Wave-Particle Duality:
Particle always remains Particle and its Wave Function always remains Wave

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Abstract

On the question of wave-particle duality, from the historic Bohr-Einstein debates a century ago, to this day, the view expressed in Niels Bohr's Complementarity Principle has become well established, confirmed by numerous experiments: If the observation is for wave nature, then the particle changes to wave, and if the observation is for particle nature, then the particle remains particle. However, recently this view has been challenged. With proof based on the definition of wave function, it has been shown that particle always remains particle and its wave function always remains wave, no mysterious change from particle to wave and vice versa.

Key words: Quantum Mechanics, Wave-Particle Duality, Complementarity, Entanglement

The Proof

By definition, wave function $\psi(\underline{\mathbf{r}}, t)$ at space-time point $(\underline{\mathbf{r}}, t)$ associated with a physical particle is a complex probability amplitude; $|\psi(\underline{\mathbf{r}}, t)|^2$ is probability density function; $|\psi(\underline{\mathbf{r}}, t)|^2 \cdot\delta v$ is the probability that the particle is in an infinitesimal volume δv at $(\underline{\mathbf{r}}, t)$; integrated over all space-time $\int|\psi(\underline{\mathbf{r}}, t)|^2 \cdot\delta v = 1$ as the particle is somewhere in space-time. According to Standard Model, all matter and energy in the universe is made up of a set of fundamental particles, classified as Fermions and Bosons. Electron is a Fermion, and photon, used in most experiments that have confirmed Bohr's Complementarity Principle, is a Boson. While particle Fermion or Boson is physical, its wave function is non-physical, because probability is a purely mathematical concept.

Point of clarification: In general, the physical particle is not a point, both due to its physical nature and due to Heisenberg's uncertainty-principle that permits only a spread in space-time. Therefore, by point $(\underline{\mathbf{r}}, t)$ we must refer to some cardinal point of the spread such as its centroid.

As probability amplitude, the wave function is necessarily defined over all space-time points $(\underline{\mathbf{r}}, t)$ in the universe where the particle can potentially be. If future developments in the Standard Model were to reveal a new set of indivisible constituents making up Fermions and Bosons, then this proof will apply to the new set.

In non-linear interactions such as parametric down conversion of a photon into multiple photons in non-linear crystals, or in nuclear interactions or in Feynman diagrams of quantum electrodynamics, the above discussion applies to each input and output particle of the interaction.

Thus, without loss of generality we limit our discussion to the linear case of single indivisible Fermionic or Bosonic particle, referred to as “the particle”, noting also that most discussions of wave-particle duality and experiments that have confirmed Bohr’s Complementarity Principle involve photons.

Any potential path of the particle in space-time along which its wave packet propagates must be consistent with the particle’s physical characteristics. For Fermion such as an electron the governing Schrodinger’s wave equation is

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

where $H = (\underline{\mathbf{p}} \cdot \underline{\mathbf{p}}/(2 \cdot m) + V)$ is the Hamiltonian = total energy E, $\underline{\mathbf{p}}$ is momentum, $i = \sqrt{(-1)}$ and $\hbar$ ($= \frac{h}{2 \cdot \Pi}$) is the reduced Planck’s constant, and for a Boson such as a photon it is

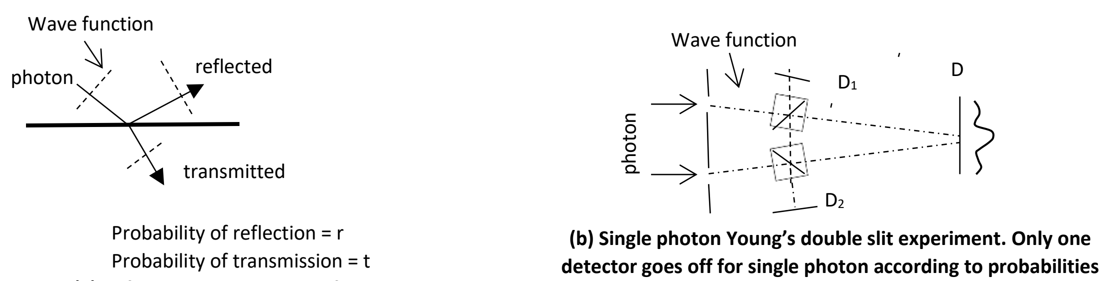
$$\delta^2\psi/\delta t^2 = c^2 \cdot \nabla^2{}_r\psi \qquad (1b)$$

