Non-observable potentials to explain a quantum eraser and a delayed-choice experiment

Masahito Morimoto*
Fitel Photonics Laboratory of Furukawa Electric Co., Ltd., 6, Yawata-Kaigandori, Ichihara, Chiba Japan

We present a new explanation for a quantum eraser. The erasure and reappearance of an interference pattern have been explained that a revolvable linear polarizer erases or marks the information of "which-path markers", which indicate the photon path. Mathematical description of the traditional explanation requires quantum-superposition states. However, the phenomenon can be explained without quantum-superposition states by introducing non-observable potentials which can be identified as an indefinite metric vector with zero probability amplitude. In addition, a delayed choice experiment can also be explained without entangled states under the assumption that an definite orientation of the non-observable potentials configured by a setup of the experiment determines the polarization of the photon pairs in advance.

INTRODUCTION

Quantum theory has paradoxes related to the reduction of the wave packet typified by "Schrödinger's cat" and "Einstein, Podolsky and Rosen (EPR)". [1, 2] In order to interpret the quantum theory without paradoxes, de Broglie and Bohm had proposed so called "hidden variables" theory. [3, 4] Although, "hidden variables" has been negated,[5] the theory has been extended to consistent with relativity and ontology. [6–10] However the extension has not been completed so far.

The author has reported the alternative interpretation for quantum theory. [11, 12] The interpretation can omit the quantum paradoxes and be applied to elimination of zero-point energy, spontaneous symmetry breaking, mass acquire mechanism, non-Abelian gauge fields and neutrino oscillation, which can lead to the comprehensive theory. For example, as reported in [11], single photon and electron interference can be calculated without quantum-superposition state by introducing the states represent a substantial (localized) photon or electron and the non-observable potentials, which are expressed as following Maxwell equations respectively.

$$\left(\Delta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{A}_{\mathrm{l}}-\nabla\left(\nabla\cdot\mathbf{A}_{\mathrm{l}}+\frac{1}{c^2}\frac{\partial\phi_{\mathrm{l}}}{\partial t}\right)=-\mu_0\mathbf{i}$$
$$\left(\Delta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\phi_{\mathrm{l}}+\frac{\partial}{\partial t}\left(\nabla\cdot\mathbf{A}_{\mathrm{l}}+\frac{1}{c^2}\frac{\partial\phi_{\mathrm{l}}}{\partial t}\right)=-\frac{\rho}{\varepsilon_0}\quad(1)$$

and

$$\left(\Delta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{A}_{\mathrm{no}}-\nabla\left(\nabla\cdot\mathbf{A}_{\mathrm{no}}+\frac{1}{c^2}\frac{\partial\phi_{\mathrm{no}}}{\partial t}\right)=0$$
$$\left(\Delta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\phi_{\mathrm{no}}+\frac{\partial}{\partial t}\left(\nabla\cdot\mathbf{A}_{\mathrm{no}}+\frac{1}{c^2}\frac{\partial\phi_{\mathrm{no}}}{\partial t}\right)=0\quad(2)$$

The gauge invariance of the localized electro magnetic field or electron flow (electric current) enables this partition. When state vectors, which represent the non-observable potentials (2), are introduced, the vectors can be identified as indefinite metric vectors with zero probability amplitudes and as waves which cause the interference. Aharonov and Bohm have pointed out the non-observable potentials can cause electron wave interferences [13] and we must realize all of physical interactions are regulated by gauge fields (gauge principle), which can not be observed alone. [14–17]

In this letter, we show the existence of the non-observable potentials can explain not only the interferences but also the quantum eraser and delayed choice experiment.

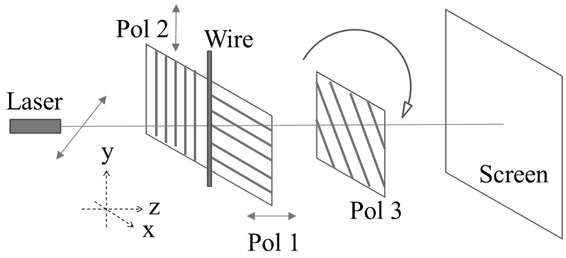

FIG. 1. Typical setup for the Quantum Eraser. Pol1 and Pol2 are fixed linear polarizers with polarizing axes perpendicular (x and y). Pol3 is a revolvable linear polarizer.

TRADITIONAL EXPLANATION FOR QUANTUM ERASER

Figure 1 shows a typical setup for the quantum eraser. [18] Without any polarizers, an interference pattern can be observed on the screen because light passing on the left of the wire is combining, or "interfering," with light passing on the right-hand side. In other words, we have no information about which path each photon went.

