Rethinking a delayed choice quantum eraser experiment: A simple baseball model

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(Received 10 June 2012; accepted 26 December 2012; published online 26 February 2013)

Abstract: In a double slit experiment, you can see an interference fringe pattern or you can know which slit the photon came through, but not both. There are two diametrically opposite theories about why this happens. One is complementarity. The other is the proposal made in this article. An experiment, published in 2000 [Y.-H. Kim *et al*., Phys. Rev. Lett. **8**, 1 (2000)] allegedly supports the idea of complementarity. With different starting assumptions, we arrive at opposite conclusions: complementarity is irrelevant to this experiment. Our assumptions come from the Theory of Elementary Waves. Waves are assumed to travel in the opposite direction: from the detector to the laser. All wave interference is located at the laser. All decisions of importance are located at the laser, not at the detectors. The "decisions" concern which of several elementary rays a photon chooses to follow (this is a probabilistic decision). If a photon is emitted in response to one such impinging ray, all wave interference is then complete. The photon will follow backwards that ray alone, with a probability of one, back to the pair of detectors from which that ray originated. Based on these assumptions, the experiment has nothing to do with complementarity. There is also no delayed choice and no quantum eraser. Conclusion: complementarity is not the only way to understand this experiment. © *2013 Physics Essays Publication*.
[http://dx.doi.org/10.4006/0836-1398-26.1.100]

Résumé: Une expérience à double fente vous permet soit d'observer une figure de franges d'interférences, soit de savoir de quelle fente vient le photon, mais pas les deux. Actuellement, deux théories diamétralement opposées expliquent ce fait. L'une parle de complémentarité, l'autre est décrite dans cet article. Une expérimentation publiée en 2000 [Y.-H. Kim *et al*., Phys. Rev. Lett. **8**, 1 (2000)] soutiendrait la théorie de la complémentarité. Mais différentes hypothèses de départ nous conduisent à d'autres conclusions: La théorie de la complémentarité est insignifiant dans le cadre de cette expérience. Nous avons basé nos hypothèses sur la théorie des ondes élémentaires. Les ondes voyageraient dans la direction opposée: du détecteur vers le laser. Toute interférence des ondes est localisée dans le laser. Toutes les décisions importantes se prennent dans le laser, et non pas dans les détecteurs. Le terme "décisions" désigne le choix que fait le photon lorsqu'il décide de suivre un seul rayon élémentaire parmi d'autres (il s'agit d'une décision probabiliste). Si un photon est émis en réponse à un tel rayon incident, il n'y a plus aucune interférence d'ondes. Le photon suivra ce seul rayon, avec une probabilité de un, vers les deux détecteurs d'où provient ce rayon. Selon ces hypothèses, l'expérience ne relève donc pas de la théorie de la complémentarité. De plus, il n'y a aucun choix retardé, ni gomme quantique. En conclusion, la complémentarité n'est pas la seule théorie permettant de comprendre cette expérience.

Key words: Complementarity; Delayed Choice; Elementary Waves; John A. Wheeler; Lewis E. Little; Marlan O. Scully; TEW; Theory of Elementary Waves; Quantum Eraser; Yoon-Ho Kim.

I. INTRODUCTION

Of the many facets of complementarity, two are relevant to this article. First, it originated in Bohr's mind 1925-1927 as he pondered wave-particle duality and was determined to show that there was no contradiction.[1] Second, in the double slit experiment, we can see interference fringes or we can know "which way" information (i.e., through which slit did the particle go?) but not both.

An experiment by Kim *et al*., "A delayed choice quantum eraser experiment," published in 2000 focuses on and promotes the concept of complementarity.[2] The experiment, which is the central focus of this article, investigates the "which way" phenomenon in a double slit experiment. The design used two entangled photons. One of them is put into a double slit experiment to establish an interference fringe pattern. At a later time, the other photon is tested in such a way that it reveals or hides "which way" information.

Wheeler's hypothesis,[3] which proves to be true when tested, is that the interference fringe pattern will be visible only when it is unknown which slit was used; it will disappear if "which way" data are known, or could be known. The hypothesis implies that it doesn't matter whether the "which way" data are known before or after the interference fringe

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pattern is established, and it does not matter whether the "which way" information is ever known. All that matters is that "which way" information could have been known, if anyone ever looked.

The experiment by Kim *et al*. appears to confirm all Wheeler's ideas. Those are an astonishing array of ideas, which are impossible to understand if you adopt classical assumptions, such as that time goes in a forward direction and cause-and-effect are local.

This article will present an alternative explanation of Kim's experiment. According to this model, the experiment tells us nothing about complementarity, there is no delayed choice and no quantum eraser. In other words, if you change your starting assumptions, you arrive at drastically different conclusions. That is the central thesis of this article. We do not claim that our alternative model is true. What we propose is that this is an unconventional model that leads to different conclusions based on exactly the same experiment and the same outcome data.

The most valuable thing about our model is that we design experiments (at the end of this article) for which quantum-mechanical (QM) and our model predict different outcomes. We offer our model in the hopes that it will prove to be productive in the laboratory.

It is essential that this article be written from a noncomplementarity point of view. Why? First, it would not make sense to use complementarity as one of our starting assumptions, when we plan to show that complementarity is irrelevant in this experiment. Another reason we avoid complementarity is because complementarity was originally designed by Bohr in 1927 to "explain" (or explain away) the apparent contradictions inherent in wave-particle duality. The theory we will use in this article, the Theory of Elementary Waves (TEW)[4] involves the idea that wave-particle duality is false. Complementarity is so intertwined with wave-particle duality that if you reject one, you must reject some aspects of complementarity. If you assume complementarity is true, then you would be unable to see anything wrong with wave-particle duality, and you would not understand this article.

II. THEORY OF ELEMENTARY WAVES

TEW is a nonQM theory. For example, TEW makes no use of the following ideas: entanglement, wave packets, superposition of states, decoherence nor wave function collapse.

