mathbf{r}, t) = \frac{R^2 \nabla \mathbf{S}}{m}. \qquad \text{(Eq. 5)}$$

One could then specify a velocity field for the system [26],

$$\mathbf{v}(\mathbf{r},t)=\frac{\mathbf{J}}{P}=\frac{\nabla \mathbf{S}}{m}, \qquad \text{(Eq. 6)}$$

so that the gradient of (Eq. 2) becomes,

$$m\frac{\partial \mathbf{v}}{\partial t}+\frac{m}{2}\nabla(\mathbf{v}\bullet\mathbf{v})+\nabla(V+Q)=0. \qquad \text{(Eq. 7)}$$

The velocity of a putative, point particle would depend only on time, not position, so such a particle would then satisfy the equation of motion,

$$m\frac{d\mathbf{v}}{dt}=-\nabla(V+Q). \qquad \text{(Eq. 8)}$$

Bohm believed this implied an ensemble of point particles, each guided individually through a unique, continuous trajectory by the wavefunction [27]. In the case of the M-Z interferometer, it can be shown with this theory [28] that an initial ensemble of photons would be steered along just one interferometer arm, then to either detector, D_0, or D_1. This reproduces the observed detection probabilities there; when BS_2 is present, and when it is not. (When the two wavepackets are overlaid, or when not.) But, as we have seen, the photon wavefunction within the interferometer, unlike the wavefunction beyond it, is not altered by the presence, or absence, of BS_2. So, the purported, single-path trajectories within the interferometer, guided by Ψ, described in the B-deB theory, are also unchanged. And, as in other interpretations, no retrocausation can be imputed.

But, let's consider another, crucially-important, quantum-measurement phenomenon, if it were to be described by the B-deB theory. Suppose that quantum system were the silver atom transiting a Stern-Gerlach magnet, which experiences a static potential, V(**r**). (I've carefully examined the Stern-Gerlach experiment previously [8].) That atom's wavefunction is $\Psi(\mathbf{r},t)=R(\mathbf{r})e^{-\frac{iEt}{\hbar}}$, where E is the total energy. Then Eq. 1 implies $\nabla\mathbf{S}=0$, and the velocity field of the purported point particles Eq. 6 would be

$\mathbf{v}(\mathbf{r},t) = 0$. Such a velocity field, obviously, does not depict atoms traveling through a Stern-Gerlach magnet.

The B-deB interpretation cannot realistically describe our prototypical example of quantum measurement. We must remember what Bohm said of his theory: "…we do not regard this as a final or definitive explanation" [29]. And, there does exist a significantly more satisfactory explanation for quantum measurement, one that is completely consistent, and much, much simpler. It can be illustrated by a very basic example.

Suppose an opaque screen can pass one photon at a time through an aperture much smaller than the photon wavelength. According to Maxwell's equations the photon's electromagnetic waveform will propagate as an expanding spherical shell, centered on the aperture. And, that single photon's wavefunction must do the same. If there are many photodetectors downstream, covering a semicircular shell some distance from the aperture, only one will capture all the photon's energy, though the wavefunction impinges on all the detectors simultaneously.

Just like the E-M wavepulse for a single photon, its quantum wavefunction, too, must always behave like a wave, until exchange of all its energy results in abrupt reduction to a single measured eigenfunction at one detector. Absorption there does not imply that the photon traveled in a straight line to that detector, like a particle. And, let's notice that the wavefunction is not some phantasmal "smoky dragon" of ambiguity between emission and annihilation [30]. Maxwell's equations explicitly resolve that mystery too.

In this explanation we would only characterize the photon as acting like a particle at the instant [31, 32] of measurement, but not before. Similar to what Bohr (not B-deB) advocated, the photon never simultaneously acts like a wave, and like a particle. But, contrary to Bohr's supposition, it always behaves as a particle at measurement, no matter how that quantum measurement is performed.

To be clear, in this article I adhere to the notion that autonomous physical objects, including photons, exist, independent of human observation. And I will associate with each physical object a singular quantum wavefunction. For physical objects with rest mass, that wavefunction is the solution to Schrodinger's equation. For a photon, the wavefunction is the solution to Maxwell's equations. (We recognize, of course, that the photon's wavefunction is not a physical, electromagnetic pulse. That wavepulse possesses energy, and mass; the wavefunction does not. Even though the photon's wavefunction and the E-M wavepulse take an identical mathematical form).

A quantum measurement shall mean reduction of the wavefunction to a single eigenfunction with a real eigenvalue. And, I will consistently interpret the quantum wavefunction as Born, not as B-deB, taught: $\Psi^*(q)\Psi(q)dq$ is the probability that the physical system represented by $\Psi(q)$ will be found to have a value between q and q + dq if that property is measured [33].

