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# A Self-Consistent Interpretation of Quantum Mechanics Based on Nonlocality

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## Abstract

Recent "loophole-free" confirmation of Bell's inequality violation inevitably leads to one of two options: either to give up realism or to reject locality. Giving up realism leads to problems with the principle of causality. We show that, (i) there are strong indications that nonlocality is a fact of nature, (ii) with the nonlocality option, we can explain all quantum phenomena observed to the present. We also present evidence that photons (as well as electrons or other particles), do not have a wave-particle duality and they are all intrinsically particles. However, their motions can be explained via appropriate wave functions that are *established instantaneously across space in accordance with nonlocality*. Furthermore, need for concepts such as collapse of the wave function, observer effect, and many-worlds interpretation do not arise. We also propose a simple experiment that can confirm our proposed mechanism.

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# 1 Introduction

Almost a century after its introduction, quantum theory has unresolved foundational and philosophical issues that go back to Einstein and Bohr; see, for example [1-5]. This has led to a number of popular books as well; see, for example [6-9]. Even though the Schrodinger equation is capable of accurately predicting the statistical outcome of experiments, many issues such as wave-particle duality, measurement problem, nonlocality, and their philosophical implications for the true nature of world related to the principle of causality remain unresolved.

Back in 1935 in their famous EPR paper [10], Einstein et al. proposed that the Schrodinger equation was incomplete -- even though it was able to predict experimental outcomes with high accuracy -- because of undiscovered fundamental features or “local hidden variables”; here the term “local” was added to emphasize his insistence that any such theory also need to be *local, i.e., physically separated events cannot influence each other instantaneously.* Furthermore, they thought such local hidden variables, once found, could make the quantum mechanical (QM) measurements consistent with locality and realism. Here *realism means any object would have well-defined properties irrespective of whether a measurement was made or not, i.e., objective realities are observer-independent.*

Thus what EPR basically proposed can be succinctly stated as, “locality and realism”, sometimes abbreviated as “local realism”. Bell [11] succeeded in deriving a mathematical inequality that can be experimentally evaluated to test whether it will be possible to have such a local hidden variable theory that would also maintain realism. An experiment violating a Bell inequality would therefore imply that either locality or realism is false.

Since then a variety of experiments have been conducted to test Bell’s inequality, showing that the inequality is violated [5,12,13]. However, all of those experiments had loopholes, and they were progressively removed with improved experiments. *In late 2015, three groups of researchers independently conducted “loophole-free” experiments [14-16] for* *the first time that fully confirmed the violation of Bell's inequality.* Thus EPR's "local realism" has been proven to be an incorrect description of nature.

*However, we contend that Einstein was correct in one aspect:* The basic problem that has led to many controversies in quantum mechanics (QM) is that Schrodinger equation is incomplete, as Einstein et al. noted [10]. Even though it can yield the correct final outcome, it does not describe the particle movement in between the source and the detector. In the Copenhagen interpretation (which assumes that the Schrodinger equation provides a complete picture), a particle is always in a superposition of states until the time of the measurement at which time it "collapses" to the observed state.

With the recent confirmation of Bell's inequality, there are two possibilities left open: either locality or realism has to be abandoned [5,12,13]; see Fig. 1.

## 2 Key Features of Our Proposed Interpretation

Our proposed interpretation rests on three premises: nonlocality of nature, realism, and that photons (as well as electrons and other particles) are always particles. We will first discuss these three critical premises.

### 2.1 Photons are Particles

It will become clear below why it is not necessary to even consider the validity of a wave-particle duality for photons or electrons (or any other particle); such an assumption is not necessary within our interpretation. First, we like to point out that it has been experimentally proven that photons are particles, not waves. What is meant by a "wave" in wave-particle duality (Copenhagen interpretation of QM) is vague and different people seem to interpret differently.

For this paper, we will start with clear and unambiguous definitions for a wave and for a particle: *A wave is a physical wave much like a ripple (caused by dropping a stone) that propagates on a water surface. A particle always occupies a localized position*. For a particle, what is spread out is the **wave function**, indicating possible locations for the particle. *Thus we will give up the notion of a wave to represent a particle and refer instead to a wave function*, which is a mathematical concept. We will present evidence that these definitions are consistent with the "nonlocal realism" that we propose to be the correct description of nature.

Historically, Newton's concept of light consisting of particles prevailed until around 1850 when it was abandoned because it could not explain interference and diffraction effects. Since then light was regarded as a wave until about 1900. Then it was realized that the concept of light as a wave could not account for many new experimental observations including the photoelectric effect, black-body radiation, and Compton scattering. Einstein [17] proposed that light is quantized to explain the photoelectric effect -- for which he received the Nobel Prize in physics in 1921 -- *and those quanta were given the name photon; they are the original "quanta" of quantum mechanics.* The fact that a photon was a particle with momentum was confirmed experimentally by Compton [18], for which he received the Nobel Prize in 1927. The photon concept has led to momentous advances in experimental and theoretical physics such as lasers, Bose–Einstein condensation, and quantum field theory.

In spite of that evidence, there had been a persistent view that light could not be composed of particles, and that many effects such as the photoelectric effect can be explained without the concept of a photon [19-21]. The final confirmation of a photon as a particle had to wait until single photon sources were developed, and in 1986 Grangier, Roger, and Aspect [22] confirmed in their anti-correlation experiments that photons are indeed particles; see Fig. 2. They measured an anti-correlation parameter, $\alpha = 0.18 \pm 0.06$, a maximum violation of more than 13 standard deviations, confirming that a photon propagated through only one leg of the interferometer at a time. If photons sometimes behave as waves, then one would observe significant number of coincidence counts. We will discuss their other experiments conducted with a second beam splitter installed at the detector in Section 4.1.