where c is velocity of light, $\nabla^2{}_r$ is the Laplacian operator.

The following facts form the basis of the proof, developed below, that the particle always remains particle and its wave function always remains wave:

1. The particle is indivisible
2. When there is more than one path that the particle can potentially take, its wave packet must necessarily cover all such paths, total probability for all paths being equal to 1, that is, its wave packet is divisible among all potential paths.

This is illustrated in Figure 1(a) for the case of reflection / transmission of a photon at a surface such as in a beam splitter, used in most experiments that have confirmed Bohr’s Complementarity Principle, and in Figure 1(b) for Young’s double slit experiment that was the subject of Bohr-Einstein debates on wave-particle duality.



(a) Reflection, transmission of photon

(b) Single photon Young’s double slit experiment. Only one detector goes off for single photon according to probabilities defined by its wave function which follows all potential paths.

Figure 1.
Indivisible particle follows only one path, its divisible wave function follows all paths

In the case of beam splitter, there are two potential paths that the photon can take: reflected path with probability r and transmitted path with probability t, with the probabilities r and t determined by the physics of interaction of the photon with the surface – for reflected path as if the photon was reflected and for transmitted path as if the photon was transmitted. Divisible wave function follows both reflected and transmitted paths, whereas the indivisible particle follows one or the other, not both. As complex probability amplitude, the purely mathematical wave function is characterized by amplitude, frequency, phase and polarization of its Fourier components.

When successive incident single particles are involved as in Young's double slit experiment, one can define coherence properties of their purely mathematical wave functions: coherence length and corresponding coherence time, and spatial alignment of their propagation vectors and polarization vectors.

When a single photon is incident on the screen with the two slits, there are two potential paths, one through each slit. In the path through the upper slit there is a beam splitter with two potential paths, one reflected and one transmitted. Likewise for the path through lower slit. Divisible wave function of the single incident photon follows all potential paths.

Experimental results have shown that when a single photon is incident, only one detector goes off, either D_1 or D_2 or a single detector D in the array at the final screen. That is, the indivisible particle follows only one of all potential paths. When successive single particles are incident, the statistics of the counts at detectors D_1, D_2 and those in array D are the probabilities defined by the wave function for each of them. Probability amplitude at a detector in array D at the final screen is the sum of probability amplitudes of (divisible) wave function components reaching that point through both slits, the resultant amplitude depending on the path difference between the two paths and alignment of propagation vector and polarization vector for the two paths. If the path difference is less that the coherence length of wave functions of successive single photons, and if wave function components through the two paths are sufficiently aligned in direction and polarization, a stable interference pattern is observed at the array D. Thus, Young's double slit experiment is explained with particle always remaining particle and its wave function always remaining wave, no mysterious change from particle to wave or vice versa.

To test Bohr's Complementarity Principle, John Wheeler [1] proposed a "delayed choice" thought experiment shown in Figure 2, versions of which form the basis of several experiments conducted since then as single photon sources, detectors and Electro-Optic Modulators with improved speed and time stamp resolutions became available, all of which have confirmed Bohr's Complementarity Principle [2], [3], [4]. Beam splitters BS_1 and BS_2 have 50% reflection and 50% transmission. Paths 1 and 2 are such that constructive interference occurs at detector D_1 and destructive interference at D_2. If BS_2 were removed, there is no interference, D_1 and D_2 go off with equal probability. That is, BS_2 present results in wave nature, BS_2 absent results in particle nature. However, if BS_2 is present when the photon passes through BS_1 but removed before reaching BS_2 (delayed choice), will the photon change back from wave to particle, and likewise, if BS_2 is absent when the photon passes through BS_1 but inserted before reaching BS_2, will the photon change from particle to wave? Experiments have shown it seems to, confirming Bohr's Complementarity Principle.