So what is TEW? It started with the idea that waves and particles travel in the opposite directions: they are countervailing. In a double slit experiment, for example, elementary waves start at every point on the target, penetrate through the two slits, and the ray through the one slit interferes with ray through the other slit at the particle source. The amplitude of that interference varies depending on the position of the target: slightly different positions on the target will produce constructive versus destructive interference at the particle source. The amplitude (squared) of the wave impinging on the particle source determines the probability that a particle will be emitted in response to that wave. All wave interference is both local (i.e., located at the particle source) and is finished prior to the emission of a particle. If a particle is emitted in response to one of these rays, it will follow that particular ray backwards with a probability of one. This means it will have a trajectory, will penetrate one and only one of the two slits, and will strike the detector at precisely that point from which its particular ray originated. Because wave equations are the same if the waves travel in the opposite direction, this model produces precisely the same interference fringe pattern on the target screen as does the QM model.

Since each particle has a trajectory (chosen in a probabilistic manner at the time of particle emission), therefore, there is no need for the concept of wave function collapse. If we get rid of wave function collapse, we are free of many headaches. For example, there would be no demand for a many worlds theory.

How could a target, which is emitting no energy to speak of, emit a wave? According to the TEW model, you live in a different world than you thought you lived in. You are immersed in an invisible ocean of elementary waves traveling in all directions and at all wavelengths, conveying no energy. We have no way to know about these rays unless a particle is following one (backwards). As de Broglie said, "every moving particle has an associated wave." What did not occur to de Broglie was the idea that the particle could be following its wave in the reverse direction. If that were true, then he would have envisioned waves interacting with particles, but no wave-particle duality. Of the various possible ways that waves and particles might interact, wave-particle duality is the most implausible.

These are unlike other waves in that they convey no energy. They are more like a pathway. Think of Feynman's "probability amplitudes." Although they involve no energy, probability amplitudes have an influence on which way a particle might go.[5] We do not mean to imply that elementary waves are probability amplitudes: they go in opposite directions and are thought of as real physical objects, not mathematical constructs. Elementary waves are also not the "pilot waves" of DeBroglie and Bohm.

If you are hiking in the woods and come to a fork in the path, would you be more likely to choose the wide path, the narrow path, or to bushwhack? No matter which, the path contributes zero energy to your hike. The path does have a probabilistic influence over your direction, for it is more likely that you will choose the wide path, and unlikely that you will bushwhack.

One place you see these proposed elementary waves is in the Purcell effect.[6] An excited Rydberg atom in a microcavity is likely to decay if the cavity has a diameter with which it is resonant, and unlikely to decay if the cavity has a nonresonant diameter.[7] So how does an excited atom know, in advance, what the diameter of the cavity is? Put aside the idea of nonlocality. By what means does the excited electron step outside the atom to measure the diameter of the cavity, so as to decide in advance whether or not to transition to a lower energy and emit a photon? According to the model we propose, there are standing waves inside the cavity (identical to what are called "modes of the cavity" or "available states") and these waves impinge on the atom. The wave carries zero energy. Of this multitude of waves, the ones we are interested in have the same frequency as the photon that will later be emitted. That frequency of elementary wave can trigger the atom to decay. All the energy comes from the transition of an electron to a lower energy state. Franco Selleri said this decades ago, when talking about zero energy waves.[8]

According to the model now under consideration, the photon would follow the wave backwards (which Selleri did not say). Even if you disagree with calling these "elementary waves," you probably agree that the presence or absence of a "mode of the cavity" of a frequency corresponding to the excited atom strongly influences whether or not that atom decays, even though the "mode" carries zero energy. The focus at the moment is on "zero energy," not on "local" versus "nonlocal."

TEW is a theory under construction. Presently that which has been published of TEW is at the conceptual level of the "old quantum mechanics." TEW has not yet published anything about how to crack the code of quantum mathematics. This would mean reading mathematical equations as a roadmap for visualizing the world of elementary waves. Since the beginning of the new quantum mechanics, people have looked at the symbols in the equations as if they were hieroglyphs, prior to the discovery of the Rosetta stone that cracked the code. Our hope is that, someday, TEW will provide the Rosetta stone. But that is not relevant to this article.

TEW is the theory of Lewis E. Little, who is currently developing a sophisticated mathematical model. This author has been inspired and encouraged by Little but does not speak for him. In this article, all we do is to present a simple model that provides a different perspective on the experiment of Kim *et al*.

It has previously been demonstrated that TEW is able to explain one of the delayed choice experiments of QM, namely an experiment by Jacques *et al*., published in *Science* in 2007.[9] According to the TEW model, Jacques' experiment involves no delayed choice and can be interpreted as evidence that wave-particle duality is wrong.[10]

III. KIM'S EXPERIMENT

When this author presented this material at meetings of the American Physical Society, most physicists in the audience have said they do not remember what the experiment was. They need to be reminded of the details. In order to describe the experiment, we will temporarily adopt the viewpoint of the experimenters, starting with some ideas from John Wheeler. The entire problem originated from the fact that if you know "which way" information, then the interference fringe pattern mysteriously vanishes from a double slit experiment.

John Wheeler proposed a thought experiment in which he would wait until the particle had passed through the double slit barrier, then, before the particle got to the target screen, he would remove that screen. Telescopes behind the screen would then provide information about which slit the particle had come through. This was considered a "delayed choice" experiment because the particle would first make a commitment by going through one or both of the slits, and then the target would vanish so the particle would register at one or both of the detectors. The question is: Would the interference fringes be visible if you subsequently discovered "which way" information? Wheeler thought, "no." The problem with Wheeler's experimental design is that it would be physically impossible to remove a target screen within a nanosecond.

A. Experimental design by Kim *et al.*

Marlan Scully (from Texas A&M University) worked with Kim and a research team at the University of Maryland in Baltimore, to design and build the apparatus in Figure 1.

