Explaining Duality without Complementarity or "which way" (welcher-weg) And also Retro-Causality and Non-Locality

Sarma N. Gullapalli
sngullapalli@hotmail.com

Abstract

An Axiom is presented and justified which (a) *Explains duality in interference without complementarity or "which way" (welcher-weg) observation* (b) Shows the equivalence: Coherence and alignment ≡ Interference ≡ No "which way" observation; No coherence or alignment ≡ No interference ≡ "which way" observation (c) Explains Wheeler's delayed choice thought experiment (d) Explains results of experimental implementations of Wheeler's experiment which show retro-causality with and without entanglement (e) Explains non-local action at a distance, and (f) Rephrases Albert Einstein's unanswered question "Is quantum mechanics complete?" at a more fundamental level than just duality and non-locality. The explanation given does not require that the particle (photon) somehow "know" about the test setup or "which way" observation or change its behavior from particle to wave and vice versa as required by currently accepted explanation based on Niels Bohr's complementarity principle. No new assumptions are made, only *a new complete interpretation* of probability which is already a fundamental assumption of quantum mechanics.

I. INTRODUCTION

Wave-particle duality has been discussed from the earliest days of quantum mechanics, but questions remain. For example, recent single photon interference experiments conducted to investigate duality have revealed the weirder phenomenon of *retro-causality* [1], [2], which stretches the current understanding of duality which is in terms of Niels Bohr's complementarity principle, especially when entangled photon pairs are used, and so a better explanation is desired. Proposed by Niels Bohr and refined through many discussions with Albert Einstein [3], the current widely accepted explanation of duality is as follows: Experiments can observe either one or the other of complementary pair of observables at a time, not both at the same time; wave and particle nature of photon (or electron) is one such complementary pair. That is, if the experimental setup is for detecting particle then wave nature (interference) cannot be observed and so the photon as a particle goes through one or the other path of the interference setup with particle sensed either with detectors or in some other way, and if the experimental setup is for detecting interference (wave nature) then particle nature does not hold and the photon travels as a wave through both paths (without paths sensed by detectors or in any other way). Albert Einstein felt that experimental setup in principle can be independent of what is to be measured and cannot determine something as fundamental as wave or particle nature. Note that here we are not talking about the loading effect of measuring instruments such as in classical networks, but a fundamental wave versus particle behavior. But all experimental evidence to date have confirmed Bohr's point of view. In a multi-path interferometer, the act of observing which path the photon took (*which way*) is thus believed today to *cause the disappearance of interference pattern*, and so "*which way*" (*welcher-weg*) has become an accepted analysis and design consideration in multi-path quantum systems. Nevertheless, the notion that somehow the photon is cognizant of the experimental setup in a dynamic way and indeed in a retro-causal way is rather unsettling and unconvincing, and so it is worth finding out if there is an explanation without such unbelievable intelligence required of the photon (particle). The Axiom proposed in this paper accomplishes that, *without requiring* "*which way*" consideration or any "knowledge" on the part of photon (particle) about the experimental setup, and incidentally redeems Albert Einstein's view that measurement may not necessarily influence wave-particle behavior.

Furthermore, the *potential* of current thinking to include the *subjective conscience* of the person performing the measurement in the determination of the wave or particle behavior has given rise to metaphysical speculations (for example Conscious Observer outside space-time [4]). Erwin Schrodinger considered interpreting the probabilistic nature of quantum mechanics to imply that the many trials underlying probability actually occur simultaneously in multiple universes, giving rise to the metaphysical concept of *multi-verse* which has been discussed by philosophers. This paper does not use metaphysics or multi-verse, and regards mathematical probability as *purely axiomatic*, following the generally accepted definition and use of *hypothetical trials* for relative frequency as a measure (see for example Papoulis [15] page 7 on the axiomatic definition of probability and on relative frequency measure).

On a related subject, Albert Einstein, troubled by the statistical nature of quantum mechanics, suggested a thought experiment in the famous E.P.R. paper [5] (1935) which he co-authored, which predicted *action at a distance* violating the *locality constraint* imposed by the relativistic speed limit of velocity of light, and therefore expressed the doubt: *Is quantum mechanics complete*? Erwin Schrodinger immediately responded [6] affirming that the phenomenon described necessarily follows from the wave function concept, and coined for it the term *entanglement*. A hypothesis of non-verifiable *hidden random variables* (as the name implies) was rendered verifiable by experiment by the landmark inequality test developed by J.S. Bell [7] (1964), improved upon by others [8], and extensively studied by experimenters gradually eliminating loop holes, to finally confirm recently [9] (2015) that *there are no hidden variables*, thus confirming action at a distance, which to date has not been satisfactorily explained.