Therefore, a photon is now categorized as an elementary particle. A photon at any wavelength is detected as a particle (one needs a physically large detector to detect one at long wavelength). It must also be noted that in 1983 when he discussed the “delayed-choice experiments”, the picture that Wheeler [23] had about a photon was that of a “wave” that could be split at the first beam splitter (A); see, Fig 4 of Ref. 23. Even though it has been 30 years since the 1986 proof [22] that photon is a particle, its implications have not been fully appreciated by the physics community.

Many physicists still talk about “wave-particle duality”, referring not only to light but also for particles like electrons. But this is totally unnecessary and leads only to confusion, as we discuss below.

## 2.2 Nonlocality

Nonlocality has already been used as an implicit assumption by Feynman [24,25] in his development of quantum electrodynamics (QED). He also used a second assumption, which is to say that both electrons and photons are particles all the time. Wave-particle duality is not even mentioned in QED. **To re-emphasize, Feynman used two assumptions in QED: (1) Electrons and photons are particles, (2) For a given experimental setup, there are many possible paths available for an electron or a photon, i.e., their wave functions incorporate all possible paths for a given electron or a photon with associated probability amplitudes for each possible path.**

In Section 2.1 above we presented evidence that photons are always particles, just like electrons. Feynman illustrated that it is not necessary to consider them as waves at all in QED [25].

As we mentioned above, Newton's corpuscular theory of light was abandoned around 1850 because it could not explain interference and diffraction phenomena. However, when Feynman [24] introduced his new approach to quantum mechanics in 1948, he provided the mechanism to explain interference and diffraction within the particle nature of light. This proposal assumed that a photon does not travel in a definite path; rather, *a multitude of paths are automatically setup according to the experimental parameters and all these possible paths need to be integrated over to describe the motion of the particle.*

He proposed that, "The probability that a particle will be found to have a path $x(t)$ lying somewhere within a region of space time is the square of a sum of contributions, one from each path in the region" (Ref.24, p. 367). Also, "the contribution $\phi[x(t)]$ from a given path $x(t)$ is proportional to $\exp(i/\hbar)\, S[x(t)]$, where the action functional $S[x(t)] = \int L(\dot{x}(t), x(t))\, dt$, is the time integral of the classical Lagrangian $L(\dot{x}, x)$ taken along the path in question" (Ref. 24, p. 371).

*Then he applied that concept to describe the propagation of photons as well as electrons in his formulation of QED [25].* The basic idea of photon propagation using "all possible paths available" has been explained in simple terms by Feynman in his introductory book [26] on QED.

Even though Feynman did not pursue the concept of a photon as a particle in QM, he did use it to develop QED. As we discuss below in Section 3, David Bohm independently developed his Bohmian theory for QM, and we will illustrate below that his formulation is consistent with the "electrons and photons exploring all possible paths" theory of Feynman. Using this theory, Feynman [26] elegantly explained the principle behind Fermat's principle of least time. Figure 3 shows the refraction of light from a source (S) in the air, to a detector (D) placed in water; a few of the possible paths are shown.

He proposed that a given photon would consider all possible paths from S to D, and map out the time taken for a photon to reach point D via multitude of points on the water surface. The change in the phase angle is shown in the plot below. The vector diagram at the bottom of Fig. 3 shows that contribution from those paths away from the expected path cancel out. We can see that most of the contribution is due to paths close to the expected path indicated by the heavy line. Even though such paths away from the expected path do not make a significant contribution in this case, presence of their contribution is beautifully illustrated in Feynman's discussion of diffraction in a grating; see pp. 46-49 of [26].

All these possible trajectories are "established" as soon the experiment is setup and even before a photon takes off from the source. **Therefore, the nonlocality was a critical assumption of Feynman, even though he did not specifically use that term.** His "ad hoc procedure" for adding up contributions due to "all possible paths" just means nonlocality. The "weight" associated with each trajectory is given by the phase factor, $e^{iS/\hbar}$. In QED, all possible paths that are consistent with the experimental arrangement are taken into account by integrating over all possible paths, i.e., via path integrals.

### 2.3 Realism

In their EPR paper [10], Einstein et al. introduced the following criterion on reality: "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity".

The importance of realism has been well-expressed by d'Espagnat [27]: "..Of the three premises realism is the most fundamental. Realism can be stated formally as the belief that a mere description of data is not at all that should be required of a theory. Even an empirical rule for predicting the patterns of future measurements is not enough. The mind demands something more: not necessarily determinism – there is nothing intrinsically irrational about randomness – but at least objective explanations of observed regularities, or in other words causes. Underlying this demand is the intuitive notion that the world outside the self is real and has at least some properties that exist independently of human consciousness".

And we want to emphasize that having realism is the least confusing approach especially if it leads to a self-consistent theory. In Sections 3 and 4, we will show that all existing QM experiments can be explained with our approach. A given QM experiment provides a set of possible outcomes (with total probability of unity), and probabilities for such outcomes can be predicted with high accuracy; see Sections 3 and 4.

### 2.4 Deeper Implications of Feynman's Work

The difficulty that Newton faced in his corpuscular theory of light without Feynman's "explore all paths" assumption is even more apparent in the following example, where we consider the reflection of light from a glass plate with parallel surfaces; see Fig. 4. Here, for a photon to get to the detector $D_R$, there are two paths available via the glass plate, as shown in Fig. 4. Feynman's assumption was that wave functions are established instantaneously via both those paths, and the sum of them would determine the possible paths for a photon.