5. The prototype for single-photon delayed choice (and its associated wave-particle duality).

The M-Z interferometer experiment carried out by Jacques and his colleagues about ten years ago [34] serves as a prototype for other single-photon delayed-choice observations, and associates wave-particle duality with that device. They employed a source of single photons on demand produced by the photoluminescence of a single color center in a diamond nanocrystal. Each photon enters a Mach-Zehnder interferometer. The first beam splitter has a reflectivity of 0.5 while the second (downstream) beam splitter can be very quickly set to a reflectivity between R = 0.0 and R = 0.5 by applying an appropriate voltage. They do this while the photon's wavefunction, and thus, the photon, is still between the first and second beam splitters, attempting a delayed-choice measurement. With R = 0 the second beam splitter is effectively absent. According to Wheeler's delayed-choice theory, each photon will transit both paths in the interferometer, or instead, only one of them, as it leaves the first beam splitter, depending on what sort of measurement is yet to be determined by the reflectivity at the second beam splitter.

However, the reality is that there must *always* be an equal superposition of two probability amplitudes along the two interferometer arms, regardless of what is done with BS_2. Jacques and his collaborators varied the phase of one of these wavepackets relative to the other. If R = 0.5 they observed interference, a sinusoidal probability for photon detection at each output port, as a result of overlapping wavepackets. [35]. They call this wave-like photon behavior because the split wavefunction must traverse both paths [36].

But, following the lead of Wheeler, Jacques et al. incorrectly concluded that the single photon must have passed along just one of the two interferometer arms; what they have called particle-like behavior, when the second beam splitter is set to R = 0. These authors mistakenly concluded that when “the output beam splitter is then absent, …each detector is therefore univocally associated to a given path” [37], supposedly implying delayed choice. According to the Born rule, however, if a photon went along just one path to a detector, then that photon’s wavepacket, too, traveled just that one way. That’s not the case in a Mach-Zehnder interferometer.

Maxwell’s equations insist that there never is one-way photon travel in the interferometer. Regardless of the situation with BS_2, the photon wavefunction within the interferometer remains unchanged. The single photon still transits both ways through the interferometer. No matter which detector absorbs it. Retrocausation is not real. (And, Bozic and his colleagues, too, using the formalism of electromagnetic field quantization, have denied this mistaken, delayed-choice conclusion [38].)

Physicists began to consider techniques that might be used to observe single-photon delayed choice, some twenty years before Jacques’ experiment, very soon after Wheeler first published his conjecture. Alley et al. [39] used a weak laser pulse that almost always injected no more than one photon into their Mach-Zehnder interferometer. Their method for discovering delayed choice was less sophisticated than that later used by Jacques et al. They disabled one arm of a M-Z interferometer by reflecting any wavepacket traveling that way to an absorber (photon detector). Not surprisingly, they found that the interference pattern was thereby eliminated. If that reflector was, instead, removed, interference returned. The novelty of this experiment is that the reflector would be installed, or removed (by rotating a wavepacket’s polarization with a Pockels cell), after the photon’s wavefunction was entirely within the interferometer. There is, nonetheless, no delayed-choice observation here. Again, the single photon’s wavepacket is always split in two, and always travels both paths beyond the first beam splitter, whether the Pockels cell reflector is active, or not.

Like Alley et al., Hellmuth and his coworkers developed a laser producing very short pulses, each containing, on average, 0.2 photons [40]. Those pulses were divided at the first beam splitter in their Mach-Zehnder interferometer. In one arm of the interferometer a Pockels cell was inserted that allowed them to block that path after the laser pulse passed the first beam splitter. Then, they always opened this path before the pulse reached the Pockels cell. The interference pattern produced this way was no different than was seen with no Pockels cell present.[1]

About two years afterward, Baldzuhn et al. used a Mach-Zehnder ring interferometer to also investigate single-photon delayed choice [41].
They, too, mounted a Pockels cell in the interferometer. It could be quickly energized to rotate the polarization of one of the photon's two wavepackets ninety degrees relative to the other. This was done, in delayed-choice fashion, after the wavefunction had already entered the interferometer. When that rotated wavepacket was recombined with the second, unrotated wavepacket at the beam splitter, no phase-dependent interference was observed [42]. But, if one wavepacket's polarization was not rotated ninety degrees relative to the other, interference was seen.

Unfortunately, these researchers concluded that the former situation implied "the case of a delayed-choice experiment for particle behavior is accomplished" [43], supposing that the photon's wavefunction must then have traveled only one way through the interferometer.