In the online version of this article, the different pathways in Fig. 1 are colored red or blue. If you are reading a printed copy of this article, devoid of colors, then think of the word "red" as referring to any line connected to the upper slit "B," and the word "blue" as referring to lines connected to the lower slit "A." Since more readers will read the online version than the printed version, we will use the colors, even

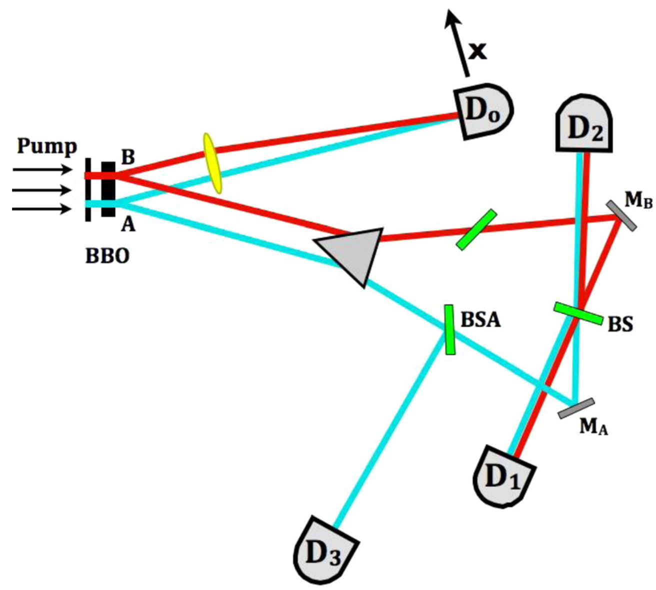

FIG. 1. (Color online) The experimental apparatus: on the left of this contraption the three arrows called "pump" symbolize a 351.1 nm argon ion pump laser. The laser beam is divided by a double slit. It is implied that each photon from the laser goes through either the lower slit (marked "A"), the upper slit ("B") or both. The BBO crystal splits each photon into two photons of 702.2 nm. These two are called the "signal" photon that travels upward, and an "idler" photon that travels downward. Photons coming out the right of the BBO crystal come out at an angle, not parallel to each other. The signal photon passes through a lens, and then registers at detector D_0. A step motor moves D_0 in the "X" direction. That upper $^1/_4$ of the contraption is a traditional double slit experiment. The idler photon travels down into the bottom $^3/_4$ of the contraption where a collection of half mirrors and mirrors direct the photon to one of three other detectors: D_1, D_2, or D_3. If detectors D_1 or D_2 click, then it is impossible to figure out whether the photon came through slit A or B. If detector D_3 clicks, then it is obvious that the idler photon came from a parent photon that went through slit A (the lower slit). A computer collects data from the joint clicking of D_0 and one of the other detectors. The research hypotheses are that data collected jointly from D_0 and D_1 will contain an interference fringe pattern. Similarly, data collected jointly from D_0 and D_2 will contain an interference fringe pattern. But data collected from D_0 and D_3 will contain NO interference fringe pattern. The contraption displayed here is interpreted as if things traveled from left to right, in the original article by Kim *et al*. The same contraption is interpreted in our TEW model as if elementary rays from the detectors travelled toward the left.

though that is inconvenient for the readers who have a paper copy devoid of colors.

If a photon goes through slit "A" the pathways are colored aqua blue in Fig. 1. If it goes through slit "B," the paths are shown in red. The photon then enters a beta barium borate (BBO) crystal where spontaneous parametric down conversion (SPDC) produces entangled photons (each of 702.2 nm wavelength), called the "signal" and "idler" photons. "Signal" and "idler" are the terms traditionally used when describing the output of a BBO crystal.

In the upper 1/4 of the contraption shown in Fig. 1, the signal photon enters a traditional double slit experiment, where it is detected by detector D_0. There is a lens (portrayed in yellow) on that pathway. The lens allows D_0 to be brought closer to the BBO crystal than the other detectors. That distance is central to the concept of "delayed choice." Detector D_0 moves in the vertical "X" direction 3 mm by means of a step motor. By moving along the "X" axis, it traverses the interference fringes.

The other photon ("idler photon") travels down into the lower 3/4 of the contraption to strike one of the three other detectors (D_1, D_2, or D_3). If that photon strikes detectors D_1 or D_2 then "which way" information is not known. This is shown in the diagram because both red and blue lines enter detectors D_1 and D_2, so if one of those detectors clicked, you would not know if you were detecting a photon that came through the upper or lower slit. If the idler photon strikes detector D_3, then "which way" information is known, namely that the photon came through slit A (i.e., only a blue line enters D_3).

Information is gathered from the joint clicking of D_0 and one of the other detectors. In other words, the computer takes all the interference fringe data from D_0 and divides it into three sets of data, depending on which detector clicked from the idler photon. Thus in the D_0 and D_1 dataset, we see how the interference fringes look if we do not know through which slit the parent photon came. The same is true of the D_0 and D_2 dataset. But in the D_0 and D_3 dataset, we see how the interference fringes look if we do know which slit the parent photon came through.

The research hypotheses are that data collected from the joint clicking of D_0 and D_1 or D_0 and D_2 will show interference fringes (because "which way" information is not known). But data collected from the joint clicking of D_0 and D_3 is expected to contain no interference fringes.

As it happens, the interference fringe patterns collected from D_0 and D_1 will be out of phase by π vis-a-vis the interference fringes collected from D_0 and D_2.

Whether or not there is another detector, D_4 is unclear. If there were such a detector, it would be symmetrical to D_3 and would tell us that the idler photon came through the upper slit. In the original article, there was no such D_4 in the diagram (see Fig. 2 in Kim's article). But in other drawings, such as the one discussed by Neil Fontaine (screen name "Architectus777") on You Tube, that detector is present. Since D_4 is not present in the original article, we will assume there was no D_4. On the other hand, logically, D_4 should be present. Why? Because if you lump together the three datasets (D_0 and D_1, D_0 and D_2, and D_0 and D_3), you would not quite get the whole original dataset collected by D_0, because of the absence of the D_0 and D_4 data.

B. Delayed choice

Because of the lens, detector D_0 is closer to the double slits, so it clicks 8 ns earlier than any of the other detectors. That 8 ns is the reason this is called a "delayed choice" experiment. The idea is that D_0 collects data first, then you later discover which slit the parent photon came through, or not.