II OUR APPROACH

Any approach to explain duality requires the understanding of the relationship between the particle and its wave function. Louis De Broglie and Erwin Schrodinger initially thought that the wave function was actually a physical wave associated with the particle, which led to problems because wave function is inherently complex and not real. This difficulty was removed by Max Born in 1926 by *interpreting the physical wave* as magnitude square of *complex probability amplitude* ψ, *the wave function*. Born states in his Nobel Prize acceptance speech [10] (italics by author) "… an idea of Einstein's gave me the lead. He had tried to make the duality of particles - light quanta or photons - and waves comprehensible by *interpreting the square of the optical wave amplitudes* as probability density for the occurrence of photons. This concept could at once be carried over to the ψ-function: $|\psi|^2$ ought to represent the probability density for electrons (or other particles)". Note that though the wave function is thus recognized as non-physical probability amplitude, it is viewed as *an interpretation of a physical wave*, especially for photon whose wave nature is more evident as physical electromagnetic wave, while for electron particle nature is more evident as physical rest mass. This view of non-physical wave function as somehow connected to some physical wave entity has persisted to this day, *requiring co-location of particle and its wave function* and *this is at the bottom of the duality issue*. The proposed justifiable Axiom *removes this co-location* and thereby explains, as shown in this paper, duality without complementarity or "which way", and also retro-causality with or without entanglement, and non-locality.

Schrodinger' wave equation defines the evolution of wave function $\psi(\underline{\mathbf{r}}, t)$ of particle system in space $\underline{\mathbf{r}}$ and in time t,

$$i \cdot \hbar \cdot \frac{\partial}{\partial t} \psi(\underline{\mathbf{r}},t) = \mathbf{H} \cdot \psi(\underline{\mathbf{r}},t) \qquad (1)$$

where $i = \sqrt{(-1)}$, $\hbar$ ($= \frac{h}{2 \cdot \Pi}$) is the reduced Planck's constant and **H** is the Hamiltonian operator of the particle system. Equation (1) is linear in ψ when **H** is independent of ψ as is usually the case for particle in free space or in a linear medium. In nonlinear media or in nonlinear interactions, as in the case of generation of entangled photons by parametric down conversion in nonlinear crystals, $\mathbf{H} = \mathbf{H}_0 + \mathbf{H}_1 (\psi)$, $\mathbf{H}_1$ being the nonlinear term.

We note the following, where (a) through (e) are generally known, and (f) is new:

(a) Regardless of whether (1) is linear or nonlinear in ψ, time t in its evolution is always monotonically increasing. Thus *entangled joint wave function evolves causally* according to (1) from the initial conditions when it is created. We shall discuss this further later in section VI on causality, retro-causality and entanglement.

(b) Because ψ is probability amplitude ($|\psi|^2$ is probability density), *ψ is a purely mathematical entity and not a physical entity*. For example, a Gaussian probability density does not represent a one to one mapping to a bell shaped physical entity; electromagnetic wave *interpreted* as probability amplitude represents the *statistical distribution* of an ensemble of real physical waves and is not a one to one mapping to a particular physical wave.

(c) Because of the non-physical nature of ψ it *need not necessarily obey any laws of physics including theory of relativity*. It can change from one state to another instantaneously over all space. Indeed, initially when the particle (photon) is created its wave function attains its full non-zero value instantaneously. Likewise, when the particle (photon) is detected its wave function disappears (collapses) everywhere instantaneously. For an entangled pair of photons when one photon is measured the joint wave function instantaneously attains its new values everywhere.

(d) *Physical process* that alters the state of the particle and hence its wave function naturally takes non-zero time. It appears that the duration of physical interaction of a photon with an electron can be as short as a hundred atto-seconds (10^{-16} second) [11]. Thus physical change from one polarization state of photon to another due to electron interaction is not exactly instantaneous, but merely delineates stages in the evolution of wave functions ψ according to (1).

(e) Regarding evolution of ψ according to (1), quantum electrodynamics (QED) provides a geometrical method (see R.P. Feynman [12]), at each point on a reflecting or refracting surface or at each point in a medium, with *all possible* *secondary wavelets* of ψ from that point *exploring all possible paths* to determine the resultant ψ. For a given physical photon (electron), QED construction thus *explores all possible paths* that the photon (electron) can take.

We now make the following key generalization of the QED construction that enables our explanations:

(f) *The propagation of non-physical wave function ψ according to (1) through all possible paths through the entire system are determined hypothetically for all time without any corresponding actual physical propagations of the photon (or electron), even if the system may change dynamically*. That is, we *decouple* the evaluation of non-physical wave function ψ from any particular path of the physical photon (or electron), and instead evaluate ψ *hypothetically for all possible paths and for all times*, just as we can do in a computer simulation even if the system changes dynamically, but in the universe of quantum mechanics *nature does it instantly*. Note that this is merely an extension of the accepted hypothetical nature of axiomatic mathematical non-physical probability.