Normally, one would expect the light reflected from the front surface *to be at a constant level* since photons are particles, *i.e., a photon hitting the first surface would have no idea whether another interface existed below or not.* Thus the zero intensity of the signal at some glass thicknesses was unexplainable in Newton's corpuscular theory.

However, QM wave functions -- which takes into account the phases and amplitudes of all possible paths -- *are established instantaneously*. *This is a consequence of the nonlocality of nature as discussed above.* In the case of Fig. 4, there are two possible paths indicated by the arrows 1 and 2 leading to $D_R$ as shown in the figure. It is important to note that the path of a given photon leaving the source (S) is predetermined from the start. Thus the question does not arise as to how the photon coming to the first surface "knows" that there is a second surface below it. There is no causality problem here, *since the QM wave function is established at the very beginning* because of the nonlocality of nature; if any changes are made to the experimental setup, the wave function will adjust *instantaneously. Nonlocality means exactly that: physical proximity is not needed.*

It is easy to see that the destructive interference leading to zero signal at $D_R$ occurs at plate widths of integer multiples of the wavelength. *As long as one uses monochromatic light, and glass with no defects, one could in principle make the width of the plate arbitrarily large.* All possible photon paths are taken into account instantaneously.

Now we will discuss a critical implication of Feynman's "a particle exploring all possible paths" or "path integral" approach, that even he did not realize.

**What happens when we increase the thickness of the (defect-free) glass plate to a value that is greater than the distance from the glass plate to the detector $D_R$?** Now, a photon reflecting off of the front surface would have had time to reach the detector before another photon going through the glass plate reaches the lower glass-air surface.

Therefore, in the absence of wave functions establishing instantaneously across both possible paths (and thus undergoing destructive interference), there CANNOT be a zero signal at the detector $D_R$, for ANY thickness of the glass plate.

*This is a crude "delayed-choice" experiment; see Section 4.1.* If the thickness of the plate is an integer multiple of the wavelength of light, then we can expect the signal at $D_R$ to be still dictated by the quantum wave function, which prevents a photon from reflecting off of the front surface. The signal at $D_R$ can be predicted to still be zero! Thus as long as the two possible paths are available (without any defects in the glass plate), **the wave function will enforce "no reflection" at the front surface.** *This is the basis of explanation of the quantum eraser and delayed-choice experiments that we will discuss below in Section 4.1.*

Thus we point out that Feynman’s idea of a photon exploring all possible paths is none other than the enforcement of nonlocality; *QED implicitly assumed nonlocality.* A wave function is instantaneously set up over all space taking into account the phases for all possible paths; there is no spatial limitation. Normally, only paths close to the stationary path contribute significantly -- and all others are cancelled out -- but in the case of entangled particles which propagate in opposite directions there can be no spatial limits.

## 3 Bohmian Mechanics

With the above model, QED successfully described the motions of photons and electrons by taking into account “all possible paths” via path integrals [25]. In our proposed interpretation of QM, electrons and photons are particles and their motion is governed by a mathematical wave function that is set up instantaneously across space taking into account the details of the experimental arrangement; interference and diffraction effects are explained by this wave function. Modification of the Schrodinger equation to accommodate this idea was proposed by David Bohm [28] in 1952, sometime after the Feynman’s1948 paper [24]. However, Bohm did not seem to have been aware of the significance of Feynman’s ideas for his work.

Bohmian mechanics is a version of quantum theory initially proposed by Louis de Broglie in 1927 and rediscovered by David Bohm in 1952; see Ref. 28. In Bohmian mechanics, a system of particles is described in part by its wave function evolving according to Schrodinger’s equation. *But this description is completed with the specification of the actual positions of the particles by a pilot wave or a guiding wave.* Bohm did not provide a justification for this approach, but in the following we point out that it is connected to Feynman’s picture of a particle exploring all possible paths via a QM wave function that is established instantaneously across space.

It turns out *that this pilot wave is a consequence of assuming the wave function to be of the form [28,29]*,

$\psi = R\ e^{iSt/\hbar}$

and then substituting it into the Schrodinger equation. This leads to an additional term in the Schrodinger equation, which Bohm called the “quantum potential” Q, given by:

$Q = -\ (\hbar^2/2m)\ \nabla^2 R/R$

On p. 29 of Ref. 29, it is stated, “This particle is never separate from a new type of quantum field that fundamentally affects it. This field is given by R and S or alternatively by $\psi = R\ e^{iSt/\hbar}$. $\psi$ then satisfies Schrodinger’s equation.”

Thus, now we can clearly see the connection of Bohm’s work to that of Feynman via the phase factor, $e^{iSt/\hbar}$. Bohm seems to have adopted this particular form by chance. However, it naturally leads to the quantum field that is established instantaneously across space. Feynman’s “exploration of all possible paths” comes via the action term, S. Furthermore, the quantum field, Q -- which establishes across space instantaneously -- depends on the details of the experimental arrangement (via R).

Thus Bohmian mechanics essentially takes Feynman’s ideas to their logical conclusion. It appears that all three (de Broglie, Feynman, and Bohm) independently came to realize the importance of the phase factor.

In Bohmian mechanics *it is explicitly assumed that the electron is a particle following a well-defined trajectory* but is always accompanied by a quantum field [28-30]. As with electric and magnetic fields, the quantum field can also be represented in terms of a potential which is called a quantum potential. But unlike what happens with electric and magnetic potentials, the quantum potential depends only on the form, and not on the intensity of the quantum field. Therefore, even a very weak quantum field can strongly affect the particle as it just maps out possible paths for the particle (*in our interpretation, this is the enforcement of nonlocality*). The role played by the quantum field can be compared to that played by a radio signal from a control tower to a ship in the ocean; the radio signal is too weak to actually control the ship, but it guides the ship in the right direction [28-30].