IV. RESULTS AND CONCLUSION ACCORDING TO KIM *ET AL.*

When the data were analyzed, they confirmed the hypothesis that if you know, or if you could know "which way" information (i.e., if D_3 clicks), then interference fringes will be absent from the data from D_0. If you cannot determine through which slit was used (i.e., either D_1 or D_2 clicks), then you will see interference fringes in the D_0 dataset.

The research team found this to be remarkable. It appeared as if interference fringes were recorded from detector D_0, and that information was preserved if the idler photon did not reveal which slit was used. On the other hand, if the idler photon did reveal which slit was used, then the interference fringes visible on D_0 were "erased" (or "quantum erased") backwards in time by 8 ns.

The concept of "quantum eraser" does not mean that you see the fringe pattern and then it abruptly disappears. Rather it implies that you never see it. Interference occurs at the level of the entire experiment (as Bohr said), so that, in a sense, wave function collapse occurs only when ALL the data has been collected, including the "which-way" information. Our model contradicts many of these ideas, but they need to be discussed if you are to understand the Kim experiment.

Kim *et al*. say that these data support the idea of complementarity. Because of the delayed choice, they could not imagine any other possible explanation. They were not aware of TEW.

V. WHAT IF THE WAVES WENT IN THE OPPOSITE DIRECTION?

When we take exactly the same experimental apparatus and outcome data, and imagine the waves traveling in direction opposite to the photons, what do we have? Let us start with the detectors. No photon could strike a detector unless it was following backwards a wave originating at that detector. Actually elementary waves do not originate at detectors, but penetrate them from behind. In other words, there would be no way for any photon to register at detector "D_N" (where N = 0, 1, 2, or 3) except by following an elementary ray coming out of detector D_N. The waves (or rays) are not present only when a photon is involved. They would come from the detectors 365 days a year, 24 h a day.

Consider the possibility that waves of all wavelengths could come out of the detectors in all directions, perpetually. They would be the fabric of nature, the canvas upon which "reality" is painted. We could ignore the vast majority of them. We will limit our attention to that tiny fraction of the hypothetical waves that come out of the detectors, have wavelength of 702.2 nm, and are heading toward the BBO crystal.

The model we are proposing here is simple minded in many ways. One reader told us, "The photon might as well be a baseball in your model." None of the sophistication of wave packet propagation will be used in our photon. While the assumptions in this model are utterly simple, explaining the whole apparatus is complex and tedious, as you will see.

We will make several assumptions about the equipment. We assume that it is so constructed that waves originating from detector D_3 are going to reach slit A (the lower slit), but are incapable of reaching slit B. Detector D_3 cannot "see" the upper slit. This is equivalent to saying that if detector D_3 clicks, we know "which way" information. In other words, neither slit B nor D_3 can "see" each other: there is no line connecting them in Fig. 1. We assume that the apparatus will allow waves originating at D_0, D_1, or D_2 to arrive at both slits. This is the equivalent of saying that these detectors do not provide "which way" information.

We assume that a BBO crystal works in the opposite way from what physicists think. A BBO crystal takes two incident elementary waves of 702.2 nm wavelength (if they are coming from the correct angle, which they would be) and merges them into one wave of 351.1 nm. The elementary rays in this model will travel from right to left in Fig. 1. Photons travel left to right.

The term "entanglement" has two meanings. One is that a BBO crystal can take a parent photon and divide it into a signal and idler photon with opposite qualities, such as normal polarizations. The other meaning, unique to QM, is that two photons at a distance from one another are such that anything you do to one changes the other instantaneously. In our model, we will use the term "entanglement" only in the first sense.

According to the model we are discussing, Kim *et al.* focused on the wrong place. They focused on the SPDC process inside the BBO crystal, whereas the more important focus would be on the double slit barrier to the left of the BBO crystal. In order to produce interference at the laser, it will require coherent elementary rays of 351.1 nm traveling through both slits and heading to the left, toward the laser. If a 351.1 nm ray travels through only one slit, there would be no wave interference, obviously. In the end, we will find that this is precisely why we have the phenomenon of the interference fringe pattern vanishing when we learn "which way" information. It is that simple.

In the drawings of Kim, the laser is missing. All they show are three arrows coming from the left margin, labeled "Pump" (see Fig. 1 above). Ironically, it is precisely at this argon laser where all the action takes place, according to our model. All the decisions that Kim thinks occur at the detectors had actually been made at the laser two dozen nanoseconds earlier. Without putting the laser in their drawings, they are demonstrating that they failed to think about that which our model would define as the pivotal issue: interference at the laser.

VI. HOW A PHOTON MAKES A DECISION

Let us consider how things look to a photon that is about to be emitted from the laser. For convenience, we will speak as if the photon were sentient, able to "make a decision." As mentioned earlier, our assumptions about this photon are so minimal that one reader has likened our photon to a baseball. That is the way it goes with model construction. Sometimes the most productive models are the simplistic ones: they can inspire new experiments. At the end of this article, we propose two experiments to test our model against QM.

According to our model, the only way a photon could move would be by following an elementary ray backwards. No photon has the capacity to move independent of elementary rays. A photon and its ray move at the speed of light in countervailing directions. The photon about to be emitted from the laser has three kinds of elementary rays impinging on it. Only one of the three will trigger the photon to be emitted in response. Which one varies from one photon to the next photon.

A. The D_0 and D_1 ray

There is an elementary ray of 351.1 nm wavelength, composed of two coherent 351.1 nm waves coming through both slits and interfering at the laser. There is constructive or destructive interference of the wave coming through the upper versus the lower slit (B versus A in Fig. 1). Each of these 351.1 nm rays is a composite of two 702.2 nm rays, coming, respectively, from D_0 and D_1 and merged inside the BBO crystal. Thus when there is wave interference, four 702.2 waves contributed to it. Depending on the intensity of the ray impinging on the laser, a photon is more likely or less likely to be stimulated. The intensity is the square of the amplitude, and that is determined by the position of detector D_0, as we will discuss below.