When polarizers 1 and 2, which are called "which-path markers", are positioned right behind the wire as shown in figure 1, the launched light polarized in 45° direction from the Laser is polarized in perpendicular (x-polarized and y-polarized) by these polarizers. Then the interference pattern on the screen is erased because "which-path makers" have made available the information about which path each photon went.

When polarizer 3 is inserted in front of the screen with the polarization angle +45° or -45° in addition to "which-path makers", the interference pattern reappears because polarizer 3 has made the information of "which-path makers" unusable.

We can produce a mathematical description of the erasure and reappearance of the interference pattern as follows. x-polarized and y-polarized photon passing through polarizer 1 and 2 can be expressed by the quantum-superposition state as follows.

$$|x\rangle = \frac{1}{\sqrt{2}}|+\rangle + \frac{1}{\sqrt{2}}|-\rangle \tag{3}$$

and

$$|y\rangle = \frac{1}{\sqrt{2}}|+\rangle - \frac{1}{\sqrt{2}}|-\rangle \tag{4}$$

where "+" and "-" represent polarizations +45° and -45° with respect to x.

The photons pass through polarizer 1 and 2 are polarized at right angles to each other as seen in the left-hand side of (3) and (4), which prevent the interference pattern. In other words, "which-path makers" have made available the information about which path each photon went. Although there are same polarized states in the right-hand side of (3) and (4), the interference patterns consisting of bright and dark fringes made by +45° and -45° polarized states are reverted images and annihilate each other. Therefore sum total of the images has no interference pattern.

When polarizer 3 is inserted with the polarization angle +45° or -45°, only $|+\rangle$ or $|-\rangle$ can pass through polarizer 3. Then the interference pattern made by either $|+\rangle$ or $|-\rangle$ of both (3) and (4) reappears, which means we can not identify which-path the photons had passed through, i.e., polarizer 3 has made the information of "which-path makers" unusable.

NEW EXPLANATION FOR QUANTUM ERASER

The mathematical description of the photon states passing through polarizer 1 and 2 for the traditional explanation requires the quantum-superposition states (3) and (4) respectively.

If Maxwell equations are deemed to be classical wave equations whose electro-magnetic fields obey the superposition principle, then the description is valid. However, applying the superposition principle to particle image, e.g., inseparable single photon, leads to quantum paradoxes.

Here we take advantage of the non-observable potentials that can eternally populate the whole of space as waves independent of existence of the substantial photons. Therefore we can replace the photon state $|x\rangle$ with $|x\rangle + |\zeta\rangle$, where $|\zeta\rangle$ is a state represent the non-observable potentials whose probability amplitudes $\langle\zeta|\zeta\rangle = 0$. The non-observable potentials can be polarized by the polarizers because the potentials exist all the time.

Note that the non-observable potentials and localized potentials that represent the substantial photons can be superposed because the both are originally a pair of Maxwell equations, i.e., (1) + (2).

Then sum of the states will behave as if the substantial photons configure the quantum-superposition states (3) and (4), i.e., the states represent the non-observable potentials can be expressed as follows.

$$\begin{aligned} |x\rangle \rightarrow |x\rangle + |\zeta_x\rangle &= \frac{1}{\sqrt{2}}|+\rangle + \frac{1}{\sqrt{2}}|-\rangle + |\zeta_1\rangle \\ |y\rangle \rightarrow |y\rangle + |\zeta_y\rangle &= \frac{1}{\sqrt{2}}|+\rangle - \frac{1}{\sqrt{2}}|-\rangle + |\zeta_2\rangle \end{aligned} \tag{5}$$

where $|\zeta_x\rangle$ and $|\zeta_y\rangle$ are the non-observable potentials exist with $|x\rangle$ and $|y\rangle$ respectively, $|\zeta_{1\mathrm{or}2}\rangle$ is non-observable potentials after passing through the polarizer 1 or 2, which is rest of the $|\zeta\rangle$ polarized by the polarizers. Therefore,

$$\begin{aligned} |\zeta_x\rangle &= \frac{1}{\sqrt{2}}|+\rangle + \frac{1}{\sqrt{2}}|-\rangle - |x\rangle + |\zeta_1\rangle = |\zeta_1\rangle \\ |\zeta_y\rangle &= \frac{1}{\sqrt{2}}|+\rangle - \frac{1}{\sqrt{2}}|-\rangle - |y\rangle + |\zeta_2\rangle = |\zeta_2\rangle \end{aligned} \tag{6}$$

The non-observable potentials can not be observed alone even if the potentials are polarized by the polarizers, which can be confirmed from (6), i. e., $\langle\zeta_1|\zeta_1\rangle = \langle\zeta_2|\zeta_2\rangle = \langle\zeta_x|\zeta_x\rangle = \langle\zeta_y|\zeta_y\rangle = 0$.