We point out that the novelty in Bohmian mechanics is the explicit inclusion of nonlocality (which comes through the phase factor), i.e., the ability of the distant parts of the environment (such as the slit system in a double-slit experiment) to instantaneously affect the motion of the particle in a significant way through its effect on the quantum field. The inclusion of the phase factor does not alter the final outcome of an experiment, and that is why the Schrodinger equation has been adequate for calculations. *But in Bohmian mechanics, particle trajectories can be traced in real time without the need for a forced wave function collapse.*

A detailed description of Bohmian mechanics can be found in Refs. 29 and 31. Calculations based on Bohmian mechanics have not been employed frequently, because it involves more work compared to the conventional Schrodinger equation. However, such calculations provide actual trajectories for the particles under consideration in real time; there is no need for a wave function collapse.

The actual trajectories have been harder to measure not because of an “observer effect”, but because an observation itself can alter the quantum field. Recent experiments have been conducted to "weakly” measure a system without appreciably disturbing the trajectories, and they have been shown [32] to be consistent with the predictions of Bohmian theory; see the reconstructed average particle trajectories in Fig. 3 of that paper. A follow-up study [33] generalized the Bohm trajectories for massive particles. Another experiment reported [34] the detection of a photon at one slit without destroying the interference pattern. Thus it is possible to figure out “which way path” without collapsing the quantum wave function. The concept of complementarity is not needed and there is no measurement problem.

Recently, an elegant experiment has been conducted that clearly illustrate the enforcement of nonlocality and realism, as well the ability of Bohmian mechanics to accurately calculate particle trajectories [35]: “..we experiment on two entangled particles (photons) and map out the trajectories of this first particle (and therefore both its position and its velocity) are indeed affected by an externally controlled influence on the distant second particle. For some choices of that control, the second particle in our experiment can be used to determine through which slit the first particle has gone..". These observations are fully consistent with our proposed interpretation, and in fact our interpretation provides an intuitive explanation.

### 3.1 Implication to Other Scientific and Philosophical Areas

We believe that "non-deterministic" is the wrong word to use in QM experiments since it gives the impression of randomness. *The reality is that a QM experiment generally has many possible outcomes, each with a defined probability*. Thus the outcomes are well-defined. But one measurement will give only one of the possible outcomes and one needs to do multiple measurements to understand the final overall outcome. However, those possible outcomes are well-defined and do not depend on an observer.

Once a measurement is made, the description provided by the wave function in complete; *the measurement finds the particle to be in one of the predicted locations with a given probability.* There is no need to invoke a continued "branching out" per "many worlds interpretation" which was proposed in order to avoid the forced collapse of the wave function in the Copenhagen interpretation; see [36,37].

There is a prevailing incorrect impression that nonlocality would automatically imply "propagation of information faster than light". There is a distinction to be made between instantaneous influence across space (which is possible) and instantaneous propagation of information (which is prohibited by the theory of relativity); see, for example, [38,39]. In Ref. 38, Popescu points to the "peaceful co-existence of relativity and nonlocality" and discusses how particles can communicate superluminally, but that experimentalists cannot use them to communicate superluminally with each other.

Then, there have been studies that show experimental violation of Bell's inequality could be explained in principle through models based on *hidden influences* propagating at a finite speed v > c, provided v is large enough; see, for example, Refs. 40,41. In a subsequent paper Bancal et al. [42], showed that, "there is a fundamental reason why influences propagating at a finite speed v may not account for the nonlocality of quantum theory", and that "If we want to keep no-signaling, it shows that non-locality must necessarily relate discontinuously parts of the universe that are arbitrarily distant" (Ref. 42, p. 870). Thus nonlocality implies instantaneous response without instantaneous transfer of physical information.

Instantaneous establishment of the wave function is an inherent assumption in Feynman's work on QED, where Feynman's "explore all possible paths" is enforced via path integrals [24,25]. Thus the key ideas that we use have been discussed by Feynman, Bohm, and others at various instances, but have not been presented in a coherent, self-consistent manner up to now.

Another important and new relevant research area is on quantum entanglement. Local realism is clearly rejected in these experiments. A multitude of quantum entanglement experiments have been conducted and their practical applications are being explored [43,44]. These observations are of course fully consistent with our proposed interpretation based on nonlocality, which states that wavefunctions are *established instantaneously* over all space. In quantum entanglement an entangled particle can *respond instantaneously* to the other entangled particle or particles. For example, there have been recent experiments on multi-particle entanglement (see, for example, [45]) and entanglement in a solid state system [46]. Entanglement and nonlocality are inter-related and co-existing realities of nature.

## 4. Discussion of QM Experiments in Terms of Proposed Interpretation

### 4.1 Delayed-Choice Experiments

The above discussed dilemma of faster than light communication also appears when trying to explain Wheeler's delayed choice interferometer experiments with the Copenhagen interpretation. These experiments have vividly brought forth the contradiction with the principle of causality if local realism is accepted as a fact; see, for example, Refs. 47-51. In the following we will discuss the main concept with our proposed interpretation that can explain the results of those experiments without violating causality.

Figure 5 shows a simple schematic diagram of an interferometer in two configurations; the first of such experiments was conducted in the same study [22] that confirmed the particle nature of a photon; see Fig. 1 of [22]. They then used a modified version of the same experiment to illustrate the appearance of interference effects. We will first describe those observations, since they provide insight into the delayed-choice experiments, which soon followed.

