Unobservable potentials to explain a quantum eraser and a delayed-choice experiment

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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 unobservable 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 unobservable 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 utilizing quantum field formalism with unobservable potentials that can be identified as unobservable gauge fields such as Araronov-Bohm effect. [11–13] 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 unobservable 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

$$\left(\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{A}_\mathrm{uo} - \nabla\left(\nabla\cdot\mathbf{A}_\mathrm{uo} + \frac{1}{c^2}\frac{\partial\phi_\mathrm{uo}}{\partial t}\right) = 0$$
$$\left(\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\phi_\mathrm{uo} + \frac{\partial}{\partial t}\left(\nabla\cdot\mathbf{A}_\mathrm{uo} + \frac{1}{c^2}\frac{\partial\phi_\mathrm{uo}}{\partial t}\right) = 0 \quad (2)$$

The gauge invariance of the localized electro magnetic field or electron flow (electric current) enables this particle.

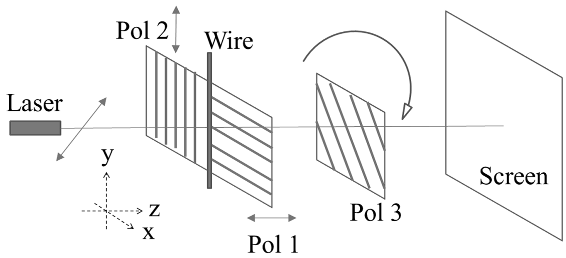

FIG. 1. Typical setup for the Quantum Eraser. Pol1 and Pol2 are fixed linear polarizers with polarizing axes perpendicular (x and y). Pol3 is a revolvable linear polarizer.

tion. When state vectors, which represent the unobservable 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 unobservable potentials can cause electron wave interferences [13] and we should 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 unobservable potentials can explain not only the interferences but also the quantum eraser and delayed choice experiment.

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 unobservable 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 unobservable potentials whose probability amplitudes $\langle\zeta|\zeta\rangle = 0$ in initial states (when there are no phase or polarization angle differences as described below.). The unobservable potentials can be polarized by the polarizers because the potentials populate the whole of space-time.

Note that the unobservable 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 the following states [11] can generate the same interference as the quantum-superposition states (3) and (4).

$$\begin{aligned} |x\rangle + |\zeta_{\phi,x}\rangle &= |x\rangle + \frac{1}{2}\gamma e^{i\phi} e^{i\theta/2}|x\rangle - \frac{1}{2}\gamma e^{-i\phi} e^{-i\theta/2}|x\rangle \\ |y\rangle + |\zeta_{\phi+\frac{1}{2}\pi,y}\rangle &= |y\rangle + \frac{1}{2}\gamma e^{i(\phi+\frac{1}{2}\pi)} e^{-i\theta/2}|y\rangle \\ &\quad - \frac{1}{2}\gamma e^{-i(\phi+\frac{1}{2}\pi)} e^{i\theta/2}|y\rangle \end{aligned} \tag{5}$$

where $\gamma^2 = -1$, ϕ and θ are the indefinite metric, the polarization angle of polarizer 3 to x-axis and phase difference between left and right paths respectively.

Therefore when we observe only $|x\rangle$ with polarizer 3, i. e., $\theta = 0$, the intensity of the interference $\langle I\rangle$ can be calculated as follows.

$$\begin{aligned} \langle I\rangle &\propto (\langle x| + \langle\zeta_{\phi,x}|)(|x\rangle + |\zeta_{\phi,x}\rangle) \\ &= \langle x|x\rangle - \frac{1}{2}\langle x|x\rangle + \frac{1}{2}\langle x|x\rangle\cos(2\phi+\theta) \\ &= \frac{1}{2} + \frac{1}{2}\cos(2\phi+\theta) = \frac{1}{2} + \frac{1}{2}\cos(2\phi) \end{aligned} \tag{6}$$

Hence the output intensity by rotation angle of polarizer 3 is correctly-reproduced.