With the above motivation and justification, we now state the Axiom, followed by applications to explain duality, retro-causality with and without entanglement, and non-local action at a distance. *Its novelty lies in that it does away with "which way" complementarity and does not require any "intelligence" on the part of the particle*.

II. AXIOM ((a), (b), (c) are already well known, (d) is NEW)

(a) *Wave function is not a physical entity, it is a purely mathematical probability construct whose probability basis must necessarily include all possible paths from the time it is generated (t_0) until it is terminated (t_T).*
(b) Non-physical wave function can change its values instantly everywhere.
(c) *For an N-tangled system (N entangled particles) t_0 is the earliest time when the joint wave function is generated and t_T is the last termination time when the last particle is fully measured, and joint wave function fully "collapses".*
(d) (NEW) *Wave function is not necessarily always co-located with the particle. At any time t_1, wave function along all possible paths is instantly defined (by nature) for all t, $t_1 \leq t \leq t_T$.*

For applications of the Axiom we begin with Young's double slit experiment with single photons because it was the center of discussion for a long time, and because "which way" sensing in Young's double slit setup is more direct while later experiments use polarization indirectly. It also helps to introduce the well-established requirement of temporal coherence and spatial alignment for interference. We shall show that in all experiments discussed below there is the following equivalence:

Coherence and spatial alignment ≡ Interference ≡ indistinguishable paths, no "which way"
No coherence or spatial alignment ≡ No interference ≡ distinguishable paths, "which way"

III YOUNG'S DOUBLE SLIT EXPERIMENT WITH SINGLE PHOTONS

Referring to Figure 1 which shows a functional set up for purpose of discussion (can be implemented in many ways to sense the path) fringes are observed only when the *coherence* length (= $c \cdot T_c$ where T_c is *coherence time* of the source and c is velocity of light for the medium of the paths) is longer than the optical path difference between the two paths, and the angle between the two paths at detector array is sufficiently small to ensure *well aligned* superposition. In quantum mechanical picture coherence and alignment is that of the wave function associated with the photon (particle). A single photon generates just one point on the interference pattern. Successive single photons overlay successive points on successive interference patterns. For this overlay not to be smeared, the wave functions of successive single photons must have *mutual coherence* (with time delay adjusted), for which the coherence time of source must be longer than the frame time over which interference is recorded. This condition is readily met with laser sources. Using functionally similar set ups it has been experimentally confirmed (for example [13] which uses polarizers to identify paths instead of beam splitter / detector) that typically either D_A or D_B or *one* of EMCCD detectors goes off per pulse. EMCCD data collected over a number of pulses (for pulses when neither D_A nor D_B goes off) shows interference pattern. The "which way" question is: When interference fringes form (by superposition of both paths) which path did the single photon take? This question consumed Bohr and Einstein, who considered various ways to sense "which way" without affecting the interference pattern, such as using mechanical recoil of hypothetical free-moving slits placed before the physical slits (instead of detectors D_A and D_B), but failed due to the uncertainty principle that precludes sufficiently accurate sensing of both energy (frequency, wavelength) and momentum (direction) of photon. The end result was Bohr's complementarity principle that both interference and "which way" cannot be measured at the same time. Later experiments such as [13] and implementations of Wheeler's thought experiment discussed later, used polarization to sense the path to avoid the problem of uncertainty principle. Note that when a polarizer is used to mark the path, say horizontal for A and vertical for B, the orthogonality (*lack of alignment*) destroys interference.