In the first configuration of the experiments [22], there was no beam splitter B at the top right, so the photon either goes through to detector $D_1$ or detector $D_2$ (see Fig. 5). Observing that photons show up in equal numbers at the two detectors, experimenters say that *each photon behaved as a particle* from the time of its emission to the time of its detection by traveling via one path *or* the other. The absence of coincidence counts firmly established that conclusion.

In the second configuration for the delayed-choice experiments, a beam splitter (B) was inserted at the top right of the apparatus as shown (Fig. 5). Now the photon coming through either leg can go to detector $D_1$ or detector $D_2$ as shown by the dotted lines. In this case, an interference pattern is seen at either detector. Experimenters explained this observation as a consequence of the wave nature of light, i.e., *each photon must have traveled by both paths as a wave since the photon could not have interfered with itself.*

However, we would like to point out that with the second beam splitter, *a photon travelling down either leg has two possible paths after the second beam splitter*, and the new wave function takes into account all four possible paths to the two detectors. If the optical paths are the same, interference should result at each detector, as observed [22]. The interference effects are due to the fact that a photon travelling down *either leg* now has two possible paths after the beam splitter B. That is the cause of interference fringes; the new QM wave function takes into account all four possible paths to the detectors.

Going back to the Copenhagen interpretation, in the first case (without the beam splitter B) the photon is said to "decide" to travel as a particle and in the second case (with B in place) it is said to "decide" to travel as a wave. Wheeler [23] wanted to know whether it could be determined experimentally the time at which the photon made its "decision." He wanted to let a photon pass through the region of the first beam-splitter (A) while there was no beam-splitter (B) in the second position, thus causing it to "decide" to travel as a particle, and then quickly place the second beam-splitter in its path. Having presumably traveled as a particle up to that moment, would the photon manifest itself as a particle with no interference effects? Or, would it behave as though the second beam-splitter had always been there and manifest interference effects?

Such experiments were conducted (see, for example, Refs. 47-51) and *did manifest interference effects even if B was put in place while the photon was in flight after passing A.* This observation led to following contradictory conclusions (based on the Copenhagen interpretation):

- The photon must have gone back in time and changed its decision to travel as a wave instead of a particle (causality violated).
- Since the photon’s choice was based on the fact that the observer made the decision to insert the second beam splitter, the observer can influence how a photon behaves, either as a particle or a wave (observer effect).

Furthermore, if the experiment was begun with the second beam-splitter in place but it was removed while the photon was in flight, then the photon did not show any sign of interference effects.

- Thus the observer again forced the photon to go back in time and behave as a particle.

Another interpretation was that until a measurement is not made, it is meaningless to talk about a measurement, i.e., realism does not hold. There is no universally accepted explanation for the above experimental observations.

However, there is no need to invoke such assumptions in our proposed interpretation. The key to the appearance of the interference fringes is the presence of the beam splitter (B) at the top right. As soon as that is in place, the two photon paths (through each leg) will lead to an interference effect (after taking into account the delay with the coincidence circuit in the time-delayed experiments). It does not matter at what time B is put into place, as long as that is done before the first photon reaches that point, *since both paths are equally likely to get a photon to point B*. Even though each experiment is different [47-51], they all can be explained with this basic concept.

### 4.2 Double-Slit and Quantum Eraser Experiments

The double-slit experiment has famously been said to contain the entire mystery of quantum mechanics and various versions were discussed by Shabolt et al. [52], who state that, "It provides a concise demonstration of the fact that single quanta are neither waves nor particles, and that in general they are neither in one single place, nor in two places at once."

*There is the assumption of locality in the above argument: It assumes that the opening of the second slit has no impact on particle trajectories through the first slit.* If the nature is nonlocal -- as experiments confirm [14-16] -- the opening of the second slit will impact the trajectories through the first slit. Therefore, *an entirely new wave function describes the motion of a particle through the double slits.* Even though the slits may be nearby, they are separated from each other. Now a particle has more paths available to it, and all possible paths (through both slits, with possible interference) should be taken into account. *This is exactly what Feynman's path integrals do and is taken into account by Bohm's pilot wave.*

Therefore, results of those experiments can be explained by particles (photons, electrons, or any other particle) whose possible trajectories are *instantaneously* mapped out by the quantum field (taking into account all possible paths). Interference patterns result from *all possible paths* for a given particle described by the wave function, and thus are observable even with a single particle (with enough repeated detections). For a given particle, possible trajectories are mapped out; a particle may go through one slit at one time, but through the next at another time.

If particle detection is attempted at one of the slits, that could significantly change the experimental arrangement leading to a new set of possible paths and thus also could destroy the interference pattern. There is no need to invoke a complementarity in the sense of needing to provide either a particle representation or a wave representation: They are always particles, but their motions are represented by the QM wave function that properly takes into account all possible paths.

A series of new experiments have been recently conducted using more sophisticated versions of the double-slit experiment, illustrating that when one tries to figure out which slit the photon went through, the interference pattern is lost. (These experiments are qualitatively similar to the delayed-choice experiments of Section 4.1). Different schemes for achieving this objective have been illustrated in Refs. 53,54, for example. It was also shown that the interference effects could be brought back by erasing the "which path information".

However, there is an easier explanation for those observations in our interpretation, where the quantum field changes instantaneously with any change in the experimental setup. For example, in the experiments of Kim et al. [53], the double-slit interference pattern was lost when they counted only those signals that synchronized with either the detector $D_3$ or $D_4$ which were sampling photons from each slit. That action automatically converted the experiment to a single slit setup. Then they inserted a beam splitter which effectively removed that "filtering" and brought back the interference fringes.