B. The D_0 and D_2 ray

There is another ray of 351.1 nm wavelength impinging on the laser, coming through both slits, from the combination of 702.2 nm waves from detectors D_0 and D_2. Once again, if a photon were to follow this wave, "which way" information would not be known. If you count the number of 702.2 nm rays that merged so as to trigger a photon, and that number is four, then "which way" information will not be known. If the number is two, then "which way" information will be known. If you understand this paragraph, then you understand the core idea of our model.

C. The D_0 and D_3 wave

Finally, there is a wave that fizzles. This "fizzle" is the key that unlocks the mystery. A coherent 702.2 nm wave come down from D_0. Elementary rays follow the red and blue pathways in Fig. 2 between D_0 and the BBO crystal. A blue wave of 702.2 nm comes up from detector D_3 (see Fig. 2). Because of the way the equipment is constructed, D_3 is unable to "see" the upper slit, and therefore there is no red line connecting D_3 and the BBO crystal in Fig. 2. Therefore when the waves all join inside the BBO crystal, the blue

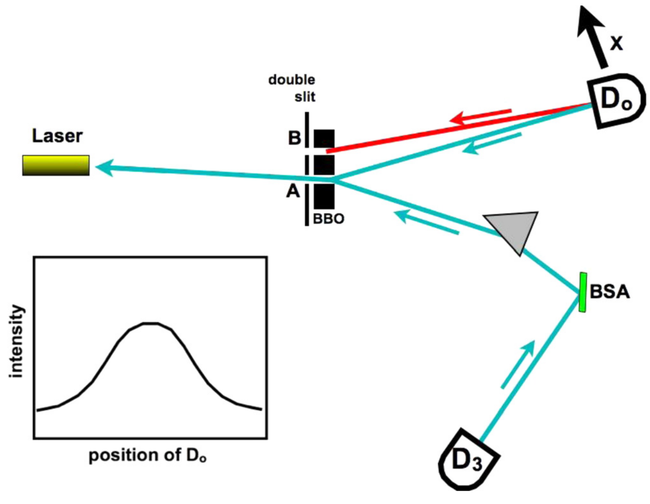

FIG. 2. (Color online) What happens whenever detector D_3 is involved. Only part of the contraption from Fig. 1 is shown in Fig. 2. Here rays come from a combination of detectors D_3 and D_0. The small graph in the lower left represents hypothetical data concerning the intensity of waves impinging on the laser, vis-a-vis the D_0 and D_3 wave combination. There is no interference fringe pattern, because the elementary rays impinging on the laser come through only one of the two slits (through slit A).

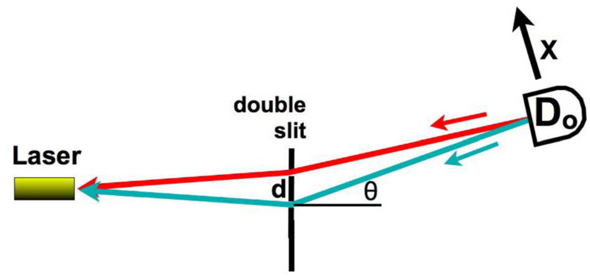

FIG. 3. (Color online) This diagram shows a traditional double slit experiment (backwards). The waves coming from detector D_0 penetrate the two slits and converge at the laser. In general, wave equations work the same no matter which way the waves are travelling. The contraption shown here has the same mathematics ($d \sin \theta = m\lambda$) as a traditional double slit experiment in which waves travel from laser to detector. There is a line normal to barrier. The angle between that line and the lower pathway is θ. We will assume that the distance "d" between the two slits is small compared with the distance of detector D_0 from the double slits.

wave that will penetrate to the left through the lower slit (A) has the two necessary components. However, this is not true of the red wave because there is no red line connecting slit B and D_3. Every signal elementary ray needs an idler partner in order to successfully transit from right to left through the BBO crystal. When D_3 is involved, there is no red idler wave available to mate with the red signal wave.

The graph in the lower left of Fig. 2 does not represent data from the experiment. Rather it represents our concept of what interference fringes would look like if there were a detector at the position of the laser, and if that detector were capable of "seeing" elementary rays, which of course is impossible. The point is that there is no interference occurring at the face of the laser, vis-a-vis the D_0 and D_3 ray impinging on the laser. It is precisely this which, according to our model, explains the final dataset in this experiment. This is why, if you know "which way" information, there will be no interference fringes visible in the D_0 data. This is the key that unlocks the mystery.

VII. WHICH OF THREE INCIDENT WAVES WILL STIMULATE THE PHOTON EMISSION?

Just to remind you where we are: The photon about to be emitted is being solicited by three waves impinging on it. Those waves come, respectively, from detectors D_0 and D_1, D_0 and D_2, and D_0 and D_3. When we speak of a wave named "D_0 and D_N" (where N = 1, 2, or 3), we mean the two coherent components a wave of 351.1 nm coming toward the laser from the upper and lower slit, respectively. Of the three waves (D_0 and D_1, D_0 and D_2, and D_0 and D_3) impinging on the not-yet-emitted photon, the first two are subject to interference (because both slits are involved) and the third has no wave interference (because only one slit is involved). When we use the word "interference," it is always located at the laser in our model, not elsewhere. If there is a sinusoidal quality to the waves impinging on the laser, the sinusoid-ality will have been produced by the double slit experiment (see Fig. 3). Whether the laser is able to see that sinusoid-ality or not will depend on the presence or absence of an idler photon at slit B. The presence or absence of an idler elementary wave at slit B is a toggle switch making the double slit sinusoid-ality visible or invisible. This is because of the nature of the BBO crystal: it merges a signal elementary wave with an idler elementary wave.

Our model will probably sound weird because all probabilities are local and located at the laser. We are not employing ideas such as probability densities located anywhere other than the laser, nor are we employing the idea of superposition of states. Correction: there is a trivial meaning of "superposition of states" in the sense that there are a variety of waves impinging on the laser, each of which is competing to stimulate the emission of a photon. Only one of these incipient waves will win the prize.