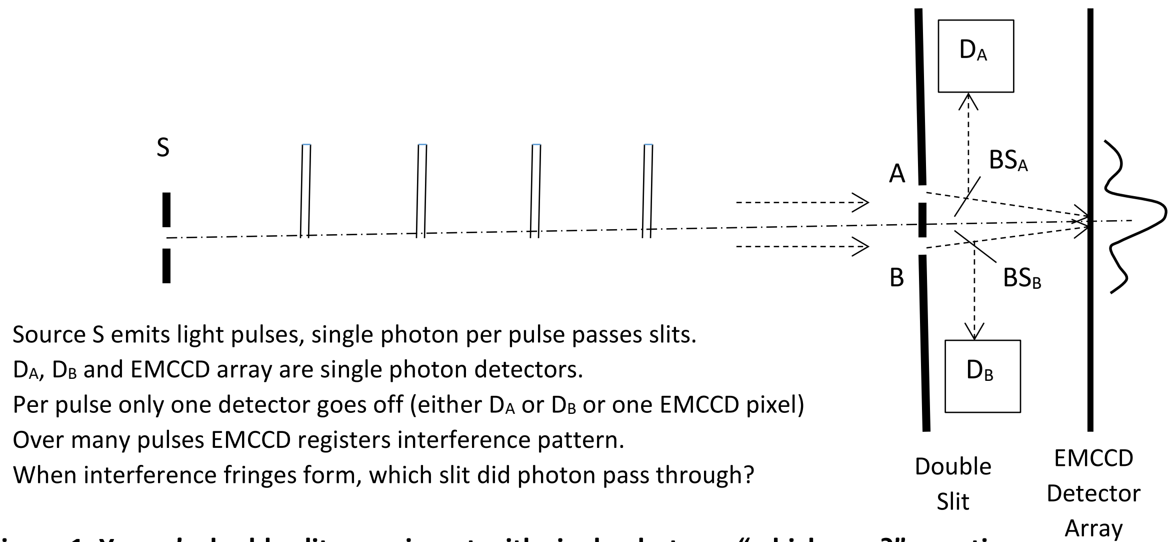

Figure 1. Young's double slit experiment with single photons; "which way?" question

This "which way" question does not arise if we accept our axiom which breaks the co-location of wave and particle. The non-physical wave function goes through both slits, the physical photon goes through only one slit, its path *always* leading to the detector that goes off.

Note that: "which way" ≡ no alignment of the paths to (D_A and EMCCD) or (D_B and EMCCD) ≡ No interference

No "which way" ≡ alignment of the two paths at EMCCD ≡ Interference.

IV WHEELER'S DELAYED CHOICE THOUGHT EXPERIMENT

In 1982 J.A. Wheeler proposed an ingenious *delayed choice* thought experiment [14] to test Bohr's explanation of duality, by *dynamically changing the setup after the photon committed to the path*.

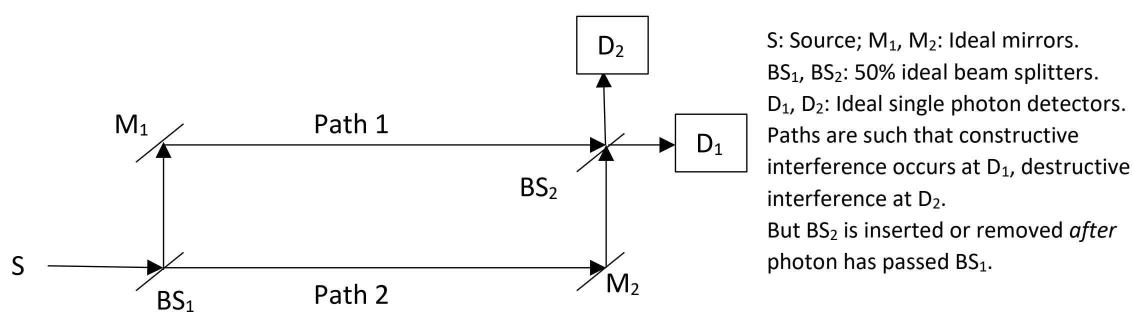

Figure 2 Wheeler's delayed choice thought experiment

When BS_2 is in place there is interference, D_1 registers counts and D_2 does not. When BS_2 is removed, there is no interference, both D_1 and D_2 register counts. That is, BS_2 in place ≡ interference, photon travels as a *wave* through *both* paths. BS_2 removed ≡ *particle*, photon travels *either* through path1 *or* path2. What happens if BS_2 is present (absent) when photon passes BS_1 so that photon is committed to both paths (one path) but is then removed (inserted)?

If we accept our Axiom which breaks the co-location of wave and particle, wave *always* goes through both paths and photon *always* goes through only one path, and there is interference when BS_2 is in place and no interference when BS_2 is not there, *regardless of which path the photon took and when*, agreeing with experimental results below.

Note that: BS_2 in place ≡ alignment of both paths at D_2 ≡ interference ≡ no "which way";
BS_2 removed ≡ no alignment of paths ≡ no interference ≡ "which way".