In the experiments of Walborn et al. [54], it did not matter whether the p photon was detected before or after the s photon. In a nonlocal universe, it does not matter whether the p photon is detected before or after the s photon; i.e., results shown in Fig. 5 and Fig. 8 (or Fig. 9) in those experiments [54] are *what they are supposed to be under nonlocality*.

The paths of the entangled photons are mapped out the moment the experimental parameters are set. It does not matter to the quantum field the relative position of the p detector compared to that of the s detector if everything else remains the same.

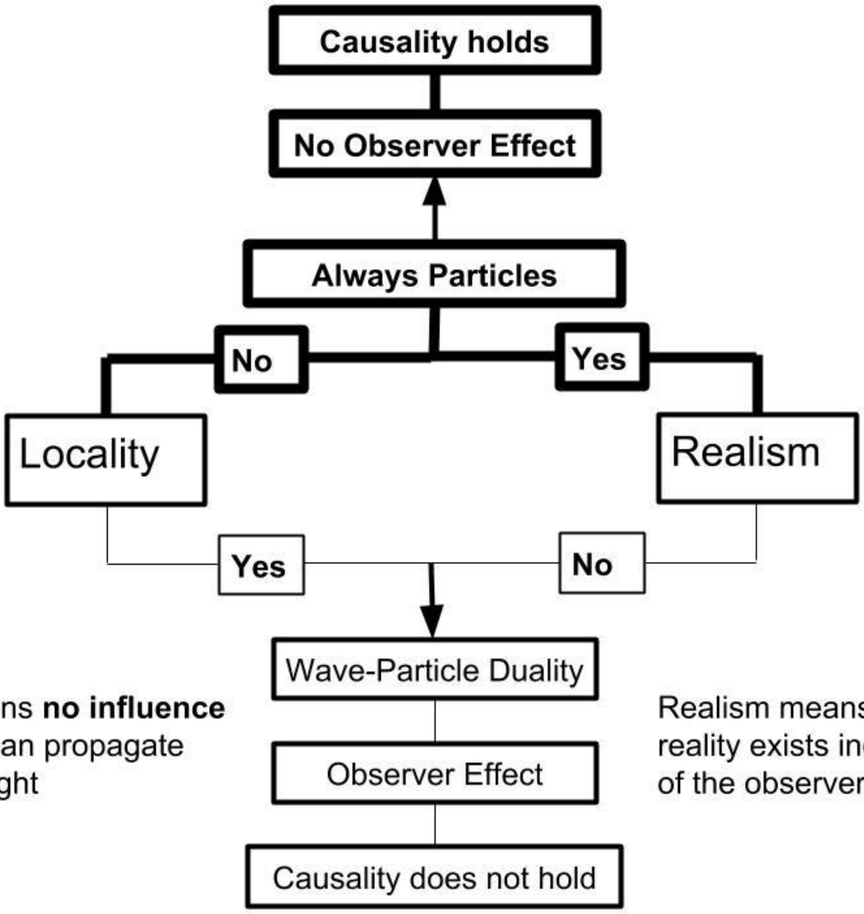
This was the key idea that we discussed per Fig. 3 (Section 2.2) and especially Fig. 4 (Section 2.4). For example, in Fig. 4, the photon hitting the first surface does not know the thickness of the glass plate; the quantum field is set instantaneously according to the experimental parameters, i.e., the thickness of the glass plate in that case. This is the principle of nonlocality.

To give another example, in their paper on quantum erasure experiments, Ma et al. [55] conclude, “Any explanation of what goes on in a specific individual observation of one photon has to take into account the whole experimental apparatus of the quantum state consisting of both photons”. That is consistent in our representation. They also state in the same final paragraph, “Our results demonstrate that the viewpoint that the system photon behaves either definitely as a wave or definitely as a particle, would require faster-than-light communication”. That statement is valid only if local realism is true. But with nonlocality, the establishment of the wave function is instantaneous, and there is no transfer of “physical information.”

## 5 Conclusions

Based on the recent ground-breaking experiments on nonlocality, we have presented a self-consistent interpretation of quantum mechanics by incorporating several key ideas of Feynman, Bohm, and others. There is no wave-particle duality: both electrons and photons are particles, but their possible trajectories are depicted by QM wave functions. The nonlocal nature leads to the establishment of quantum fields instantaneously across space based on the experimental arrangements at any time. With the incorporation of the phase factor (which incorporates the non-locality of nature or Feynman’s “a particle explores all paths” assumption), the Schrodinger equation fully describes the motion of a particle between the starting and the end points, and the description becomes complete.

The Schrodinger equation has been able to successfully calculate the final outcome because the inclusion of the phase factor does not affect the final outcome. Thus, there is no measurement problem and experimental observations are fully causal in our nonlocal universe.



Locality means **no influence** of any kind can propagate faster than light

Realism means physical reality exists independent of the observer

**Figure 1.** Two options are open as a result of the confirmed violation of Bell's inequality. We present evidence that the option on the top (nonlocality/realism) is fully consistent with all observations up to now, and is also consistent with the principle of causality. The other option (at the bottom of the figure) is associated with the Copenhagen interpretation.