We now know that inference to be mistaken. Maxwell's equations tell us that the photon's E-M wavepulse is always divided in two at the beam splitter, and always travels both ways through the interferometer. Regardless of polarization rotation. The single photon wavefunction acts identically. And, two wavepackets with orthogonal polarizations never interfere.

6. Can wavefunction travel along both paths be considered particle-like?

Ionicioiu and Terno published a very influential article in 2011 suggesting that the second beam splitter (or its equivalent quantum device) in a M-Z interferometer could be configured as a quantum superposition of "absent" and "present" [44]. Meaning that the ancilla signal controlling it would be in a superposition of off and on. Since then, many

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[1] Actually, the Pockels cell was not removed, but instead, that path was opened with an appropriate voltage to the cell.

researchers have incorporated the suggestions of Ionicioiu and Terno into their own work.

Most importantly, Ionicioiu and Terno chose to redefine what it means for a single photon to act like a particle within a M-Z interferometer. They wrote that “we adopt an operational definition of ‘wave’ or ‘particle’ to stand for ‘ability’ or ‘inability’ to produce interference” [45]. Such terminology clearly eviscerates Bohr’s description of a complementary, particle-like photon, which must only travel along one path through the device [46]. Their imaginative photon “particle” will always traverse both paths, wave-like, though with no second beam splitter, interference is not seen. Interference implies two-way, wave-like photon travel, but absence of interference does *not* imply one-way (which-way) transit. Remarkably, Ionicioiu and Terno correctly wrote their conceived particle-like photon’s wavefunction as a superposition of *both* paths, $\left|\psi_{particle}\right\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\phi}|1\rangle)$[47]. But they don’t seem to recognize the contradiction in “concluding that the photon traveled along a single arm, showing particle properties” [48]. Such an inconsistent and iconoclastic definition does not change the real world we observe, but does render meaningless any proffered conclusions of delayed-choice, or of wave-particle duality.

In one of the subsequent experiments said to observe delayed choice retrocausation, (and wave-particle complementarity) Kaiser and his coworkers [49] use a source supplying two polarization-entangled photons, $\frac{1}{\sqrt{2}}(c_H^\dagger t_H^\dagger + c_V^\dagger t_V^\dagger)|vacuum\rangle$. One photon labeled t, for “test”, is sent to a M-Z interferometer and the other, labeled c for “corroborative” enters a separate device which will measure its polarization. Here $c_H^\dagger$ signifies the creation operator for a horizontally-polarized corroborative photon, and $t_V^\dagger$ is the creation operator for a vertically-polarized test photon, etc.

The test photon’s wavefunction enters the first beam splitter of their interferometer, where it will be equally divided, and so will *always* travel both paths through it. Maxwell’s equations insist on that. No matter that the second beam splitter is one with a reflectivity of R = 0.5 for vertically-polarized test photons and a reflectivity of R = 1.0 for those with horizontal polarization. Because the two photons from the source have entangled polarizations, a vertically polarized t photon at their second beam splitter (such that R = 0.5) implies a vertically polarized c photon in the adjacent, corroborative part of the apparatus. Similarly, a horizontal t photon at the second beam splitter (R = 1.0) correlates with a horizontal c photon. No matter. The t photon always traverses both arms of the interferometer, something labeled wave-like behavior by these researchers.

And they even recognize the photon's consistent, two-way travel. The photon wavefunction that is equally likely to be absorbed at either interferometer output port, independent of phase shift, is depicted as $\left|\psi_{particle}\right\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\varphi}|1\rangle)$ [50]. But, following the misguided definition of Ionicioiu and Terno, they label this photon's wavefunction behavior as particle-like. According to Bohr, there can, however, be no wave-particle complementarity in the interferometer if the photon always follows both paths. And, according to Wheeler, no delayed-choice retrocausation if this wavefunction's behavior is not altered, in the past, by how it is measured in the present.

Peruzzo and his coworkers performed an experiment in which the second beam splitter of a Mach-Zehnder interferometer is said to be in a superposition of present and absent [51]. They fabricated their apparatus as an integrated, quantum-photonic circuit, rather than employing the more usual macroscopic optical elements. Unhappily, they also followed the inapt "particle" definition provided by Ionicioiu and Terno, characterizing a single photon wavefunction that passed through both interferometer arms, $|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\phi}|1\rangle)$ [52] as particle-like, if a detector recorded no interference. But it is not true that an "…experimentalist is free to choose which experiment to perform (interference or which-path, thus testing the wave or particle aspect) once the particle is already inside the interferometer" [53]. Not if we respect Bohr's seminal, wave-particle complementarity, which insists that the photon is only particle like if it travels just one interferometer arm. And, there is, of course, no delayed-choice retrocausation in this experiment, as Wheeler supposed, because the photon wavefunction is always divided in two at the first beam splitter. It never goes just one way as a result of how it will be measured in the future.