III IMPLEMENTATION OF WHEELER'S DELAYED CHOICE THOUGHT EXPERIMENT

Using two orthogonal polarizations as path identifiers for the two paths, and with the availability of extremely fast electro-optic modulator (EOM) devices, it became possible to electro-optically implement the role of insertion or removal of beam splitter BS_2 in Wheeler's delayed choice thought experiment. Among several experimental realizations, we shall discuss Roch et al [1] (without entanglement) and Yoon-Ho Kim et al [2] (with entanglement) that claim to be closest to Wheeler's thought experiment. Starting with [1], referring to the simplified schematic in Figure 3 (see [1] for details) source S is a single N-V (Nitrogen-Vacancy) color center in a diamond nanocrystal, which when excited by a laser pulse emits a single linearly polarized photon within 45 ns of the narrow 800 ps excitation pulse, enabling precision timing of the photon emission. The photon goes through a polarizing beam splitter PBS in BS_1, whose H and V orthogonal polarization outputs (single indivisible photon goes to *either* H *or* V channel) are separated into two 48 meter long paths, path1 for H and path2 for V. After 48 meters these two paths enter BS_2 consisting of a half wave plate followed by a polarization beam splitter PBS which combines the two (V and H) paths, followed by an electro-optic-modulator (EOM) which when turned on rotates plane of polarization by $\pi/4$, followed by a Wollaston Prism (WP) which separates *its* H and V polarizations which then terminate in single photon counting detectors D_1 (count N_1) and D_2 (count N_2) respectively. N_c is coincidence count. Phase difference ϕ is introduced between paths to D_1 and D_2 by tilting PBS in BS_2. The transit time of 160 ns to traverse 48m allows practical implementation of dynamic change while photon is in midflight, ensured by the timing.
EOM off: H and V go to D_1 and D_2 respectively (verified by blocking one channel in the 48m path), "which way" is known, D_1 and D_2 counts are same, do not vary with ϕ, no interference.
EOM on: No "which way", rotated H and V are mixed by WP, with $\phi = 0$ polarization planes aligned in D_2 (counts) and counter-aligned in D_1 (no counts), that is, interference. Counts vary sinusoidally with ϕ, D_2 out of phase with D_1. When EOM is turned on or off when photon is in midflight, according to complementarity principle it must change from particle to wave or from wave to particle retrospectively, that is, *there is retro-causality*.

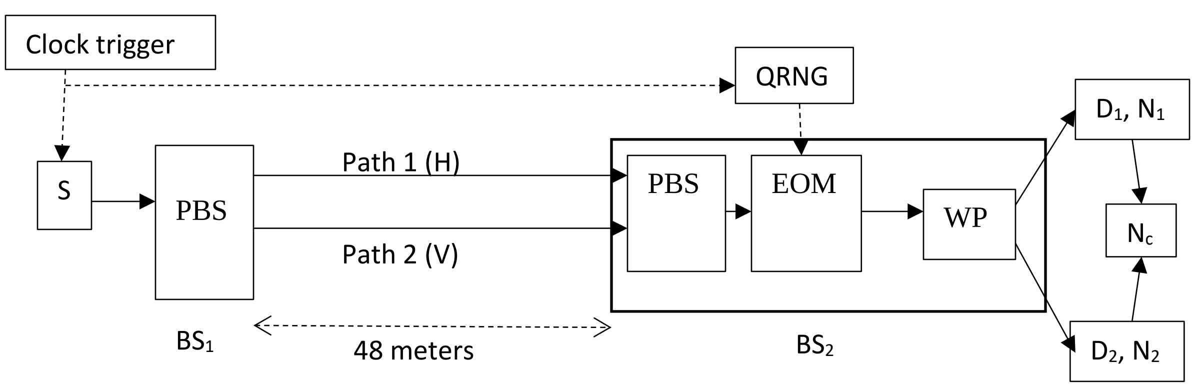

Figure 3 Simplified schematic of Implementation of Wheeler's delayed choice thought experiment by Roch et al [1]

We can readily explain these results using our axiom. The non-physical probability amplitude wave function travels along both H and V channels till it terminates upon detection either by D_1 or D_2. Let the photon be on one channel, say H channel, inside the interferometer (about 12 to 25m from BS_1) when EOM is switched, say from off to on. When the wave function (and photon) reach EOM, say with $\phi = 0$, the probability amplitude is accordingly 1 for

D_2 and 0 for D_1, and so the photon goes to D_2. Note that there is path for the single photon to go from the H channel to D_2 because of the projection in PBS in BS_2 when EOM is on (equivalent to inserting BS_2 in Wheeler experiment in Figure 2). If, on the other hand EOM were switched from on to off, when the wave function (and photon) reach EOM, the wave function accordingly sets probability of 0.5 for D_1 and 0.5 for D_2, and the photon goes to D_1 (if it were on V channel it would go to D_2). Thus the physical photon does not change its behavior in midflight from one polarization to both polarizations (say H to H and V) or vice versa, it simply follows the probability density determined by the non-physical wave function which travels on both paths *at all times*. Photon follows only one path. Note that because photon remains particle all along, by this Axiom *there is no retro-causality* in this experiment.

Note that: EOM on ≡ *alignment* of both planes of polarizations ≡ interference ≡ no "which way";
EOM off ≡ *no alignment* of the two planes of polarizations ≡ no interference ≡ "which way".

IV DELAYED CHOICE QUANTUM ERASURE EXPERIMENT WITH ENTANGLED PHOTON PAIRS

Quantum erasure has been even more dramatically demonstrated when entangled photon pairs are used, each pair denoted by "signal" photon and its entangled companion "idler" photon, with idler photons used to "erase" the "memory" of signal photons regardless of the time sequence. Figure 4 shows the schematic of implementation of Wheeler's delayed choice thought experiment using entangled photon pairs by Yoon-Ho Kim et al (see [2] for details).