In Fig. 3, there will be maxima in the interference fringes appearing at the face of the laser when the following relationship is true:

$$d \sin \theta = m\lambda \tag{1}$$

where m is an integer (0, ±1, ±2, etc.) and λ is 702.2 nm. When there are maxima in the amplitude of the elementary waves incident to the laser, there will be maxima in the number of photons triggered. That surge of photons will travel back to detector D_0 and cause maxima in the data collected from D_0. This equation is well known from physics textbooks. But our model has the waves traveling in what physics textbooks would define as "the wrong way."

If, on the other hand, the variable m took values ±0.5, ±1.5, ±2.5, etc., then there would be minima in the intensity of elementary rays impinging on the about-to-be-emitted photon, and therefore minima in the number of photon triggered, resulting in minima in the number of photons detected by D_0. In other words, in the final graphs published by Kim *et al*. the maxima and minima of the number of photons detected at D_0 are an indirect measure of the maxima and minima in the intensity of waves impinging on the laser.

According to our model, that which is detected by D_0 is precisely what is really happening two dozen nanoseconds earlier at the laser.

Figure 3 omits the BBO crystal and the "idler wave" coming from detector D_N (where N = 1, 2, or 3). The point here is tricky. If this were simply a double slit experiment with no BBO crystal, as shown in Fig. 3, then the wave interference at the laser would be determined by the phase shift of the rays coming through slit A versus B, as they impinge on the laser. That oscillation in interference would be determined by the angle θ, which is controlled by a step motor slowly moving detector D_0 in the "X" direction.

However, when a BBO crystal is inserted into the experiment, to the right of the double slit barrier, the picture changes. Then the presence or absence of idler photons at the BBO crystal will be a toggle switch. A sinusoidal signal photon can only reach the laser if it has an idler photon for a partner.

To restate the same thing in more detail: The red "signal" ray from D_0 is a 702.2 nm wave heading toward the upper slit, but in order for things to work properly, it needs its "mate," which is a 702.2 nm red "idler" wave coming up from detector D_N (where N = 1, 2, or 3). In the case of D_3, there is no such red idler wave. For precisely that reason, every time an idler photon clicks at detector D_3, we know that there was no interference at the laser (which is equivalent to saying we do know "which way" information).

So here is the core idea in our model: The rule is that if and only if there is interference at the laser, will interference fringe patterns be visible (at a later time) at D_0. What D_0 detects is the reality of what happened a couple of dozen nanoseconds earlier.

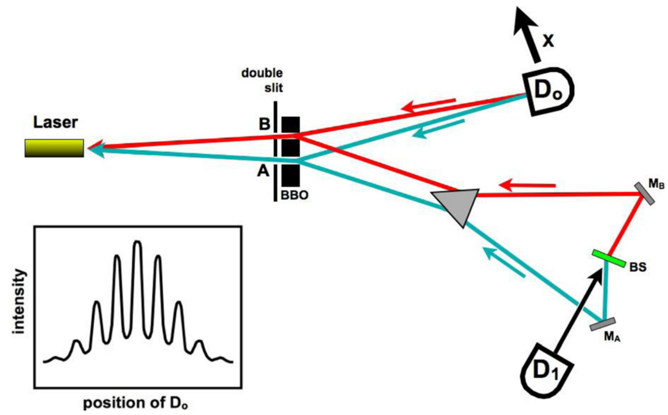

FIG. 4. (Color online) This diagram also shows only part of the contraption from Fig. 1. Here rays coming from detector D_0 above, join at the BBO crystal with rays coming from detector D_1 below. Once the lines converge inside the BBO crystal, there emerge two vectors pointing left, which penetrate the two slits (B and A), and converge at the laser. The intersection of those vectors is interpreted as if it were "interference of elementary rays." In the lower left, there is a graph of the intensity of elementary ray interference at the laser (hypothetical data). There is a sinusoidal pattern. The horizontal axis of that graph, the "position of D_0" is a proxy for the angle θ (see Fig. 3). Our hypothesis is that the maxima in the little graph trigger a maxima in the number of photons emitted from the laser, which results in a maxima in the number of photons detected by D_0. Both our model and the QM model agree that detector D_0 will display an interference fringe pattern when detector D_1 is involved. The difference is that our model has a little graph of hypothetical data located in the bottom left of Fig. 4, while the QM model lacks such a little graph.

VIII. HOW THE D_0 AND D_1 WAVE WORKS

There is a robust interference at the laser vis-a-vis the waves coming from D_0 and D_1, as shown in the lower left corner of Fig. 4, where there is a hypothetical graph of the intensity of the interference impinging on the laser. That interference fringe pattern cannot be directly measured, because there is no direct way to detect elementary waves. You need a particle in order to "see" them. The sinusoidal aspect of the graph is the contribution of the "signal" ray coming down from the double slit experiment (detector D_0).

To reiterate, interference is always located at the laser, and is based on coherent elementary waves coming through both the upper and lower slit (slits B and A). The interference fringe pattern is well known from the usual double slit experiment (Fig. 3), depending on the angle θ: the "position of D_0" (the horizontal axis) is a proxy for θ. There will be interference of the upper and lower 351.1 nm waves at the laser, as shown in the graph in the lower left corner of Fig. 4, if and only if waves are impinging on the laser from ***both*** the upper and lower slit.

So now we have learned a lot about what is going on inside this experiment, but we have failed to answer the initial question: which of the three waves (D_0 and D_1, D_0 and D_2 or D_0 and D_3) will trigger a photon about to be emitted? There are two answers to that question. First, it depends on the intensity of the wave impinging on the photon (see the hypothetical data charted in the lower left corner of Fig. 2 versus Fig. 4). The second answer is that it is random. There are probabilities in TEW. But they are local probabilities and easy to understand, in contrast with the "probability waves" and "probability densities" of QM, which are nonlocal and hard to understand. For any given photon, we cannot predict which pathway it will choose. But if the experiment is repeated thousands of times, we can predict the expectation values.