When we observe $|x\rangle$ and $|y\rangle$ with polarizer 3, the intensity is obtained as follows.

$$\begin{aligned} \langle I\rangle \propto &\left(\langle x| + \langle\zeta_{\phi,x}| + \langle y| + \langle\zeta_{\phi+\frac{1}{2}\pi,y}|\right) \\ &\cdot \left(|x\rangle + |\zeta_{\phi,x}\rangle + |y\rangle + |\zeta_{\phi+\frac{1}{2}\pi,y}\rangle\right) \end{aligned} \tag{7}$$

Because $\langle x|y\rangle = \langle y|x\rangle = 0$, then

$$\begin{aligned} \langle I\rangle \propto &(\langle x| + \langle\zeta_{\phi,x}|)(|x\rangle + |\zeta_{\phi,x}\rangle) \\ &+ \left(\langle y| + \langle\zeta_{\phi+\frac{1}{2}\pi,y}|\right)\left(|y\rangle + |\zeta_{\phi+\frac{1}{2}\pi,y}\rangle\right) \end{aligned} \tag{8}$$

By using (6), we can obtain

$$\begin{aligned} \langle I\rangle &\propto \frac{1}{2} + \frac{1}{2}\cos(2\phi+\theta) + \frac{1}{2} + \frac{1}{2}\cos(2\phi+\pi-\theta) \\ &= 1 + \frac{1}{2}\cos(2\phi+\theta) - \frac{1}{2}\cos(2\phi-\theta) \end{aligned} \tag{9}$$

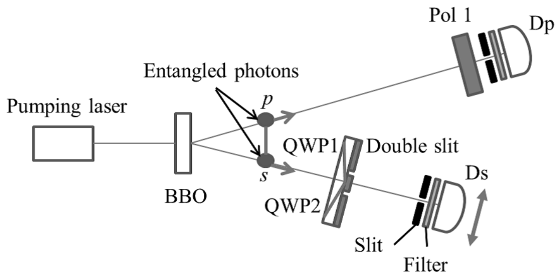

FIG. 2. Typical setup for the Delayed Choice Quantum Eraser. QWP1 and QWP2 are quarter-wave plates aligned in front of the double slit with fast axes perpendicular. Pol1 is a linear polarizer. BBO ($\beta{-}BaB_2O_4$) crystal generates entangled photons by spontaneous parametric down-conversion. [19]

When $\phi = \pm\pi,\ \pm\frac{1}{2}\pi$ then $\langle I\rangle \propto 1$ and $\phi = \pm\frac{1}{4}\pi$ then $\langle I\rangle \propto 1 \pm \sin\theta$, which reproduces the interference correctly.

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 unobservable potentials create the same interference as the superposition state of $|+\rangle$ and $|-\rangle$ as described above. In case of single photon, the interference can be calculated by (5) replacing $|y\rangle$ with $|0\rangle$. Then $\langle I\rangle \propto 1+\frac{1}{2}\cos(2\phi+\theta)-\frac{1}{2}\cos(2\phi-\theta)$ is obtained. Note that when we calculate the single photon interference by using photon number operator $\mathbf{n}$, we can obtain exact expression $\langle I\rangle \propto \frac{1}{2}+\frac{1}{2}\cos(2\phi+\theta)$ because $\langle 0|0\rangle = 1 \neq \langle 0|\mathbf{n}|0\rangle = 0$. [11]

The new explanation can describe that $|0\rangle + |\zeta\rangle$ which can be identified as vacuum, creates and annihilates the substantial photons through the interference.

Loosely speaking, the unobservable potentials are oriented by the polarizers such as (5). Then the substantial photons surf on the sea of the oriented potentials which can change into substantial photons through the interference.

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 unobservable potential $|\zeta\rangle$. These combination of the states create the same interference as 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]

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

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|x\rangle_s|y\rangle_p + |y\rangle_s|x\rangle_p\right) \qquad (10)$$

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 unobservable 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 unobservable 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 ϕ which is measured from the polarization angle ψ of created photons, the vacuum is oriented to $|0\rangle + |\zeta_\phi\rangle = |0\rangle + \frac{1}{2}\gamma e^{i(\phi-\psi)}e^{i\theta/2}|0\rangle - \frac{1}{2}\gamma e^{-i(\phi-\psi)}e^{-i\theta/2}|0\rangle$ at polarizer 1 and propagate to BBO. BBO is forced to generate the photon pair with polarization $p:\ \phi$ and $s:\ \phi \pm \frac{1}{2}\pi$ according to the arrival potentials. More precise explanation is as follows. By applying a photon creation operator $\hat{a_\psi}^\dagger$ to the polarized vacuum, i. e., $\hat{a_\psi}^\dagger|0\rangle + \hat{a_\psi}^\dagger|\zeta_\phi\rangle =$

$$|\psi\rangle + \frac{1}{2}\gamma e^{i(\phi-\psi)}e^{i\theta/2}|\psi\rangle - \frac{1}{2}\gamma e^{-i(\phi-\psi)}e^{-i\theta/2}|\psi\rangle \qquad (11)$$

can be calculated as the created photon state at BBO. There is no phase difference $\theta = 0$ because there is no other path in the setup. Then the intensity of the created photon can be calculated as follows.

$$\langle I\rangle \propto \frac{1}{2} + \frac{1}{2}\cos(2\phi - 2\psi) \qquad (12)$$

In order to create a photon, i. e., $\langle I\rangle = 1$, $\psi = \phi$ will be required.