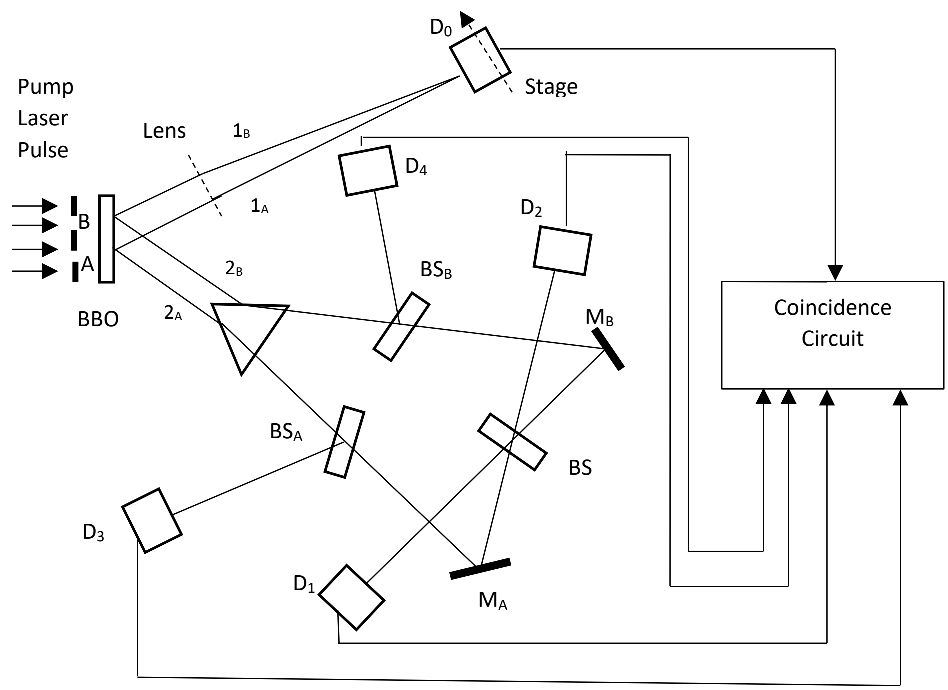

Figure 4. Schematic of Wheeler's Delayed Choice Thought Experiment Implemented using entangled photon pairs by Yoon-Ho Kim et al [2]

Each pump laser pulse excites close-by atoms say A and B in BBO crystal, each of which emits by cascade decay a pair of entangled photons 1 and 2 in two different specific directions, that is, entangled pair 1_A and 2_A from atom A, and entangled pair 1_B and 2_B from atom B. Excitation is such that 1_A and 1_B are mutually coherent, and by entanglement so are 2_A and 2_B. Photons 1_A and 1_B are focused by lens on single photon counting detector D_0, which is on a stage that can be moved laterally, introducing path difference between 1_A and 1_B at the detector. Because of coherence and alignment, as the stage is moved interference is observed, *conditional on what happens to their entangled partners 2_A*

and 2_B, because an entangled pair of particles share the same non-factorable joint wave function, and because interference here is between the two joint wave functions of A and B pairs, the interference of entangled pairs A and B *requires* interference of 1_A and 1_B *as well as* interference of 2_A and 2_B.

Beam splitter (50%) BS_A sends 2_A either to detector D_3 or towards mirror M_A each with 50% probability. Likewise, 2_B is sent by BS_B either to detector D_4 or to mirror M_B each with 50% probability. After reflection from M_A and M_B, photons 2_A and 2_B are combined in beam splitter BS and sent to detectors D_1 and D_2, where they can interfere. D_3 and D_4 unambiguously provide the "which way" information (path A or path B) whereas detections at D_0, D_1 and D_2 do not provide "which way" information. When 2_A goes to D_3 or when 2_B goes to D_4, clearly there is no spatial alignment between 2_A and 2_B and so there can be no interference, whereas at D_1 and D_2 there is spatial alignment between 2_A and 2_B and so there can be interference. The path length to D_0 is much shorter than path lengths to D_1, D_2, D_3 and D_4, so that detection at D_0 occurs much earlier than at D_1, D_2, D_3 and D_4. With time stamps adjusted for this difference, the coincidence circuit measures coincidences between (D_0, D_1), (D_0, D_2), (D_0, D_3) and (D_0, D_4) for each position of the stage on which D_0 is mounted. Plotted versus stage position, coincidences (D_0, D_1) and (D_0, D_2) show interference, while coincidences (D_0, D_3) and (D_0, D_4) do not show interference. Thus when "which way" is sensed by D_3 or D_4 there is no interference, and when "which way" is not sensed (by D_0, D_1 and D_2) there is interference, confirming Bohr's complementarity view of duality. Moreover, because detection at D_0 occurs much earlier than at D_1, D_2, D_3 or D_4, interference (or not) is determined *retrospectively*. In this experiment, both "which way" and interference are sensed at every time sample, but as ("which way", no interference) and (interference, no "which way") pairs. This experiment thus dramatically demonstrates what appears to be *retro-causality*. It is as if past "memory" of 1_A and 1_B is *erased*, and so this is considered to be a *quantum eraser* experiment.