IX. WHEN A PHOTON IS EMITTED

When a photon is emitted, all wave interference relevant to that photon is finished, according to our model. One might think of a pitcher having no further control over a baseball after it leaves his or her hand. The photon follows its one specific elementary ray backwards with a probability of one, through one and only slit, then through the BBO crystal. Why does the photon of 351.1 nm split into a signal and idler photon? It splits because its wave bifurcates. The photon has no intrinsic cohesiveness, apparently. When its ray bifurcates, the photon bifurcates. According to our model, a BBO crystal has no direct impact on a photon. The impact is indirect: elementary rays are the intermediary.

What will be the pattern with which the signal photon strikes detector D_0? What D_0 records is an indirect measure of what appears in the little graphs in the lower left of Figs. 4 and 2. If there was interference at the laser, then detector D_0 will etch sinusoidal curves. If there was no interference at the laser, which would happen if waves impinging on the laser used only one of the two slits, then there will be no interference fringes detected at D_0.

The implicit idea in the minds of Kim *et al*. is that interference occurs either at detector D_0, at the level of the experiment as a whole, or that interference cannot be localized. Therefore, they have an idea that (according to our model) is incorrect: that interference fringe patterns will occur at D_0 and then be "quantum erased" if the idler photon happens to strike detector D_3. Had detector D_3 been removed in the last picosecond before a photon made it click, then there would be no quantum erasure, according to their model.

Our argument with that idea is, that if the idler photon was following the ray coming from detector D_3, then we already know that there was no interference at the laser (see the little graph in the lower left of Fig. 2), and that absence of interference is what will be displayed at D_0. According to our model, there was nothing to erase!

According to our model, Kim *et al*. are focusing on the wrong place. They are focusing on the detectors, which have very little to do with this experiment. Our model proposes that detectors accurately detect reality. That is all they do. Detectors are almost as boring as our photon. Kim *et al*. are failing to think about the laser: they failed to include it in their diagram. Our model proposes that everything about this experiment is decided probabilistically at the laser. Implicit in this paragraph is the idea that Kim *et al*. are using the concept of complementarity, whereas we are avoiding complementarity in order to look inside the guts of the experimental equipment. Complementarity would say that it is impossible "to look inside the guts of the experimental equipment."

X. THREE CONCLUSIONS

Based on our model, there is no quantum eraser. Why? Because "eraser" implies there was something to erase. According to our model, detector D_0 will see interference fringe patterns if and only if there was interference occurring at the laser. If in the final dataset there are no interference fringes found by D_0, then there was no interference. That in turn could only happen if elementary rays were impinging on the laser through one, but not both slits. Any time detector D_3 clicks, it is because the idler photon is following backwards an elementary ray coming out of detector D_3 and such an elementary ray is incapable of producing interference at the laser for the simple reason that there is no pathway between slit B and D_3: they are unable to "see" each other. Kim *et al*. would say that the absence of a pathway prevents a photon from taking that route. Our model looks at that route two dozen nanoseconds earlier, and reports that an elementary ray from D_3 was unable to take that route.

Furthermore, according to our model there is no delayed choice. The concept of delayed choice means the signal photon is detected at D_0 8 ns before the idler photon at any other detector. According to our model, all decisions were determined at the laser, two dozen nanoseconds before D_0 clicked.

A third conclusion is that there is no need for the concept of complementarity to explain this experiment. It is easy to understand this experiment using elementary waves, providing you avoid complementarity. When it is so simple to understand the experiment down to the smallest detail, why would you choose to use the mysterious, global, and fuzzy approach of complementarity?

The whole idea of complementarity in this experiment pivots on what is called "which way" information. But "which way" information is important for the sole reason that it tells us whether elementary rays were impinging on the laser from one or both slits. We know "which way" information if and only if one of the detectors is unable to "see" the BBO crystal (and vice versa). So detector D_o should be trusted. Its data are accurate.

Thus our model agrees with Kim *et al*. in saying that if you know "which way" information, you will see no interference fringes. But for a different reason.

XI. TWO PROPOSED EXPERIMENTS TO TEST TEW VERSUS COMPLEMENTARITY

When does wave interference occur in a double slit experiment: before or after a particle is emitted? According to QM, interference occurs during and after the emission of a particle. Until a particle is fired, there are no waves. According to TEW wave, interference occurs before and during the emission of a particle. Once a particle is emitted, any further wave interference is irrelevant to the trajectory of that electron.

Let us design an experiment which uses a gate to divide time into two parts: before versus after a particle is emitted. We will place a gate at one of the two slits. In Fig. 5, the gate consists of a powerful laser firing straight down and blocking that slit. According to our design, the laser blocks that slit, starting at precisely that picosecond when a particle is fired. The electrons are fired one at a time, with a pause before the next electron: long enough for the laser to turn off.

According to TEW, waves from the target would already have penetrated through two open slits before the laser blocks one slit. By the time a particle is emitted, interference at the laser has already occurred. The rule is that a detector detects reality. There will be an interference fringe pattern if and only if there was previously interference at the particle source.

Thus the two theories predict different results. This experiment has never been conducted. One physicist told us at an annual meeting of the American Physical Society that the experiment had previously been conducted and

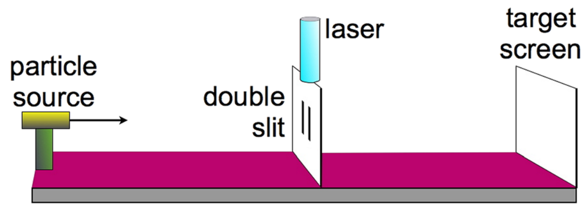

FIG. 5. (Color online) This is a proposed experiment for which QM and TEW predict different outcomes. A traditional double slit experiment plus a laser located above one of the slits. The laser would fire and thereby block that slit, starting at precisely that picosecond when a particle is emitted on the left. QM predicts no interference fringe patterns will appear on the target. Our model predicts that $^1/_2$ the interference fringe patterns would be visible. Why? Because in our model elementary rays will have travelled from right to left through both slits prior to the particle emission. Thus the interference at the particle source would occur, despite the laser, which had not yet fired.