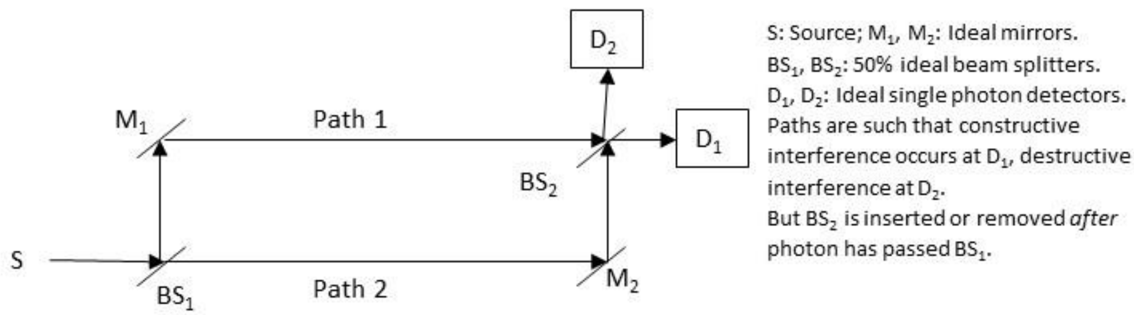


Figure 2
John Wheeler's delayed choice thought experiment to test Bohr's Complementarity Principle

But the results can be readily explained without invoking Bohr's Complementarity Principle. Potential paths 1 and 2 are followed by the divisible wave function which divides at BS_1. When the two branches of wave function reach the location of BS_2 (a) if BS_2 were present they will interfere constructively to D_1 and destructively to D_2 (b) if BS_2 were absent they will reach D_1 and D_2 setting equal probability for them. This explanation for specific complicated experimental setups in [2], [3], [4] that implement Wheeler's thought experiment is given in [5].

This ground-breaking result does not contradict Bohr's Complementarity Principle, it makes it unnecessary. The important consequence is that there is no mysterious change from particle to wave and vice versa, which Richard Feynman had called the "only mystery" of quantum mechanics. The mystery is thus solved, and objectivity is restored to physics, with no subjectiveness as implied in "observation" which has led to mystical interpretations of quantum mechanics by some scientists, who are quoted by non-scientists to further mystify science, which is detrimental to scientific progress. This also redeems Albert Einstein's view in the Bohr-Einstein debates that the inanimate particle photon cannot possibly know whether the experiment is to observe wave nature and accordingly change itself to a wave.

In general, wave function of an ensemble of N fundamental particles is the joint probability amplitude $\psi(\underline{\mathbf{r}}_1, \underline{\mathbf{r}}_2, \ldots \underline{\mathbf{r}}_N, t)$, defined over all space-time points where the ensemble can potentially be, a special case of which is entanglement of a two-particle system that has been extensively studied, stimulated by the landmark paper by Einstein, Rosen and Podalsky [5] and used in several experiments that have confirmed Bohr's Complementarity Principle. All such results have been explained in [6] without invoking Bohr's Complementarity Principle.

Bohr's Complementarity Principle has also led to some interesting other concepts such as "interaction free quantum measurement" [7], [8], [9], [10], "quantum Zeno effect" [11], [12], [13], and "counterfactual quantum communications" [14], [15], [16], [17], [18], all of which involve the mysterious change of particle to wave and vice-versa, and all have been explained in [19] without particle mysteriously changing to wave and vice-versa.

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