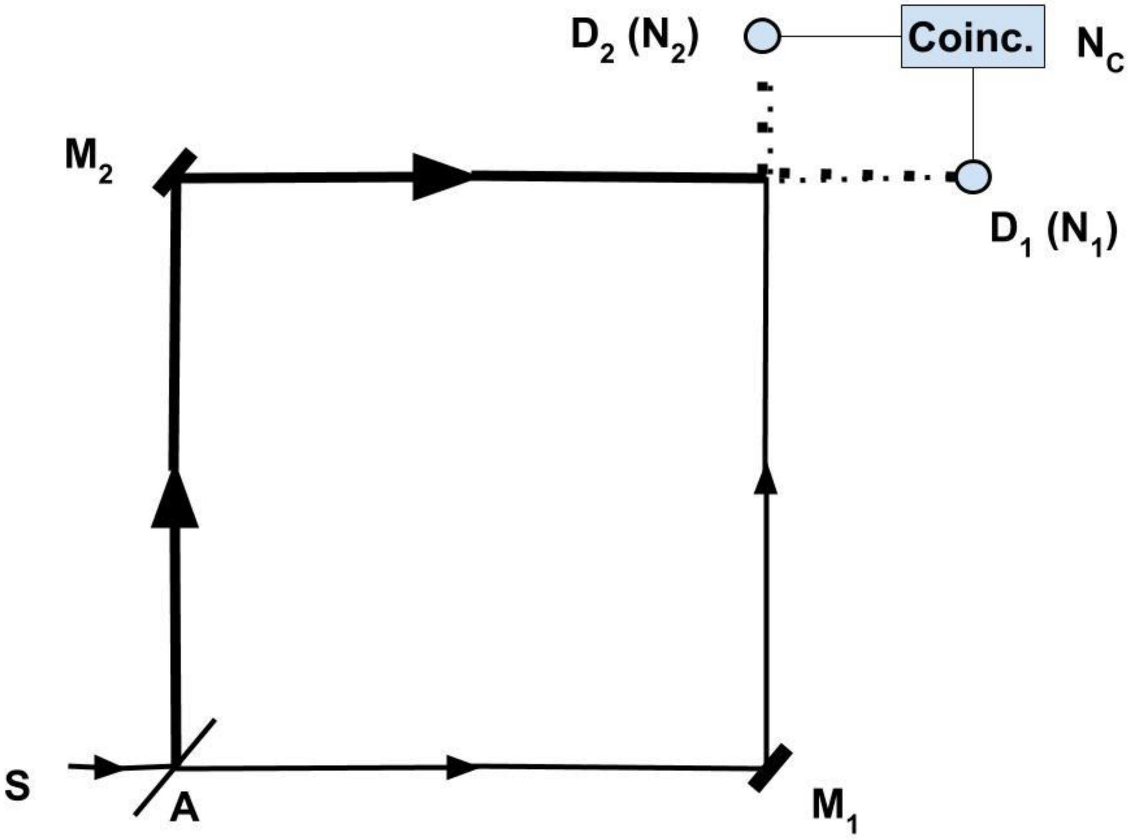


**Figure 2.** Single photons generated at S are sent through a beam splitter and signal via each leg is detected at $D_1$ and $D_2$. If a photon sometimes acts like a wave, there should

be coincidence counts ($N_C$) at the two detectors and those are monitored as well. *The anti-correlation parameter was close to zero,* confirming that a given photon always takes one path at a time and behaves as a particle [22].

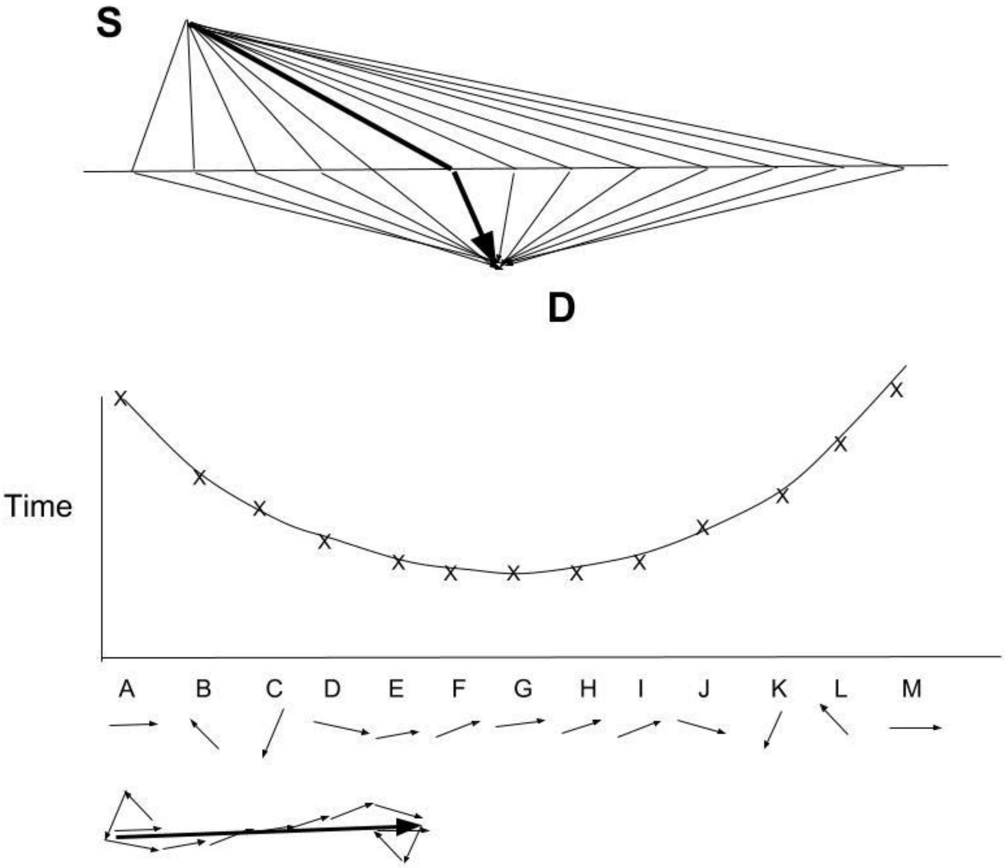


**Figure 3**. Light from S can go to the detector D via “all possible paths”. Once again, the major contributions come from those paths close to the expected arrow indicated by the heavy arrow, and the Fermat’s principle of least time is recovered with this “particle representation” (adapted from Feynman [26]).