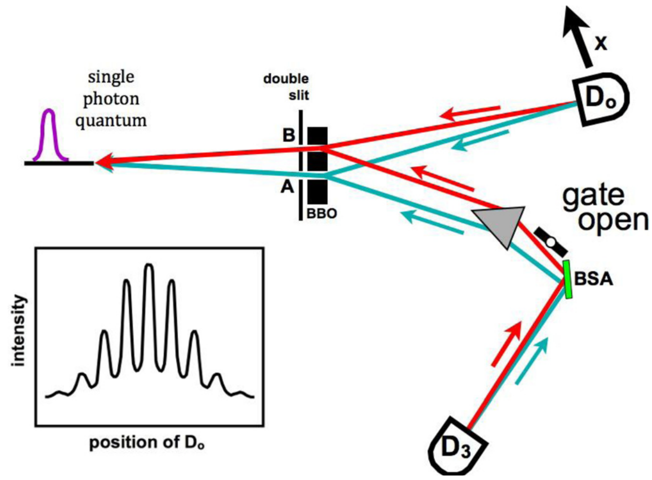

FIG. 6. (Color online) This is another experimental design for which QM and TEW predict different outcomes. The contraption from Fig. 1 is modified. The laser on the left has been replaced with a photon source capable of emitting one photon at a time, with a pause between photons. Also a gate has been inserted on the right. In this figure, the gate is open, and the graph on the lower left shows that elementary ray interference is occurring at the photon source. Because the source is seeing interference (depending on the position X of detector D_0), therefore there will be maxima and minima in the number of photons stimulated to be emitted in response, and thus maxima and minima in the data collected at D_0. The latter data are not shown in this figure.

published. When we looked up his references, we found no evidence to support his claim.

The pivotal issue that makes this experimental design different is the timing. If the timing is off by a nanosecond or two, the results would be rubbish and tell us nothing. A research group in Poland tells us that they plan to build this apparatus and conduct the experiment. Diotr Kolenderski said that the value of QM is not its picture of reality (it has none), but its ability to make predictions mathematically. But the idea of an experiment that QM would be unable to explain, excited him.

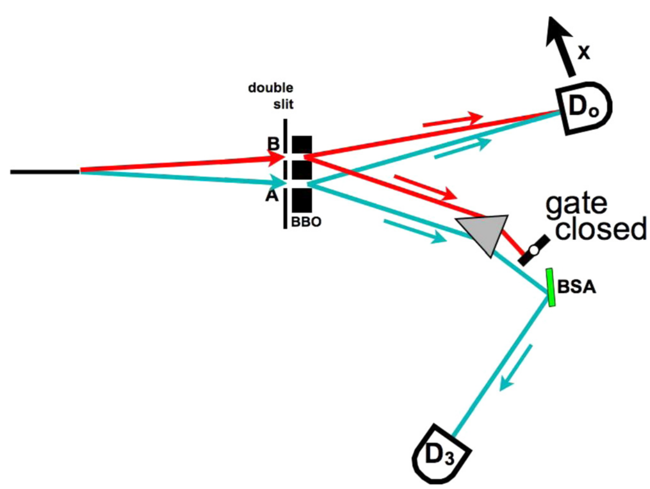

FIG. 7. (Color online) This diagram is identical to Fig. 6, except that the gate is now closed. This prevents a photon from reaching D_3 through slit B. QM predicts that no interference fringes will be evident in the final dataset. Why? Because we know "which way" information. TEW predicts that all the interference fringes will be visible at detector D_0. Why? Because elementary wave interference had already occurred prior to the gate closing.

XII. SECOND EXPERIMENTAL DESIGN

In Fig. 6, we made three modifications to the experimental apparatus used by Kim *et al*. First, we have changed the photon source on the far left from a laser to a device capable of emitting one photon at a time, with a pause before emitting the next. Second, we rearranged the apparatus so that detector D_3 can now "see" both slits. Third, we introduced a "gate" on the right that the researchers can close at precisely that picosecond when a photon is launched.

When the gate is open (see Fig. 6) elementary rays can reach the photon source through both slits, so there will be wave interference. Here QM and TEW agree. The two theories disagree when the gate is abruptly closed after a photon is emitted (see Fig. 7).

XIII. CONCLUSIONS

The experiment reported by Kim *et al*. in 2000 claims to be based on and to provide support for complementarity. It is widely but incorrectly believed that there is no other possible explanation of this experiment.

Let us ponder the same phenomenon from two different perspectives. Imagine that an idler photon "clicks" at detector D_3. That means that a photon came through the lower slit. According to complementarity there will be no interference fringe pattern visible at detector D_0, because we know "which way" information.

A TEW analysis also starts with an idler photon "clicking" at D_3. The only possible way that could happen is if the photon were following backwards an elementary wave coming out of D_3. Photons do not jump from one ray to another. Once emitted, they stick with that particular ray that initially stimulated that emission. They select their elementary ray at the laser, and then are loyal to that ray.

Slit B and detector D_3 are unable to "see" each other. Therefore there will be no interference at the laser when the photon randomly decides to follow the D_0 and D_3 elementary ray, rather than the other two possible choices. Both slits must be used for there to be interference. Therefore, when a 351.1 nm photon is triggered in response to an incipient wave, if that is the D_0 and D_3 wave, there will have been no interference. Detector D_0 will report no interference fringes because of the simple rule: what detectors "see" is reality. Also implied in this sentence, is that there is such a thing as "reality."

Thus, we both look at the same phenomenon. The usual way of "explaining" what happened is to call it complementarity, which is a fancy way of saying that you can not explain it. Our model explains the data by looking inside the details of the experiment and infer what must have happened to produce the final data. Our model differs from complementarity[11] in that it implies there is such a thing as physical reality at the quantum level, and that this physical reality has integrity no matter how you observe it.

ACKNOWLEDGMENTS

Lewis E. Little made helpful comments on an earlier draft of this article.

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