In this new explanation, the polarization of substantial photons is fixed and the photons can not pass through the polarizer whose polarization angle is different from that of photons. However, the non-observable potentials are forced to form states as if the states are superposition state of $|+\rangle$ and $|-\rangle$ by the polarizers. Then portion of the non-observable potentials can pass through the polarizer. Therefore the non-observable potentials passing through the polarizer 3 produce exactly the same interference explained by (3) and (4). In case of single photon, the interference can be explained by cross terms of $\langle\pm|\zeta\rangle = \langle\zeta|\pm\rangle^*$. Note that even if no photon exists, i.e., $|x\rangle$, $|y\rangle$, etc. $= |0\rangle$ (vacuum state), the non-observable potentials can exist as $|0\rangle + |\zeta\rangle$ with zero probability amplitude as seen in (6). Hence $|0\rangle + |\zeta\rangle$ can be identified as vacuum instead of $|0\rangle$.

For example, a photon $|x\rangle$ passing through polarizer 1 can not pass through polarizer 3 with the polarization angle +45° or -45°. Then either the polarization component of the potentials $\frac{1}{\sqrt{2}}|+\rangle$ or $\frac{1}{\sqrt{2}}|-\rangle$ (define $|\zeta_1\rangle_+$ or $|\zeta_1\rangle_-$

respectively.) can pass through polarizer 3 depending on its angle. Then after the potentials pass through polarizer 3, $|\zeta_1\rangle_+$ and $|\zeta_2\rangle_+$ or $|\zeta_1\rangle_-$ and $|\zeta_2\rangle_-$ are superposed, e.g., $|\zeta_1\rangle_+ + e^{i\theta}|\zeta_2\rangle_+ = \frac{1}{\sqrt{2}}|+\rangle + \frac{1}{\sqrt{2}}e^{i\theta}|+\rangle$, depending on the polarization angle and the superposed potentials recover the interference pattern as a photon. Where θ is a phase difference between the paths. That is the superposed components formed by the first or second terms on the central formula of (6) change from the potentials into a substantial photon.

From the law of conservation of energy, the energy of the superposed potentials is derived from that of the incident photon in this single photon case. Therefore the new explanation can describe that $|0\rangle + |\zeta\rangle$, which can be identified as vacuum as described above, creates and annihilates the substantial photons.

Then the single photon change from the potentials (denoted by $|1\rangle$) makes self-interference by the non-observable potentials as follows.

$$\begin{aligned}
&(\langle 1| + \langle\zeta|)\,\hat{a}^\dagger\hat{a}\,(|1\rangle + |\zeta\rangle)\\
&= \langle 1|\hat{a}^\dagger\hat{a}|1\rangle + \langle 1|\hat{a}^\dagger\hat{a}|\zeta\rangle + \langle\zeta|\hat{a}^\dagger\hat{a}|1\rangle + \langle\zeta|\hat{a}^\dagger\hat{a}|\zeta\rangle\\
&\propto 1 + \langle 1|\zeta\rangle + \langle\zeta|1\rangle + \langle\zeta|\hat{a}^\dagger\hat{a}|\zeta\rangle\\
&= \frac{1}{2} \pm \frac{1}{2}\cos\phi
\end{aligned} \tag{7}$$

where $\hat{a}^\dagger$, $\hat{a}$ are photon creation and annihilation operators respectively, ϕ is a phase difference between the single photon and non-observable potentials, $\langle 1|\zeta\rangle = \langle\zeta|1\rangle^* = \pm\frac{1}{4}e^{j\phi}$ and $\langle\zeta|\hat{a}^\dagger\hat{a}|\zeta\rangle = -\frac{1}{2}$ are used. [11, 12]

Loosely speaking, the non-observable potentials are oriented by polarizers such as (6). Then the substantial photons surf on the sea of the oriented potentials which can change into substantial photons depending on the energy balance. In addtion, the state after cast the photon in the polarized non-observable potentials is indistinguishable from quantum-superposition state.

Note that (5) are not the superposition states of $|+\rangle$ and $|-\rangle$. Instead, the states are composed of substantial states $|x\rangle$ or $|y\rangle$ and states of non-observable potential $|\zeta\rangle$. These combination of the states behave like the superposition states of $|+\rangle$ and $|-\rangle$. Therefore there is no wave packet reduction and fulfillment of engineering applications utilizing the wave packet reduction such as quantum teleportation or computer will be pessimistic conclusion.