We now apply our Axiom to explain the results of this experiment without "which way" complementarity consideration or any "erasure" of photons' "memory". Because our Axiom (i) breaks the co-location of particle and its wave function, and (ii) all non-physical mathematical probabilities are known at any time by hypothetically evaluating wave propagation for all time along all possible paths, at the time of detection of 1_A and 1_B by D_0 the following outcomes are known (by nature) for the entangled wave function A and entangled wave function B (both of which originated together at the source (BBO)),: probability of detection of 2_A at D_3 (which precludes interference between 1_A and 1_B at D_0), probability of detection of 2_B at D_4 (which precludes interference between 1_A and 1_B at D_0), probability of detection of 2_A and 2_B at D_1 (which allows interference between 1_A and 1_B at D_0) and probability of detection of 2_A and 2_B at D_2 (which allows interference between 1_A and 1_B at D_0). The actual events occur according to these probabilities *which are known at the time of detection at D_0*, and in that sense there is really no retro-causality. Thus the results are explained by the Axiom, photons remain particles throughout and wave functions travel all possible paths at all times, and so the real underlying cause of what is observed is entanglement that occurred *initially* at the source and in that sense also there is really no retro-causality. We shall discuss further this issue of causality and retro-causality in entanglement later in section VI.

Note that: Alignment (at D_1 or D_2) ≡ interference ≡ no "which way"
No alignment (at D_3 or D_4) ≡ no interference ≡ "which way"

V. EPR NON-LOCAL "ACTION AT A DISTANCE" DUE TO ENTANGLEMENT

As shown in Figure 5, a pair of polarization-entangled photons a and b generated by source S at time t_0 travel in two different spatial directions, and the state of polarization **a** of a and **b** of b are measured by respective instruments, at A at time $t_A > t_0$ corresponding to distance $L_{SA} = c_A \cdot t_A$ where c_A is velocity of light in channel SA and at B at time $t_B > t_A$ corresponding to distance $L_{SB} = c_B \cdot t_B$. Because there are no hidden variables [7, 8 and 9] that could define polarization of a and b before measurement, polarization of a and b remain *undefined* due to the mixed state of entanglement till the first measurement at t_A at which time b *instantly* becomes polarized parallel to **a**, at point B_1 at distance L_{SB1} from S, $L_{SB1} = c_B \cdot t_A < L_{SB}$. Treating the measurement **a** at A as the cause and **b** (parallel to **a**) as its *instantaneous* effect at B_1, and noting that the distance from A to B_1 is greater than zero, it is seen that the effect is non-local with respect to A because it reaches B_1 faster than speed of light in free space which is the upper limit set by Einstein's theory of relativity (hence the EPR paradox). However, while this is true, it does not represent the full picture of cause and effect because *the effect will be non-existent if* a *and* b *were not entangled by* S *at time* t_0 *to begin with*. The full picture of cause and effect is a two-input (entanglement by S at time t_0 AND measurement at A at t_A) single output (effect at B_1 at time t_A) relationship, and since B_1 is reached from S at speed of light, it cannot be claimed that the effect is entirely non-local. This observation does not diminish the significance of the instantaneous effect at time t_A, it only points out that there is a bigger picture. In the bigger probabilistic picture, entanglement defines an infinite number of *pairs* of states for (a, b) from which measurement at A picks one, just as in the non-entangled case measurement picks one value out of an infinity of all possible states.