Then the polarization of the photon pair is fixed by the unobservable potentials instead of the entangle state (10). 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 unobservable potentials can not be observed, we are not aware of the determination of the polarization of the photon pair by the unobservable 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 unobservable 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 unobservable 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 unobservable potentials obeying Maxwell equations propagate at the speed of light, the above time period that prevents the unobservable potentials from being oriented should be longer than the distance between BBO and the shutter divided by the speed of light.

The above new explanation is based on the preselected polarization by the setup. However even if the polarizations of the photon pair are randomly selected, the measurement results seem like the long-range correlation beyond the causality as follows. From (5), the measurement results of photons s and p are expressed as follows.

$$\begin{aligned} \langle I_s\rangle &\propto = \frac{1}{2} + \frac{1}{2}\cos(2\phi) \\ \langle I_p\rangle &\propto = \frac{1}{2} - \frac{1}{2}\cos(2\phi) \end{aligned} \tag{13}$$

There is no such a classical correlation. The long-range correlation beyond the causality will be created by the interference between the photons and unobservable potentials.

CONCLUSIONS

We have presented the quantum eraser can be explained without quantum-superposition states by introducing the states represent the unobservable 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 unobservable potentials which are oriented by the setup of the experiment in advance. In addition, even if there is no determination of the polarization by the setup, measurement results seem like the long-range correlation beyond the causality. 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 and conclude that engineering application utilizing wave packet reduction or entangled states will fail.

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[1] J. D. Trimmer, Proceedings of the American Philosophical Society **124**, 323 (1980).
[2] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev **47**, 777 (1935).
[3] D. Bohm, Phys. Rev. **85**, 166 (1952).
[4] D. Bohm, Phys. Rev. **85**, 180 (1952).
[5] J. S. BELL, Rev. Mod. Phys. **38**, 447 (1966).
[6] X. Oriols and J. Mompart, ArXiv e-prints (2012), arXiv:1206.1084 [quant-ph].
[7] P. Pylkkänen, B. J. Hiley, and I. Pättiniemi, ArXiv e-prints (2014), arXiv:1405.4772 [quant-ph].
[8] D. Durr, S. Goldstein, T. Norsen, W. Struyve, and N. Zanghi, Royal Society of London Proceedings Series A **470**, 30699 (2013), arXiv:1307.1714 [quant-ph].
[9] V. Allori, S. Goldstein, R. Tumulka, and N. Zanghi, ArXiv e-prints (2012), arXiv:1206.0019 [quant-ph].
[10] G. Dennis, M. A. de Gosson, and B. J. Hiley, Physics Letters A **378**, 2363 (2014).
[11] M. Morimoto, viXra e-prints (2013), 1312.0097 [quant-ph].
[12] M. Morimoto, viXra e-prints (2014), 1406.0177 [quant-ph].
[13] Y. Aharonov and D. Bohm, Phys. Rev. **115**, 485 (1959).
[14] C. N. Yang and R. L. Mills, Phys. Rev. **96**, 191 (1954).
[15] T. T. Wu and C. N. Yang, Phys. Rev. D **12**, 3845 (1975).
[16] S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967).
[17] R. Utiyama, Phys. Rev. **101**, 1597 (1956).
[18] P. K. Rachel Hillmer, Scientific American , 90—95 (2007).
[19] S. P. Walborn, M. O. Terra Cunha, S. Pádua, and C. H. Monken, Phys. Rev. A **65**, 033818 (2002).

[20] D. Salart, A. Baas, J. A. W. van Houwelingen, N. Gisin, and H. Zbinden, Phys. Rev. Lett. **100**, 220404 (2008).
[21] Y.-H. Kim, R. Yu, S. P. Kulik, Y. Shih, and M. O. Scully, Phys. Rev. Lett. **84**, 1 (2000).
[22] A. Aspect, P. Grangier, and G. Roger, Physical review letters **47**, 460 (1981).
[23] A. Aspect, P. Grangier, and G. Roger, Physical review letters **49**, 91 (1982).
[24] A. Aspect, J. Dalibard, and G. Roger, Physical review letters **49**, 1804 (1982).
[25] J. F. Clauser and M. A. Horne, Physical review D **10**, 526 (1974).