An innovative approach to a purported, single-photon, delayed-choice observation is due to Tang et al. [54]. The functioning of their apparatus seems to be most discernibly represented in FIG.1 (b) of their preliminary report [55]. A single photon produced by a quantum dot is split by a beam divider into two separated paths (labeled Path 1 and Path 2 in FIG.1 (b). It then enters their novel Mach-Zehnder interferometer. Their polarization-dependent beam splitter, PBS1, transmits horizontal polarization and reflects vertical. If two vertically-polarized wavepackets exit PBS1 they will be overlapped by the beam splitter, BS, displaying interference at each detector (given a path-dependent phase shift). Or, if two wavepackets are horizontally polarized they will both avoid the beam splitter, BS, and display no interference. An intermediate mode is made possible by rotating the incident polarization to angle, α, between vertical and horizontal.

It is, however, essential that we recognize that the two wavepackets from a single photon always travel both distinct paths to the detectors, no matter what measurement will be made. Observation of interference, or its absence, is selected by the choice of polarization angle, α, at the entrance to the interferometer. But there exists no delayed-choice retrocausation here. In spite of the spurious particle definition advanced by Ionicioiu and Terno, absence of interference does not demonstrate the single-photon's wavefunction traversing just one path to either detector. By continuously varying α, Tang et al. can observe more, or less, interference. But, that does not mean, in the real world, that they observed more, or less, delayed choice.

Finally, Yan and his colleagues employed a source of heralded, narrowband single photons, each with a correlation length of about 120 meters, in their M-Z interferometer [56]. Their first beam splitter divides the single photon's wavefunction equally into two wavepackets, one vertically polarized, and the other with horizontal polarization. A piezoelectric transducer varies the path length through one arm such that the wavefunction at the second beam splitter is $|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\phi}|1\rangle)$ [57]. The second beam splitter is also polarization dependent, and has a single output port where the two orthogonally-polarized wavepackets are overlapped. An electro-optical modulator (EOM) beyond this port can be rapidly energized in order to rotate each wavepacket's polarization by forty-five degrees, aligning the two, and producing observable interference. Or, the EOM may not be energized, in which case a downstream polarization-dependent beam splitter again separates the two orthogonal wavepackets prior to detection.

Acquiescing to the misguided "particle" definition given by Ionicioiou and Terno, these researchers claim a detected photon acted like a particle if no interference ensued. Even though that photon's wavefunction, and every photon's wavefunction in their apparatus, obviously traveled along both arms of the interferometer. That two-way behavior is not altered, as delayed-choice retrocausation, by choosing to energize, or not energize, the EOM.

Because each photon wavefunction has such extended coherence length, these researchers were able to switch off the EOM while a wavefunction was still passing through it. Notably, they observed an interference pattern when the front portion of a wavefunction was detected. And no interference if, instead, the latter portion was detected [58].

7. Comments.

Recognition that the quantum wavefunction description of a single photon is identical with Maxwell's-equations' description of its E-M pulse is an extremely powerful tool for deciphering many quantum-measurement analyses. Though there have been numerous reports of delayed-choice observations, I've used that understanding here to show that no empirical evidence for single-photon, delayed-choice retrocausation actually exists. A present measurement does not determine whether a single photon transited just one path, or both simultaneously, in a Mach-Zehnder interferometer, in the past.

Though Wheeler never mentioned wave-particle duality in his delayed-choice analyses, such properties are now often attached to delayed-choice, interferometer experiments. Still, there also exists no evidence that a single photon acted like a wave, or rather, like a particle, because of a photon measurement that will occur some time in the future. A photon's wavefunction, like its electromagnetic pulse, is always divided at the first beam splitter, and always goes along both routes, whether interference is arranged at the output, or not.

One quantum-measurement interpretation, that of Bohm-DeBroglie, claims concurrent, rather than complementary, wave and particle traits. But, I've been able to prove, based on a recent, careful exposition of the Stern-Gerlach experiment, that the B-deB interpretation cannot realistically describe atoms traversing that apparatus, and so lacks tenability, as a consistent, believable, quantum theory. I've suggested, instead, that the photon always acts like a particle when it is measured. And, until then, that photon, just like its wavefunction, acts like a wave.

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