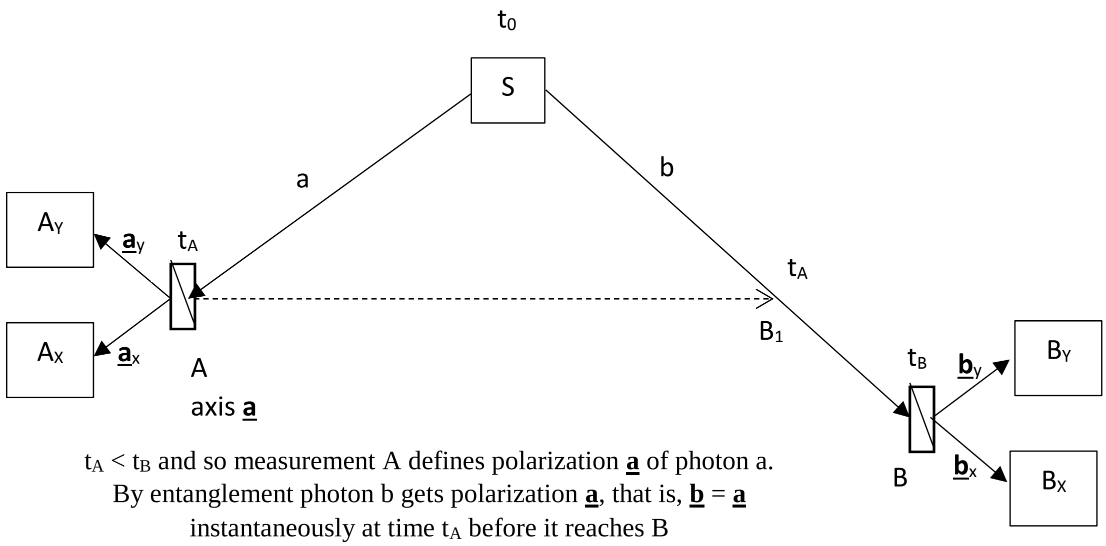

Figure 5: Non-local action at a distance by polarization-entangled photons

Our Axiom explains the narrower non-local view (measurement A at t_A causing change in state of b at t_A) and the larger local view (entanglement at t_0 causing change in state of b at t_A due to measurement A). The real mystery is in the fact that non-physical mathematical probability explains physical reality, which is the underlying unexplained mystery of *all quantum mechanics*, not just entanglement.

VI CAUSALITY, RETRO-CAUSALITY AND ENTANGLEMENT

While classical physics allows deterministic ordering of events in time with arbitrary accuracy, quantum physics is fundamentally probabilistic and uncertainty principle can introduce unavoidable spread in time measurements. Therefore causal structure in quantum mechanics can be expected to be different from that in classical physics, *but it is there*. Let us separate quantum systems into two categories: 1. System of particles that are not entangled with each other and 2. System of entangled particles. In both cases the evolution of wave function is governed by the same kind of equation (1), but in the non-entangled case (1) evolves in time *separately* for each particle, whereas in the entangled case the *single joint wave function* evolves in time, *at the speed of light and so locality holds in either case*. Also the independent variable time is *always monotonically increasing, and so causality holds in either case.* It is only when we take the narrow view and ignore the role of entanglement as an underlying cause that we find non-locality. We must view the act of measurement of an entangled system as selecting one out of the many probable *combinations* of allowed member particle states, and not merely as measurement of a single member particle.

VII THE UNANSWERED QUESTION

The fundamental assumption of quantum mechanics, that physical reality is explained in terms of complex mathematical probability amplitudes which are recognized by all to be non-physical, which the proposed Axiom interprets in a more complete way, leaves the following *single* question unanswered: *Why is physical reality explainable in terms of non-physical purely mathematical probability functions?* That it explains reality is not sufficient, the question is "*why?*" This question existed from the earliest days of quantum mechanics, and rephrases at a more general fundamental level (not just in the context of action at a distance discussed in the EPR paper, or duality discussions with Bohr) Albert Einstein's question in the EPR paper: *Can quantum mechanical description of physical reality be considered complete?* Until this fundamental question (assumption) of quantum mechanics is satisfactorily explained, we have to agree with Albert Einstein and regard quantum mechanics as incomplete.

VIII DISCUSSION, CONCLUSIONS

1. The proposed Axiom makes no new assumptions, but makes new interpretation of the existing fundamental assumption of quantum mechanics that non-physical mathematical probabilities can explain physical reality.
2. By explaining duality without "which way" complementarity, with particle remaining particle throughout and its wave function remaining wave throughout, the proposed Axiom enhances clarity.
3. By doing away with complementarity to explain duality, this paper redeems the view of Albert Einstein that measuring instruments cannot influence the fundamental wave – particle behavior (the "loading" effect of measuring apparatus, that the measuring system and the measured system must be considered as a whole, is not the issue)
4. This paper remains objective in explaining duality, does not use subjective metaphysical conscience or multiverse.
5. This paper suggests inclusion of the event of entanglement as the underlying cause for a more complete perspective on "action at a distance" and "retro-causality".
6. All issues are reduced to a single unanswered question that already existed from the beginning of quantum mechanics: "Why physical reality is correctly described by non-physical purely mathematical probability amplitudes?" which, until answered, validates Albert Einstein's question: "Is quantum mechanics complete?"
7. The following equivalence is shown:

   Particle behavior, "which way" ≡ no interference ≡ no coherence or alignment

   Wave behavior, "no which way" ≡ interference ≡ coherence and alignment

Thus, classical considerations of coherence and alignment for interference suffice, there is no need for "which way".

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