NEW EXPLANATION FOR DELAYED CHOICE QUANTUM ERASER

In this section, we show new explanation for Delayed Choice Quantum Eraser as shown in figure 2 which consists of an entangled photon source and two detectors. The delayed choice has been demonstrated when the distance from BBO to polarizer 1 is longer than that from BBO to the double slit. [19]

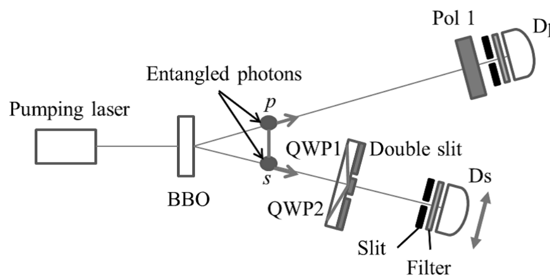

FIG. 2. Typical setup for the Delayed Choice Quantum Eraser. QWP1 and QWP2 are quarter-wave plates aligned in front of the double slit with fast axes perpendicular. Pol1 is a linear polarizer. BBO (β−BaB_2O_4) crystal generates entangled photons by spontaneous parametric down-conversion. [19]

Here we should take particular note of the fact that the polarization angle of polarizer 1 has been chosen before the entangled photons are generated. S. P. Walbornet et al. [19] have pointed out that "the experiment did not allow for the observer to choose the polarization angle in the time period after photon s was detected and before detection of p". From the principle of causality, their point will be reasonable.

However, mathematical description for the phenomenon requires entangled state such as

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|x\rangle_s|y\rangle_p + |y\rangle_s|x\rangle_p\right) \tag{8}$$

The entangled state declares that the state of the whole system is a quantum-superposition state consist of $|x\rangle_s|y\rangle_p$ and $|y\rangle_s|x\rangle_p$. Therefore when the state of one photon (s or p) is observed and determined to be $|x\rangle$, that of the other photon (p or s) suddenly changes from the quantum-superposition state into $|y\rangle$ even if the photons separate from each other, which postulates the existence of long-range correlation beyond the causality (spooky action at a distance).

Hence we consider physical phenomenon from the moment we choose the polarization angle of polarizer 1 to the moment BBO generates the entangle photon pairs.

The non-observable potentials, which can change from the potentials into substantial photons, eternally populate the whole of space not forgetting the space between BBO and Polarizer 1 independent of substantial photons. Hence the space will be populated by the non-observable potentials which are oriented by polarizer 1 as described above. More precisely, the potentials determine the polarization of substantial photons in the space in advance depending on the polarization angle of polarizer 1.

For example, if we choose the polarization angle of polarizer 1 to 0°, the non-observable potentials are oriented to $|\zeta_x\rangle = \frac{1}{\sqrt{2}}|+\rangle + \frac{1}{\sqrt{2}}|-\rangle - |x\rangle + |\zeta_1\rangle$ at polarizer 1 and propagate to BBO. BBO is forced to generate the photon pair with polarization $p : x$ and $s : y$ according to the arrival potentials. Then the polarization of the photon pair is fixed by the non-observable potentials instead of the entangle state (8). Therefore when the polarization angle is set to the fast axis of QWP (Quarter-wave plate) 1 or 2, the interference pattern can be observed.

Because the non-observable potentials can not be observed, we are not aware of the determination of the polarization of the photon pair by the non-observable potentials. This is the reason why the state seems to be "entangled" and the choice of the polarization angle of polarizer 1 seems to be "delayed".

In order to confirm the new explanation, we should make experiments with a shutter between BBO and polarizer 1 as follows. First, close the shutter not to make a definite orientation of the non-observable potentials. After the entangled photon pairs are generated, open the shutter. When the photon s is measured by Ds, close the shutter again. After a time period, we excite BBO to generate the next entangled photon pairs. When the next pairs are generated, open the shutter again. By repeating these procedures, we can make a comparison between the traditional results and new result. If the definite orientation of the non-observable potentials as mentioned above is valid, no interference pattern can be observed even if the polarization angle of Polarizer 1 is set to the fast axis of QWP 1 or 2 throughout the experiment.

Note that because the non-observable potentials obeying Maxwell equations propagate at the speed of light, the above time period that prevents the non-observable potentials from being oriented should be longer than the distance between BBO and the shutter divided by the speed of light.

CONCLUSIONS

We have presented the quantum eraser can be explained without quantum-superposition states by introducing the states represent the non-observable potentials whose probability amplitudes are zero. The explanation presents a image of vacuum that can create and annihilate the substantial photons.

We have also investigated the delayed choice experiment under the assumption that the polarization of the photon pairs is determined by the non-observable potentials which are oriented by the setup of the experiment in advance. The new explanations obtained in the present letter are more general and appear to be physically more consistent than traditional explanations which require paradoxical quantum-superposition states and entangled states.

The other experiments and considerations have been reported, which seem like paradoxes. [20–25] We believe the paradoxes can be avoided by the new explanation.

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* morimoto@ch.furukawa.co.jp

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