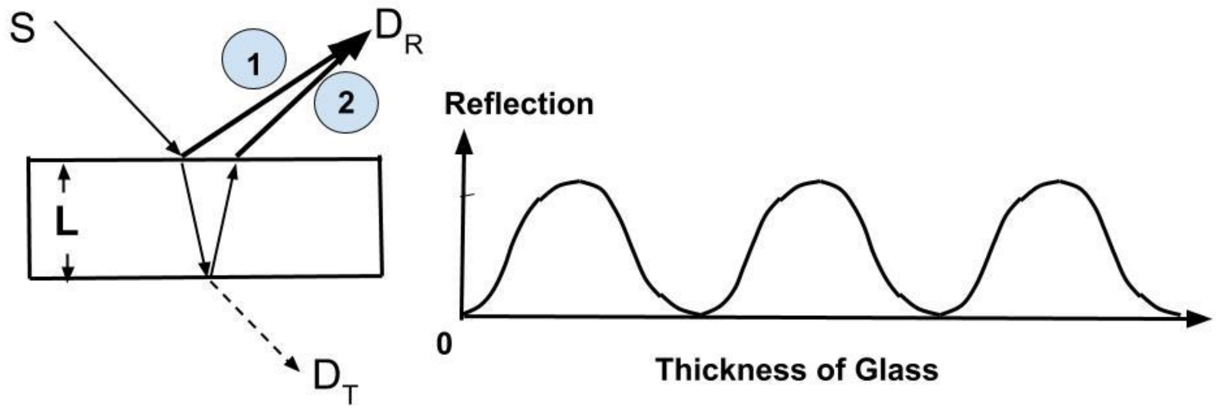


**Figure 4**. Reflection and transmission of light by a glass plate. Photons can get to detector $D_R$ by reflecting off of either the front surface or the back surface (only the predominant paths are shown). Alternatively, they can go through both surfaces and end up at the detector $D_T$ (adapted from Feynman [26]).

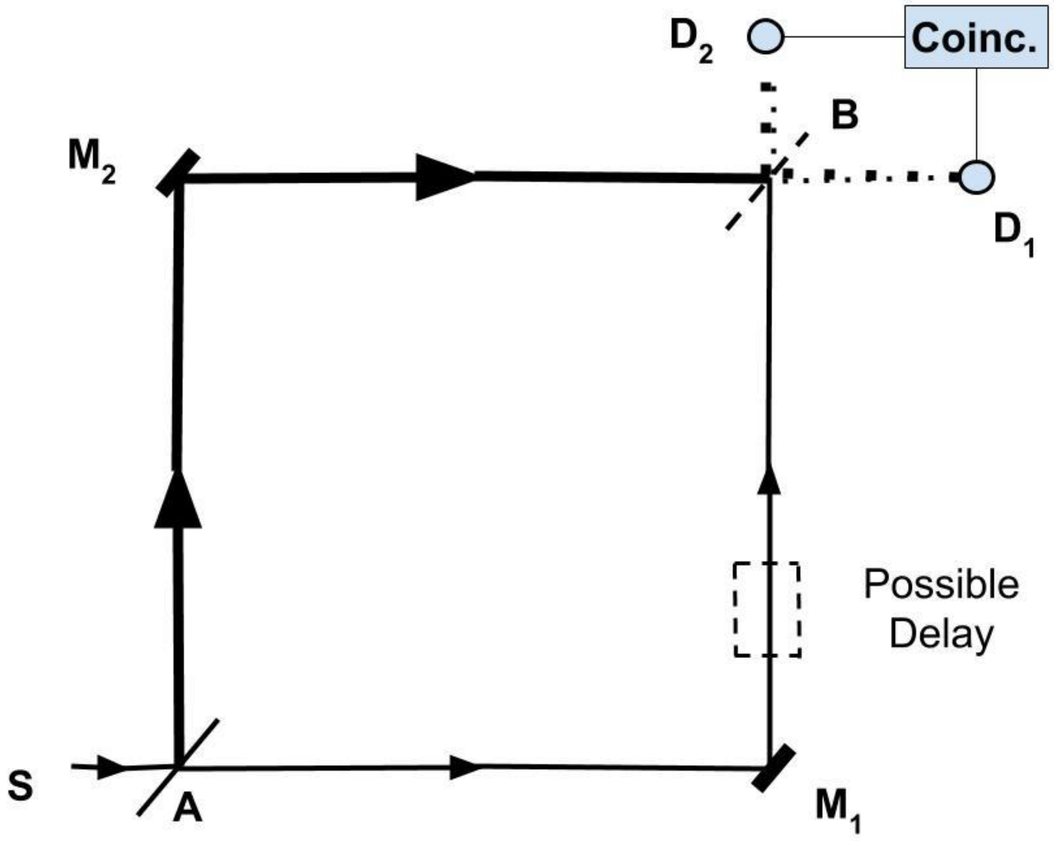


**Figure 5.** Schematic diagram of the Wheeler's delayed-choice experiment for photons passing through a beam splitter at A and reflected by mirrors $M_1$ and $M_2$ to be directed to the detectors at $D_1$ and $D_2$. A second beam splitter B can be inserted at any time, *especially while the photon is in flight after passing A*. The two possible paths for a photon are indicated by the heavy and light lines. A time delay between the two photon paths can be accomplished by adjusting the length of an arm as indicated.

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